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Step by step error assessment in braided river sediment budