

1 Laser Scanning – Evolution of the Discipline

ANDREW R.G. LARGE¹ AND GEORGE L. HERITAGE²

¹School of Geography, Politics and Sociology, Newcastle University,
Newcastle Upon Tyne, UK

²JBA Consulting, Greenall's Avenue, Warrington, UK

A BRIEF HISTORY OF LASER DEVELOPMENT FOR TOPOGRAPHIC SURVEYING

Since its introduction in the 1960s, the laser has assumed a central role in the accurate measuring of natural environments. The historical background to laser scanning began in 1958 when two scientists, Charles Townes and Arthur Schawlow, suggested the potential for a narrow beam of very intense monochromatic radiation travelling over large distances that could be precisely directed (Price & Uren 1989). The first solid-state ruby laser was developed in 1960 and emitted powerful pulses of collimated red light. The period 1962–68 saw basic development of laser technology ('laser' is an acronym for *Light Amplification by the Stimulated Emission of Radiation*), and was followed in the 1970s by a period of improvement in the reliability of the technique. It was not long before the potential for a narrow, straight, reflectable beam as a reference direction in alignment was recognised. Early surveying instruments were developed specifically for laboratory use, the first laser distance-measuring instrument appeared in 1966 and the first alignment laser was marketed from 1971 onwards (Price & Uren, 1989). Despite reliability issues (the first instruments only had an

operating life of 1000 hours), commercial success followed and the 1970s saw a rapid uptake in the use of lasers in engineering surveying and the construction industry. Once the early systems were adapted into weather-proofed machines that were specifically designed for more rugged situations, environmental scientists rapidly took up the new technology, and the 1980s and 1990s saw a wide range of applications in a broad range of environmental systems. Initially there was commercial inertia: Price and Uren (1989) quote a survey of commercial operators in the UK and USA which showed that, less than two decades ago, only 5% of commercial contractors in the UK used lasers at some time in their work (the comparative figure for the US was 95%).

Today, laser-based instrumentation is standard in a wide range of applications, with laser surveying instruments falling into three categories: fixed beam, rotation beam and distance measurers. Since the end of the 20th century the pace of technological progress has been breathtaking and field scientists now have the ability to rapidly measure environmental systems virtually in their entirety.

THE THEODOLITE AND THE EDM

Prior to development of laser scanning instrumentation, the theodolite was the most versatile and extensively used of all surveying instruments. This versatility was due to the manner in which

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all theodolites performed two simple operations – measuring angles in horizontal and vertical planes (Ritchie *et al.*, 1988). To date, theodolites remain standard surveying tools due to their versatility, accuracy and ease of operation.

The development of Electromagnetic Distance Measuring (EDM) devices designed for accurate distance measurement had a great influence on the discipline and soon became one of the most widely used pieces of technology for surveying exercises based on either triangulation, traversing and radiation, all of which have accurate distance measurement at their heart. In essence, an EDM can rapidly record spot heights and distance measurements in the field in the laying out of baselines over much longer distances than were obtainable with conventional methods. Most EDMs use a near-visible light source, or electromagnetic beam in the form of a modulated sine wave. In earlier instruments, the signal generated by the EDM was reflected back by a prism, with distance calculated by measuring the phase shift between the outgoing and returned signals. Distances measured can only be less than the wavelength of the carrier wave. Given that the wavelengths of the usual light sources are very typically short (e.g. infra-red at about 0.0009 mm), EDMs use a carrier wave (near-visible radio, microwaves) which can be modulated to allow it to carry a more useful wavelength. For example, if the carrier wave is modulated to 10 m, the instrument is capable of measuring the phase shift of the modulated wave to an accuracy of 1–2 mm. The shorter the wavelength of the carrier wave, the higher the accuracy of distance measurement (but with a trade-off – the wavelength of the carrier controls the distance over which accurate measurements can be taken). Most modern EDM instruments use a near visible light source as this has the least cost and power requirement. More recent machines have dispensed with the need for prisms – a development which has again speeded up the rate of data acquisition.

Until recently, EDM proved an efficient and reliable way of collecting the data necessary to produce a DEM. Questions have been posed, however, as to the best way to represent features in the field (Chappel *et al.*, 2003; Brunsten:

Chapter 5, this volume). Most workers interpolate elevations using an arbitrary mathematical surface fitted through some of the data to form a regular grid. This assumes, however, that data are spatially dependant, yet this is rarely determined or quantified (it may also introduce additional sources of error). While different sampling strategies can emphasise the effect of data redundancy on DEM generation it is undeniable that, the more data points used, the more representative the DEM will be of the ‘real-world’ situation.

Intensive mapping in large (>1 km²) natural systems using traditional theodolite EDM may exert a high demand on operator time and cost, especially when including the survey of all detail at a scale larger than the geomorphological unit (gravel bar, riffle, dune slack, moraine etc.). Sub-unit morphology (e.g. chute channels, sediment lobes) may be ignored to rationalise time in the field or at the photogrammetric plotter; however these features may represent significant changes in sediment storage within the channel system, and comprise important habitat for biota within these dynamic systems as they are subject to intermediate levels of disturbance (Cornell, 1978). Airborne LiDAR is thus a useful tool for the acquisition of such terrain data as, while methods like EDM and DGPS also have potential for rapid topographic data acquisition (e.g. Brasington *et al.*, 2000), areal extent remains a limiting factor for these other techniques. Laser scanning techniques have the ability to vastly increase the data collection ability and, theoretically, to improve the accuracy of DEM representations of a range of natural environments.

REVIEW OF PREVIOUS DEVELOPMENTS

From point sampling to data clouds – a sea change in laser surveying

LiDAR, variously termed in the literature as *Laser Induced Direction and Ranging* (Marks & Bates, 2000) or, more commonly, *Light Detection and Ranging* (e.g. Wehr & Lohr, 1999; Smith-Voysey, 2006), provides laser-based measurements of the distance between an aircraft carrying the sensor

and the ground. The resulting measurements can be post-processed to provide a digital elevation model with a precision within 15 cm (Charlton *et al.*, 2003). LiDAR consequently has significant potential for generating high-resolution digital terrain surfaces accurately, representing complex natural and semi-natural environments incorporating morphological features at a range of scales (e.g. McHenry *et al.*, 1982; Jackson *et al.* 1988; Ritchie, 1995; Ritchie & Jackson 1989; Ritchie *et al.*, 1992a, 1992b, 1994, 1995; Krabill *et al.*, 1995; Wadhams, 1995; Gauldie *et al.*, 1996; Bissonnette *et al.*, 1997; Parson *et al.*, 1997; Innes & Koch, 1998; Irish & White, 1998; Geist *et al.*, 2003; Godin-Beckman *et al.*, 2003; Ancellet & Ravetta, 2003; Staley *et al.*, 2006). As such, LiDAR technology has huge attractions for the environmental scientist. Hodgetts (Chapter 11, this volume) summarises these as follows:

- The technology is characterised by very high speed data collection – for example the Riegl LMS420i terrestrial laser scanner can scan at up to 12,000 data points per second (later generation machines being faster), with each data point having *x,y,z* positional information, reflection intensity and colour provided by a calibrated high resolution digital camera. Speed of collection is, however, machine-dependant.
- Datasets, once collected, may be interrogated at a later date for information which was not the focus of the original project.
- There is a high degree of coverage – therefore the LiDAR data can be returned to at a later stage in order to look for other features which may have initially been missed in the field.
- Accurate spatial data can be easily collected.

The downside, it has to be said, is cost: typical entry costs for terrestrial laser scanning equipment is currently in the order of £100,000 (*circa* £70,000 for hardware and £30,000 for processing software). LiDAR costs are prohibitive and ownership of this equipment is restricted to consortia and governmental research councils (in the UK the main provider is the Airborne Remote Sensing Facility (ARSF) section of the government-funded Natural Environment Research Council). Despite these restrictions, the techniques have considerable advantages over

conventional surveying techniques (see other chapters in this volume for numerous examples of how they have recently been widely applied in the environmental sciences). Certain fields have been slower to adopt the technology; use of LiDAR for hydrologic and hydraulic applications has, for example, been relatively limited (Hollaus *et al.*, 2005). Wealands *et al.* (2004) have discussed the usefulness of remotely sensed data for distributed hydrological models, while Brügelmann and Bollweg (2005) describe how roughness coefficients can be used to derive hydraulically relevant cover classes (see case study below for an expansion on this topic). Pereira and Wicherson (1999) describe the potential for airborne laser scanning for collecting relief information for use in river management, and in the UK the Environment Agency regularly uses LiDAR-derived flood surface predictions as a public education tool.

How does LiDAR work?

Position for any *x,y,z* point on the Earth's surface is generated from three sources: (i) the LiDAR sensor, (ii) the Inertial Navigation Unit (INU) of the aircraft and (iii) GPS. The LiDAR measurements must be corrected for the pitch, roll and yaw of the aircraft, and the GPS information allows the slant distances to be corrected and converted into a measurement of ground elevation relative to the WGS84 datum. The measurements are taken from side-to-side in a swath as the aircraft flies along its path (Baltsavias, 1999); those measurements at the centreline of the swath are more precise than those near the edge (Figure 1.1). Brinkman and O'Neill (2000) also observe that both horizontal and vertical precision depend on the flying height (where horizontal precision is 1/2000th of the flying height); horizontal precision will thus be 'accurate to 15 centimetres or better' when the flying height is at or below 1200 m. The standard altitude for airborne LiDAR acquisition is *circa* 3,500 m.

Airborne LiDAR sensors generally emit anything between 5000 and 50,000 laser pulses per second, although Smith-Voysey (2006) states a higher figure of 100,000 pulses per second, a figure claimed for machines such as the Optech ALTM3100EA

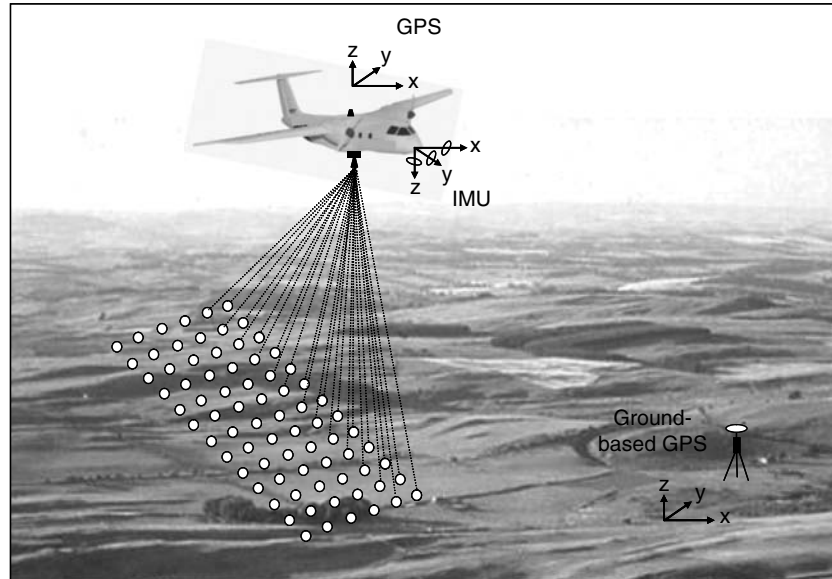


Fig. 1.1 Typical operation of an airborne LiDAR survey. The sensor operates in swaths across the terrain surface (shown by small open circles in this diagram), and is georeferenced by an inertial navigation unit (INU) in the aircraft and a ground-based differential GPS.

which operates at 167 kHz laser pulse repetition frequency. The spacing of these points is determined in two directions. In the in-flight direction, point spacing is determined by aircraft speed and altitude, whereas in the cross-flight direction (normal to the angle of flight direction), point spacing is defined by scan angle and altitude. In terms of what is actually emitted, each pulse has a diameter, or 'footprint' (typically between 0.5 and 1 m) and a length defined by the time between the laser pulse being switched on and off. In essence therefore, each pulse is a cylinder of light. On their own, these reflected pulses are not enough to construct a terrain surface; accurate x - y - z position using differential GPS is needed relative to ground-based GPS base stations, the roll, pitch and yaw of the aircraft needs to be measured by an inertial measuring unit (IMU), which in turn allows the angular orientation of each laser pulse to be determined. Finally, the times taken for each laser pulse to reflect off the ground (or whatever surface) and return to the sensor is measured. This is termed the 'return'. In essence then, laser

scanning depends on knowing the speed of light, approximately 0.3 m/ns. Using that constant, we can calculate how far a returning light photon has travelled to and from an object:

$$\text{Distance} = (\text{Speed of Light} \times \text{Time of Flight})/2 \quad (1.1)$$

The return operates in two modes (both of which are described by contributors in this volume):

First-pulse: Measures the range to the first object encountered – in many this is vegetation, for example tree foliage.

Last-pulse: Measures the range to the last object – the ground surface under the foliage.

Machines like the Optech ALTM (Airborne Laser Terrain Mapper) system can measure both tree-heights and the topography of the ground beneath in a single pass.

LiDAR sensors are capable of receiving multiple returns. As some are up to five returns per pulse, a 30 kHz sensor has to be able to record up to 150,000 returns per second. Multiple returns

are characteristic of 'soft' cover (e.g. vegetation) with a 'first return' indicating, for example, the top of the tree canopy, and other returns being indicative of branches etc. While in theory the last return represents the underlying ground, this is not always the case. Danson *et al.* and Overton *et al.* (this volume) discuss the issues and opportunities associated with LiDAR and vegetation cover in greater detail. LiDAR technology has also proven extremely versatile for studies on the Earth's atmosphere; NASA's Cloud Aerosol and Infrared Pathfinder Satellite Observations (CALIPSO) satellite will use LiDAR to determine atmospheric composition based on scattering of the laser pulse accurately measured to micrometre level (10^{-6} m).

LiDAR accuracy and precision

The integration of airborne LiDAR with GPS facilitates the wider use of high resolution DEMs in a wide range of physical applications. The method of survey is rapid, relatively economic and allows survey of difficult terrain, and large areas. According to Marks and Bates (2000) LiDAR permits rapid gathering of topographic data for areas at rates of up to 90 km² per hour. This makes it an attractive alternative to ground-based survey methods and, due to the advantages outlined above, airborne-laser scanning has become the primary choice for gathering precise and dense DEMs of large areas for a wide range of applications. While LiDAR is currently the most efficient method for data acquisition, airborne laser-scanning does have reliability issues. It is difficult to determine the level of precision of LiDAR measurements for any one survey and, in complex topography, small lateral offsets associated with the IMU and GPS will be translated into vertical error in the LiDAR surface. This is less of a problem on open, unvegetated surfaces than in areas with tall vegetation cover. If the flight layout can be optimised for GPS (with at least six satellites in view) then precisions of 7–8 cm are theoretically achievable.

Katzenbeisser (2003) has outlined a number of other issues with a primary concern being the fact that users are frequently confronted with artefacts, mis-match of flight strips and distortions in the

rendering of data. These can arise for a number of reasons but invariably involve the measurements and calculations of three basic elements: (i) sensor position, (ii) distance to reflecting object and (iii) viewing direction to reflecting object. Sensor position is calculated by post-processing DGPS on-the-fly algorithms (Katzenbeisser, 2003) and requires acquisition at 1 Hz dual frequency and a stable satellite constellation (PDOP <2.5) with no signal disruption. The ground-based GPS reference station should ideally be located within the survey area but be no more than 25 km away. As distance cannot be measured directly, the time from emitting a laser pulse until an echo is received (termed 'time of flight') is measured and converted into distance, typically by counting the number of cycles of an oscillator operating at a certain frequency. According to Katzenbeisser (2003), any offset will cause a shift of the elevation model with a slight distortion and widening of the swath width. Should the offset be negative, the elevation model will be heightened, distortion will dip at the margins and the swath width will narrow. Hetherington (Chapter 6, this volume) also discusses these reliability issues. In terms of beam direction, all LiDAR systems use a GPS for navigation along with an inertial measurement unit (see Figure 1.1). Using the continuous DGPS position and the vectors of movement, direction and speed, a very precise beam attitude can be calculated. Finally, it should be noted that the individual measurements necessary for a precise final result (position, sensor attitude, and distance and beam deflection) are all taken by different parts of the LiDAR sensor system at different times. Therefore, it is necessary to know precisely the time at which each measurement was taken, or the time difference between measurements, to allow correction. Ultimately, these corrections as well as other outlined here need to be applied at an early stage of the data processing (Katzenbeisser, 2003).

Other issues persist. Airborne LiDAR has problems accurately delineating stream channels and shorelines normally visible on the ground or in photographic images. As an example, in gravel-bed rivers deeper sections of the channel show up

Table 1.1 Dissemination of research on airborne laser altimetry 1999–2004 (percentages in brackets).

Topic area	Scientific journal	Conference proceedings	Website/e-newsletter	Unpublished PhD	Book chapter
Overview papers	4 (44%)	3 (34%)	1 (11%)	1 (11%)	
Filtering, flight adjustment: algorithms and methods	2 (6%)	29 (88%)	2 (6%)	2 (10%)	1 (5%)
DEM generation: terrain and fluvial applications	11 (55%)	6 (30%)			
Calibration, error assessment and quality control	2 (12%)	11 (69%)	3 (19%)		
Commercial LiDAR	1 (33%)		2 (67%)		
Forestry applications	11 (69%)	3 (19%)	2 (12%)		
Urban applications	7 (29%)	11 (46%)	6 (25%)		
Other applications: glaciated landscapes, earthquake hazards, fire, flood modelling, vegetation structure, bird population models, coasts, roads	13 (76%)	3 (18%)		1 (6%)	
Intensity	1 (20%)	2 (40%)	2 (40%)		
Totals	52 (36%)	68 (48%)	18 (13%)	4 (3%)	1 (<1%)

Source: Values adapted from Allen (2004).

as blanks in the dataset (Charlton *et al.*, 2003). In addition, as manual processing is required, contours derived from LiDAR are not normally hydro-corrected to ensure down-contour flow of water in the digital elevation data – a bane of earlier efforts to model flood scenarios in the UK and elsewhere. For such applications, unedited LiDAR-derived contours may therefore be unacceptable, requiring the incorporation of manual break lines along linear features such as river channels (adding to project costs). Generation of airborne LiDAR-derived surfaces also remains problematic in highly sloping terrain.

While a significant amount of material has been published in relation to airborne laser scanning, a survey of the literature between 1999 and 2004 illustrates a dissemination issue (Table 1.1). Of 143 publications surveyed, only 36% were in (a rather narrow selection of) peer-reviewed international scientific journals, almost half (48%) were in conference proceedings and a further 13% published *via* the Internet. The publications in scientific journals focused more on applications of the technology, whereas those on methodology issues and specifications tended to appear as less widely-circulated conference proceedings.

LiDAR has been rapidly taken up in the natural sciences because digital elevation data created using the technology are less expensive than those

created from traditional surveying methods. In addition, the increasing application of laser surveying systems and the ease of data capture that they offer have enabled non-specialist operators from outside traditional surveying disciplines to efficiently generate detailed information in evermore challenging and complex environments. The result is that the technique is now widely recognised as a leading technology for the extraction of information of physical surfaces (Filin, 2004). At the same time, a new range of issues are arising. Of paramount importance is the question of how data is gathered, collated, processed and managed. This is particularly important in the more recently developed technologies of terrestrial laser scanning (TLS) and the allied field of High Definition Survey (HDS).

TERRESTRIAL LASER SCANNING

Since the development of the first terrestrial laser scanner in 1999 (Bryan, 2006), laser scanning technology has seen a continued phase of product development, growth and expansion into many areas of survey (e.g. Bellian *et al.*, 2005). As Lim *et al.* (Chapter 15, this volume) state, the development of sensors able to rapidly collect 3D surface information, has enabled high-density

measurements to be made across landscapes that are unsuited to more conventional approaches due to their inaccessibility, hazardous nature or spatial extent. In addition, the increasing application of TLS systems and the ease of data capture they offer have enabled non-specialist operators from outside traditional surveying disciplines to efficiently generate detailed information in evermore challenging and complex environments. This gives rise to a problem: of all the survey techniques available, TLS has the least standardised control practices and error assessments (Lichti *et al.*, 2005). This is due to both the relative infancy of TLS as a survey tool, the ease of its operation and the apparently complete and satisfactory outputs it provides.

A major advantage is in the rate of data acquisition. Using *Leica* machines as an example, early pulse-scanners laid emphasis on long range, high precision machinery while later generations (from 2004) concentrated on speed of data acquisition and shorter ranges (Table 1.2). From machines in 1998, which collected 100 points per second, the newest generation machines collect approximately 500 times that amount. The ability to accurately position objects so rapidly

involves production of a large amount of data. This data, commonly referred to as a 'point cloud', can provide a 3D shape or visualisation of the feature being measured. It should not be forgotten that the 3D terrestrial laser scanner is still providing 3D positional information in a similar way to a total station. The outcome is that the user can either collect denser amounts of data points or significantly reduce survey time (or achieve a combination of both). The maximum range achievable with a laser rangefinder depends strongly on the meteorological visibility; at lower visibility, the maximum range is reduced due to atmospheric attenuation.

The traditional scanning methodology is to use measurements to a number of common targets (reflectors). This allows multiple scans to be related to each other, a process known as 'meshing', or to be related to an existing control network. In essence, the scanner is placed at one location about the survey site and measurements taken to a number of targets as well as to the actual feature of interest (see case study below). The scanner is then moved to a second location and the process repeated, using at least three common targets from the first scanner location.

Table 1.2 A sample of available laser scanning machinery showing evolution of terrestrial laser scanning technology since 1998.

Date	Machine	Emphasis	Data collection rate
Pulse scanning			
1998	Leica Cyrax 2400	Long range, high precision	100 points sec ⁻¹
2001	Leica Cyrax 2500	Long range, high precision	1000 points sec ⁻¹
2005	Trimble GX	Short range	5000 points sec ⁻¹
2004	Leica HDS3000	Long range, high precision	2000 points sec ⁻¹
2006	Leica ScanStation	Long range, high precision	4000 points sec ⁻¹
2006	Optech ICRIS-3D	Long range (up to 1500 m)	2500 points sec ⁻¹
2006	Optech CMS	Short range	100,000 points per survey max.
2007	Leica ScanStation 2	Long range, high precision	50,000 points sec ⁻¹
2007	Riegl LMSZ390i	Short range	Up to 11,000 points sec ⁻¹
2007	Riegl LMSZ420i	Long-range	11,000 points sec ⁻¹
2007	Riegl LMSZ210ii	Short-range	Up to 10,000 points sec ⁻¹
Phase scanning			
2004	Leica HDS4500	Short range, high speed	250,000 sec ⁻¹
2006	Leica HDS6000	Short range, high speed	500,000 points sec ⁻¹

The process continues until full coverage of the site is achieved and any 'shadow areas' fully scanned. Newer machines (e.g. Optech ICRIS-3D) do not require reflector targets to be located in the area being surveyed, but 'memorise' common features to allow meshing of scans to take place. This is especially advantageous in areas where there may be difficulty in access, for example, opposite banks of rivers in spate.

TLS survey data remain subject to many issues that will generate inaccurate, misleading or inappropriate information if not considered. As Lim *et al.* (Chapter 15, this volume) state, error in TLS measurement is spatially variable, given the variation in survey range, spot size and incidence angle onto the target surface. The combination of separate scans, either spatially or through time, has the potential to introduce inconsistencies in the orientation, resolution and positioning of individual surveys. Clear attention has to be given to planning, data collection and processing to minimise these disadvantages. In addition, most currently available laser scanners are not well specified regarding accuracy, resolution and performance (Hetherington: Chapter 6, this volume) and only a minority are checked by independent institutes regarding their performance and whether they actually comply with manufacturer specifications (Boehler *et al.*, 2003).

CASE STUDIES REFLECTING EVOLUTION AND AVAILABILITY OF LASER SURVEYING TECHNOLOGY

A series of case studies on river systems in the north of England provide a useful insight into the evolution of laser scanning technologies and the attendant change in the way landscape models can be rendered and interpreted. The period of research, 1997–2007, coincided with the development of LiDAR and terrestrial laser scanning, and application of these techniques is described here. As such, the case studies described below provide useful context to research on other fluvial systems, sandy beaches, cliffs, archaeological and heritage sites, forest systems, engineered features

and geological sites described elsewhere in this book. The section below describes how different scanning and surveying technologies have been used for modelling system function and sediment transport over different scale resolutions on two river systems, the River Coquet and the River South Tyne, both of which flow through Northumberland, northeast England.

The River Coquet, Northumberland, UK: EDM and LiDAR surveys

The River Coquet rises in the Cheviot Hills (776 m) in Northumberland, northern England. Here, the focus of geomorphological research over a ten year period has been a river system characterised by a high degree of lateral instability and channel avulsion (Fuller *et al.*, 2003) due to its position in a piedmont setting at the upland fringe in the catchment, draining an area of *circa* 255 km² (Figure 1.2). The valley as a whole is similar to other gravel-bed rivers in northern England, and displays a characteristic 'hourglass' valley morphology with alternating confined and unconfined sections.

Research in the period 1998–2000 was aimed at accurately quantifying annual sediment transfers across a 1 km long reach of the River Coquet at Holystone, Northumberland. As this was prior to widespread use of LiDAR, channel planform and cross-profile surveys were based on theodolite-EDM survey across the active wandering gravel-bed river system, focusing on breaks of slope. This exercise generated a series of *x-y-z* coordinates from which Digital Elevation Models (DEMs) of the reach were constructed – 'detailed' was a term used in resultant publications (e.g. Fuller *et al.*, 2003) to describe the survey resolution based on the technology available at the time (Figure 1.3). Calculating the difference between DEM surfaces provided a measure of volumetric change between surveys. Error analysis, comparing the surveyed cross-profiles with sections abstracted from the DEMs, indicated a mean gross error between surveyed and DEM profiles of around twice the value of the D_{50} of the surface sediment in the reach (51 mm: Fuller *et al.*, 2002, 2005).

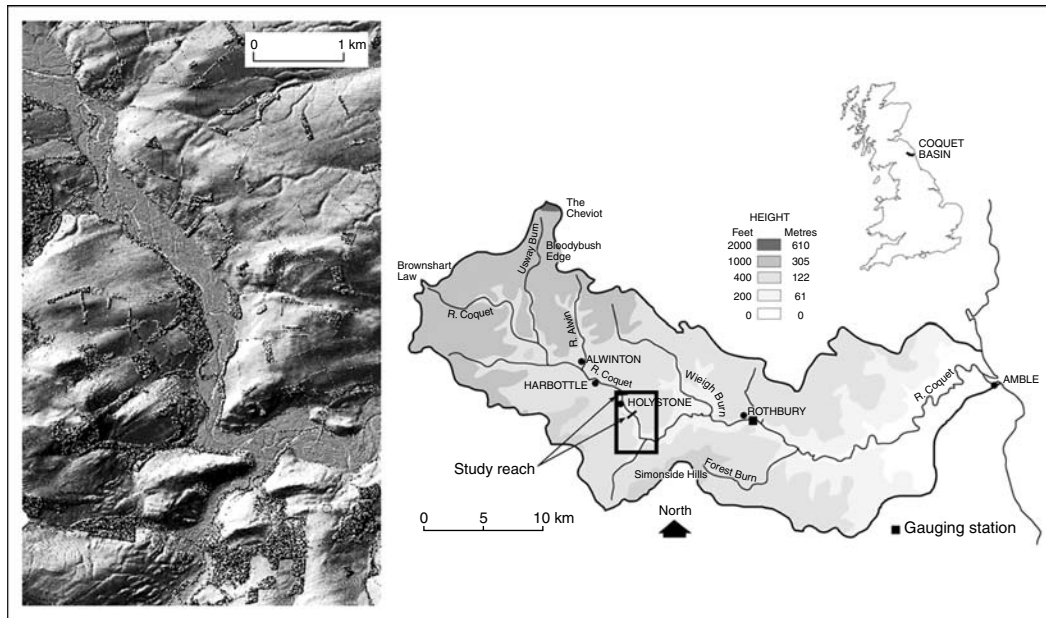


Fig. 1.2 The River Coquet catchment, Northumberland, UK with inset detail showing the valley configuration as depicted by airborne LiDAR flown in March 2006 by the UK Natural Environment Research Council.

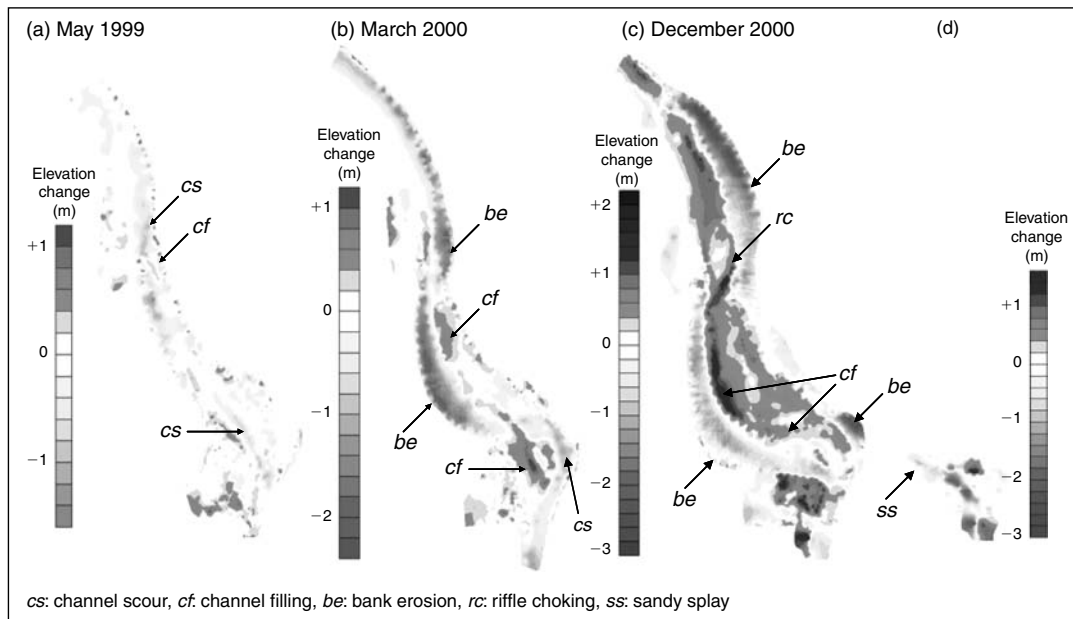


Fig. 1.3 Theodolite repeat surveys of the River Coquet, Northumberland, UK at ~ 0.05 points m^{-2} resolution. Inset (d) shows a re-survey 7 days after a flood event caused avulsion at the lower end of the reach (after Fuller *et al.*, 2003). See Plate 1.3 for a colour version of this image.

A Sokkia Set 5F Total Station (with a precision of ± 5 mm) was used to survey channel planform and monumented cross-profiles in March 1999 and 2000. Sediment budgets were calculated using the morphological budget described in detail by Fuller *et al.* (2002). This approach integrates both planform and cross-profile data, with vertical changes in area along each cross-profile calculated and standardised to net gain/loss values per square metre. These values were then multiplied by the corresponding planform area values to give a net gain/loss value in cubic metres for each morphological unit within the sub-reach. In 1999, 2661 points were surveyed within the active channel area ($50,509\text{ m}^2$) at Sharperton Northumberland, producing a mean point density in the reach of $0.05\text{ points m}^{-2}$. In 2000, 2985 points were surveyed within the same area (Figure 1.3), producing a mean point density of $0.06\text{ points m}^{-2}$ (Table 1.3). However, these low reach-scale averages mask much higher sampling densities in areas of rapid topographic change (e.g. bar edges, riffles, banks).

Subsequent surveys used DGPS technology to produced georeferenced DEMs allowing greater resolution than previously available using theodolite-EDM. The construction of a DEM for each survey was undertaken within Surfer™ GIS, with data interpolation using kriging at a grid interval of 0.25 m. While mathematical interpolation of elevation for DEM construction assumes that the data are spatially dependant, the data from long linear systems (such as river channels) are usually anisotropic. As such, this grid interval was necessary to ensure a DEM sensitive to more subtle changes in morphology; coarser grid intervals

may lead to the loss of potentially important breaks in slope within the channel environment (Brasington *et al.*, 2000; Brunsden: Chapter 5, this volume). Kriging, being a geostatistical gridding method, which can use irregularly spaced data (Dixon *et al.*, 1998), was ideally suited to the morphologically-driven but irregularly-spaced datasets collected for the River Coquet. The accuracy of the DEMs produced using theodolite EDM was quantified using residual analysis, which indicated that more than 96.3% of the interpolated surface is accurate to ± 5 cm (equivalent to the surface sediment *D50*) for both the 1999 and 2000 DEM surfaces. DEM methodology based on the morphological unit scale was seen, therefore, to provide a rigorous identification of spatial patterns of erosion and deposition.

Airborne LiDAR survey

In the late 1990s the UK Environment Agency commissioned LiDAR surveys of a number of river and coastal environments as part of a flood prediction exercise. The River Coquet was flown in March 1998. As such, the exercise proved timely and permitted comparison with the theodolite-EDM and DGPS surveying in progress during that period (Charlton *et al.*, 2003). Figure 1.4 depicts a mosaic of two adjacent 1 km^2 tiles for the River Coquet at Sharperton, Northumberland, viewed as an illuminated surface from the south-west. No vertical exaggeration has been applied. As well as showing the undulation of the valley sides, and some faintly visible palaeochannels on the floodplain, vegetation cover is clearly visible. In the study area, white patches indicate where

Table 1.3 Comparison of laser surveying methods used on rivers in Northumberland during the period 1999–2008 and their respective resolutions of survey.

Survey date	Method	Point resolution
1999 ($50,509\text{ m}^2$)	Theodolite EDM (Sokkia Set 5F™ Total Station)	2661 points ($0.05\text{ points/m}^{-2}$)
2000	Theodolite EDM (Sokkia Set 5F™ Total Station)	2985 points ($0.06\text{ points/m}^{-2}$)
2002–2004	DGPS (Scorpio and Thales Promark 3)	15,000 points ($0.30\text{ points m}^{-2}$)
2002 and 2006	Airborne LiDAR (NERC-ARSF)	$\sim 64,000$ points km^2 (3.9 points m^{-1})
2005–2008	Terrestrial laser scanning (Riegl Instruments LMS-210™ scanning laser)	Up to 26,000,000 points per survey ($\sim 515\text{ points m}^{-2}$)

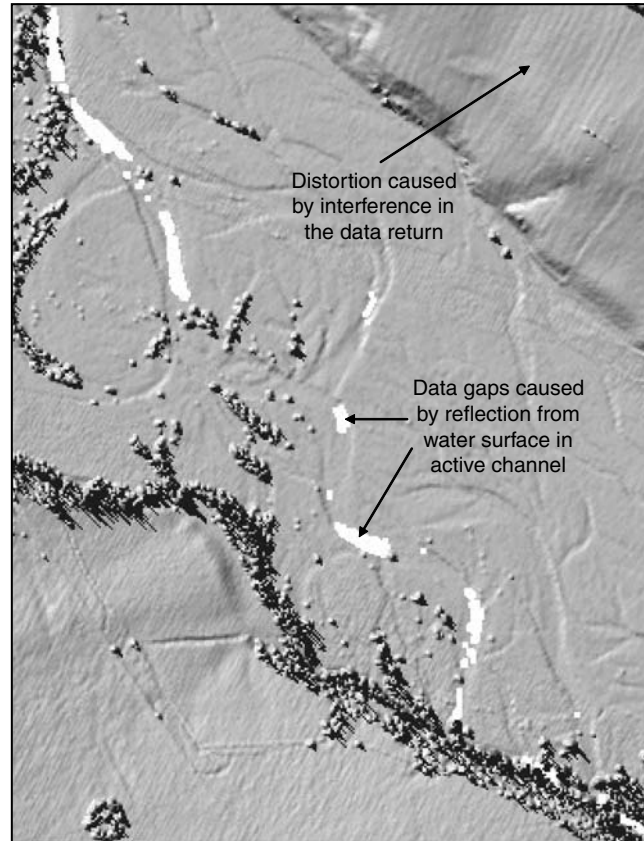


Fig. 1.4 1998 LiDAR survey of the River Coquet valley, flown for the UK Environment Agency for flood mapping purposes. The two juxtaposed 1 km × 1 km LiDAR tiles equate to UK Ordnance Survey national grid squares NT 9502 and NT 9602.

the LiDAR sensor has failed to make a reading. It should be noted that these data gaps are all in the river channel and represent lack of data from the water surface itself (the LiDAR data was first-return only, although last return data also encounters this problem, as still water acts as a specular surface – see Chapter 2). Coincident with the LiDAR flight, channel cross-profiles were surveyed from monumented pegs on the riverbank using theodolite-EDM survey with a Sokkia Set 5F Total Station. This ground survey took one week around the date of the LiDAR acquisition flight, thus ensuring minimal discrepancy between LiDAR and ground survey cross-profiles due to morphological change over time. The ground survey measurements were made at every break of slope across the channel. The locations of the ground survey measurements were georeferenced

by comparison with OS LandLine data. Six cross-sections were selected for detailed comparison on the basis that they covered the full range of channel morphology within the reach. Georeferenced height values were calculated from the LiDAR data at 0.25 m intervals along the six cross-sections using the surface profiling facilities available in Arc/INFO GIS. In total, this supplied 9152 estimates of elevation for the cross-sections. By comparison, there were only 551 measurements of elevation available from the ground survey; there is a drawback in that measurements derived from the LiDAR surface were not necessarily taken at precisely the same positions along the cross-profile as those from the ground survey. To resolve this, the surface profiling facilities in Arc/INFO were used to generate interpolated values from the digital elevation model at a set of

regularly spaced locations, within the mesh spacing of the model. Cubic splines (Press *et al.*, 1989) were fitted to these measurements (splines have the useful property that they pass through all the observed data points), and values were then interpolated from the spline function at positions corresponding to those along each cross-section at which ground survey elevations were obtained (Charlton *et al.*, 2003). Elevations from the ground survey data were adjusted to the LiDAR elevation at the monumented peg for each cross-section, so that the first data point in all cross-sections had the same z-value as the LiDAR elevation for that specific location (thus removing any systematic bias component of the error associated with both the LiDAR measurement and the survey of the monumented peg). Two features were apparent from this exercise:

- Sections of the banks colonised by stands of mature trees were evident on the cross-section LiDAR plots as 'spikes' in the elevation data.
- The 1998 LiDAR data traded off the frequency of measurement by the detector against pulse separation, and the nature of the single return measurement meant deeper water was poorly represented.

From the above exercise, it could be concluded that, in relatively vegetation-free environments, use of single return LiDAR offers a rapid method of acquiring high resolution data. In reality, however, while this survey method operates in three-dimensions, it is often only '2.5 dimensional' in nature due to shadowing, data loss in densely vegetated areas and absence of bathymetric resolution. While not fully addressing the bathymetric issues, terrestrial laser scanning offers the potential of bridging the gap between the need for survey over extended areas and the need for suitable ecological resolution at the micro-scale (incorporating edges and boundary zones in ecosystems). To improve ecological status, there is a need to advance the understanding of geomorphological, hydrological and ecological functional links in ecosystems. Key international legislation now mandates this: the EU Water Framework Directive, for example, has the concept of 'ecological health' or status at its core. In river systems an emerging key question is

whether hydromorphology can be characterised at a spatial scale that truly accounts for instream ecological dynamics. However, interactions are highly complex and remain poorly understood. Terrestrial laser scanning systems offer potential for accurately characterising ecosystems at ecologically-relevant scales, bridging scale issues concerning environmental protection legislation. Using the EU Water Framework Directive as our example again, policy is aimed at the catchment ('River Basin') scale with the reach being the unit of measurement for a range of indicative variables. However, biota respond on scale of the morphological unit down to the micro-scale (substrate, vegetation etc.) and therefore ground-based terrestrial laser scanning with its ability to measure surface elevations to sub-centimetre accuracy may offer real potential as a management tool.

Terrestrial laser scanning – an ecologically-applicable surveying technique?

For a section of the River South Tyne in Cumbria, surface roughness was measured using a random field of spatial elevation data collected using a Riegl LMSZ210 scanning laser. The aim was to reliably quantify instream hydraulic habitat defined by water surface characteristics using random field terrestrial laser scanner x-y-z data. A range of research has demonstrated that the mosaics of hydraulic habitat types present in a reach (and defined by roughness) are very important in determining biodiversity (e.g. Dodkins *et al.*, 2005). Over the last decade a number of international initiatives have focused on characterisation of instream habitat using hydraulic variables as these are deemed central to the inhabiting biota. Biotopes (Padmore, 1998; Newson & Newson, 2000) provide a standard, descriptive assessment of instream physical structure based on consistent recognition of features. They have their basis in the development of typologies to underpin the 'Habitat Quality Index' developed as a framework for the protection of rivers (Raven *et al.*, 1997), and provide a means of integrating ecological, geomorphological and water resource variables for management purposes. Essentially, the biotope concept allows

Table 1.4 Descriptions of flow types used to field map fluvial biotopes (Newson & Newson, 2000).

Flow type	Description	Associated biotope
Free fall	Water falls vertically and without obstruction from a distinct feature, generally more than 1 m high and often across the full channel width	Water fall
Chute	Fast, smooth boundary turbulent flow over boulders or bedrock. Flow is in contact with the substrate, and exhibits upstream convergence and downstream divergence	Spill – chute flow over areas of exposed bedrock Cascade – chute flow over individual boulders
Broken standing waves	White-water 'tumbling' waves with crest facing in an upstream direction. Associated with surging flow	Cascade – at the downstream side of the boulder flow diverges or 'breaks'. Rapid
Unbroken standing waves	Undular standing waves in which the crest faces upstream without breaking	Riffle
Rippled	Surface turbulence does not produce waves, but symmetrical ripples which move in a general downstream direction	Run
Upwelling	Secondary flow cells visible at the water surface by vertical 'boils' or circular horizontal eddies	Boil
Smooth boundary turbulent	Flow in which relative roughness is sufficiently low that very little surface turbulence occurs. Very small turbulent flow cells are visible, reflections are distorted and surface foam moves in a downstream direction. A stick placed vertically into the flow creates an upstream facing 'V'	Glide
Scarcely perceptible flow	Surface foam appears to be stationary and reflections are not distorted. A stick placed on the water's surface will remain still	Pool – occupy the full channel width. Marginal deadwater – do not occupy the full channel width

for a standard, descriptive assessment of instream physical structure based on consistent recognition of features over a range of spatial and temporal scales (Table 1.4). However, to become an alternative to hydraulic models, biotopes need a robust, empirical and practical channel typology/taxonomy to be developed to allow rapid characterisation of reaches.

Figure 1.5 outlines a potential framework for investigating climate, hydrology and their impacts on physical habitat in UK rivers, emphasising the importance of quantification of biotope types in delimiting characteristic reaches. It can be hypothesised that accurate biotope quantification *via* ground-based LiDAR survey can be key to spatial definition of ecological status and its scaling up towards the reach scale (still the most appropriate scale for monitoring and management of system biodiversity).

With this in mind, efforts were made to use terrestrial laser scanning to accurately quantify biotope distribution for a series of rivers in the north of England. Here, we can outline the approach for the River South Tyne, Cumbria, a river which has been described (Macklin & Lewin, 1986) as divided into five 'sedimentation zones', separated by more stable reaches. As mentioned above, a Riegl LMSZ210™ scanning laser was used to collect water surface roughness data from a bridge. The instrument works on the principle of 'time of flight' measurement using a pulsed eye-safe infrared laser source emitted in precisely defined angular directions controlled by a spinning mirror arrangement. A sensor records the time taken for light to be reflected from the incident surface. Angular measurements are recorded to a precision of 0.036° in the vertical and 0.018° in the horizontal. Range error

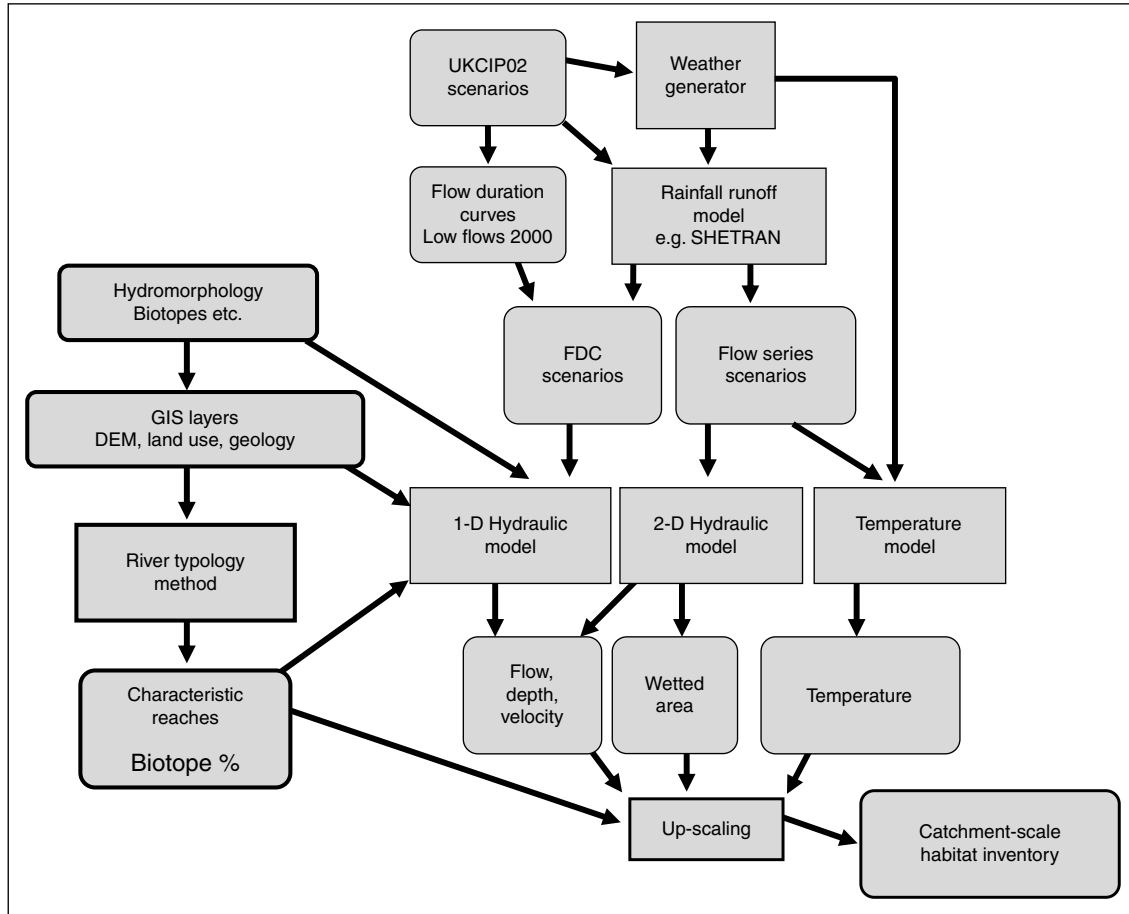


Fig. 1.5 A framework for investigating climate, hydrology and their impacts on physical habitat in UK rivers, emphasising the importance of quantification of biotope types (Chris Kilsby, personal communication).

is 0.025 m to a radial distance of 350 m. Survey control was facilitated by RiScan-Pro™ survey software, capable of visualising point cloud data in the field. Scans were generally restricted to 240° in front of the scanner and repeat scans were collected ensuring that any effects of water surface turbulence on biotope definition were minimised. This also increased the point resolution across the surface and reduced the possibility of unscanned areas due to the shadowing effect of roughness elements along the line of each scan. Before scans were taken, a total of 20 reflectors were placed on and around the study reach. These

reflectors were tied into the project co-ordinate system using an EDM theodolite and these were automatically located by the RiScan-Pro™ software and matched to the project coordinates using a common point configuration algorithm. Estimation of laser scan accuracy and calculation of the threshold of accurate detection for the base model is addressed in Heritage and Hetherington (2005). The laser scan data were used to generate a 0.05 m resolution DEM of the point-bar surface. Delauney triangulation with linear interpolation was employed as an exact interpolator.

Characterisation of DEM uncertainty is difficult since validation requires comparison between the derived DEMs and a second, more accurate, surface (Brasington *et al.*, 2000, 2003). Usually acquisition of this second surface is not possible; DEM validation is thus often based on quantifying model uncertainty through diagnostic surface visualisations or field 'ground truthing' (Wechsler, 2000; Heritage & Hetherington, 2005). In this study the use of the 3D terrestrial laser scanning allows the second surface to be obtained up to a vertical accuracy of 2mm. As the machine can operate over distances of several hundred metres while maintaining comparable levels of accuracy, it potentially offers a valuable tool for quantifying hydraulic habitat based on

water surface characteristics. If the technology allows accurate characterisation of water surface roughness (a primary determinant of biotope classification in the field), it in turns offers a tool for such typologies to be derived at the reach scale – thus approaching the scale at which management policies for ecological status operate.

The surface data were initially transformed into a regular grid with a 0.02 m spacing to determine the local standard deviation of sub areas across the surface. Figure 1.6 shows, from top, (a) the data cloud produced from the laser scanning exercise and (b) biotope distribution as defined by visual observation – the method derived by Newson and Newson (2000) and used by the UK Environment Agency, the primary management

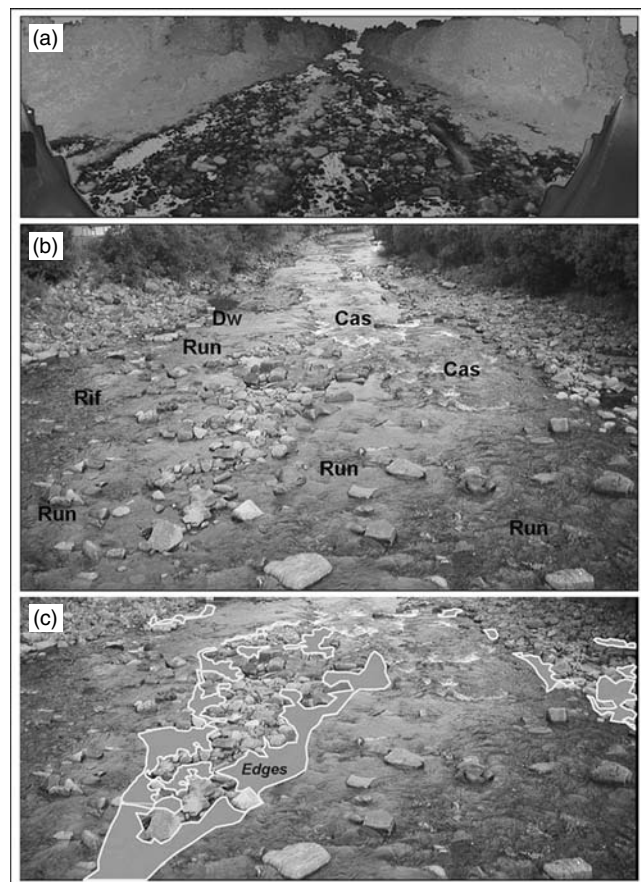


Fig. 1.6 Reach of the River South Tyne showing (a) data cluster cloud from laser scanning run, (b) visual classification of biotopes using the methodology of Newson and Newson (2000), and (c) 'edges' unclassified by the standard biotopes methodology. Rif=riffle, Run = run, Cas = cascade, Dw = Deadwater (Large & Heritage, 2007).

authority for river systems in England and Wales. The bottom image (Figure 1.6c) shows 'edges' unclassified by the standard biotopes methodology. These edges constitute what may be termed *critical channel components*, that is they are the areas used by biota for a range of activities including oviposition, providing refugia during spates, feeding sites, sites for emergence, and shelter under shade in vegetated systems. These parts of the instream mosaic of hydraulic units have inherent environmental value as part of the living space or habitat for instream biota, yet are missed under standard monitoring approaches in the UK

(Newson & Newson, 2000) and certainly on the scale of the proposed rapid habitat survey methods for streams on mainland Europe (e.g. EAWM, 2004) which emphasise typing of entire reaches under a single biotope denotation.

Figure 1.7 shows the DEM derived from the laser scanning exercise with biotopes as defined by the factored standard deviation surface of the study reach. The results show overlap between the riffle and run habitat types. This is to be expected; these categories lie beside each other in the visual definition field (see Table 1.4) and, as stage rises and fall, biotopes merge and change

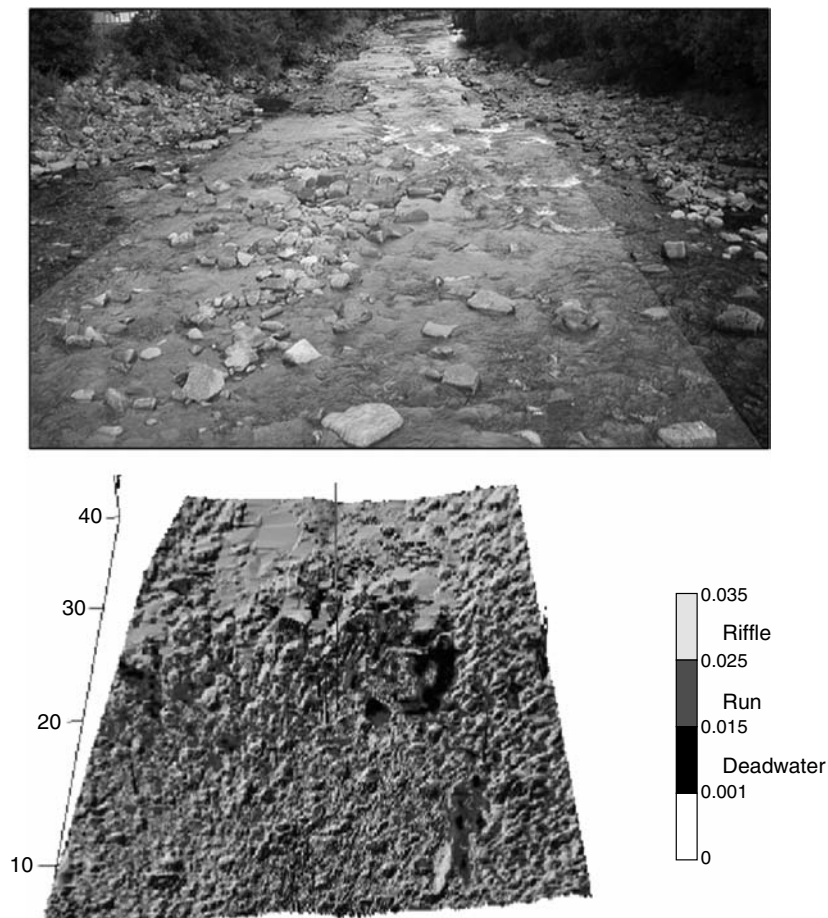


Fig. 1.7 Spatial distribution of biotope types for the reach shown in Figure 1.6 defined by laser scan water surface roughness measurement (Large & Heritage, 2007). See Plate 1.7 for colour version of this image.

from one type to another. One implication from the point of view of instream hydraulics may be that these biotopes are providing very similar habitat to each other (Heritage *et al.*, 2009; Milan *et al.*, 2009).

SUMMARY

This series of case studies over the decade 1997–2007 show how evolution of laser scanning technology and its application in morphologically similar systems (here gravel and cobble-bedded rivers) allow significantly higher resolution surveys to be taken with commensurate lowering of error. It also shows how the technology has potential value in feeding into major legislative approaches involving measuring and monitoring of these systems. Issues arise: the amount of data being generated is vastly increased – protocols are required for data archiving. Data mining and data redundancy are also an issue; the earlier theodolite-based surveying exercises focused attention on breaks of slope and more dynamic sections of reaches in order to gain higher resolution. Using LiDAR and TLS, data acquisition is as fine-scale over stable ecosystem components as those more prone to change. How to deal with this data ‘overload’ has not yet been adequately considered. Other chapters in this volume begin to address these issues.

THIS BOOK – LASER SCANNING FOR THE ENVIRONMENTAL SCIENCES

Both airborne and terrestrial laser scanning (LiDAR) are now well established methods for the acquisition of precise and reliable 3D geo-information. Beyond the primary tasks of digital terrain model generation, airborne laser scanning has also proven to be a very suitable tool for general 3D modelling tasks and landscape analysis. At the same time, terrestrial laser scanning is successfully used to acquire highly detailed surface models of objects like building facades, statues and industrial installations. Despite large differences in resolution and accuracy between

airborne and terrestrial laser scanner data, the research problems such as automatic registration, feature extraction and 3D modelling are very similar. As Lim *et al.* (Chapter 15) point out, as TLS systems mature from state-of-the-art instruments to become standard practice for recording complex topography, a change of emphasis is required; moving from using the system simply as a method of data capture to its use within a systematic surveying framework with well-established data collection and analytical protocols. This will be vital if terrestrial laser scanning is to achieve its undeniable potential in a wide range of environmental systems, each posing their own particular challenges to the accurate collection and interpretation of information.

This volume is divided into three main sections. The first – *new directions in data acquisition* – places particular emphasis on laser technology and reviewing the range of sensors and platforms available. Heritage and Large (Chapter 2) examine general theory and principles of laser scanning; scanning technologies and their advances as related to conventional approaches. Charlton *et al.* (Chapter 3) describe issues of data models and their representation, general data handling, accuracy, protocols, 2D and 3D representations (rasters, vectors, DEMs, TINs, etc.) and computational and visualisation issues. In the second section – *Land surface monitoring and modelling* – Devereaux and Amable (Chapter 4) describe data acquisition, instrumentation, deployment and survey design, as well as data processing while, in Chapter 5, Brunnsden discusses principles and procedures of interpolating spatial variation; inverse distance weighting; spline models, kriging, covariates and general spatial modelling. Finally, Hetherington (Chapter 6) discusses data handling issues; there are many issues concerning the new challenges of database integration, dealing with extremely large datasets and grid integration, and new survey protocols are undoubtedly required.

The final section (Chapters 7–16) examines the application of the new technology in a range of environmental systems and for a range of purposes including flood and flow modelling; vegetation cover and landscape change modelling

and archaeological surveys. Issues are addressed here with regard to managing data in terms of scale issues, dissemination, databases, software, and methods for DEM construction (2D and 3D triangulation) described for a range of systems. In Chapter 7, Entwistle and Fuller describe a method to reliably quantify the population grain-size distribution of natural gravel surfaces using random field TLS data and generate maps from which large-scale facies assemblages are identifiable. Straub *et al.* (Chapter 8) describe approaches for automatic feature extraction for segmentation and classification of forest areas, road extraction and building extraction. Using spatially distributed datasets, Milan and Heritage (Chapter 9) examine the effect of changing the resolution of topography and height grids on velocity and turbulence flow predictions in a three-dimensional hydraulic model.

The advent of airborne LiDAR makes it possible to quantify three-dimensional change in beach topography at the spatial scales needed to monitor erosion over long segments of coastline quickly, accurately and economically. Starek *et al.* (Chapter 10) present a detailed study of the application of airborne LiDAR to quantify beach dynamics. Using case study examples, Hodgetts (Chapter 11) discusses the LiDAR workflow in geology, covering collection of data, processing, geological interpretation and visualisation. In Chapter 12, Crutchley describes the development and use of LiDAR in archaeological survey, as well as examining practical issues *via* a series of case study examples. Danson *et al.* (Chapter 13) consider the nature of the interactions of laser light with vegetation canopies, emphasising the importance of multiple scatters within a single laser beam. The authors also illustrated this with reference to a range of airborne and ground based laser scanning experiments. In Chapter 14, Overton *et al.* describe the use of LiDAR for flood modelling in large river systems, using the example of the River Murray in Australia. Even in such a large system, small elevation differences create a multitude of different flooding regime habitats, and flows are often driven by water level differences of only a few centimetres. Airborne

LiDAR is the only technique able to capture such levels of detail over such large distances and, as such, is ideal for these types of environmental application. Lim *et al.* (Chapter 15) complete the section, emphasising field survey procedures and data protocols using linear features (transportation links and coastlines) as exemplars. Finally, in Chapter 16, we ask: what of the future for laser scanning survey? What should be the priorities as the technologies evolve in terms of data volume and archiving, extraction and handling, modelling and rendering; and what potential does evolution of the technology offer for monitoring and mapping natural environments *via* high definition survey?

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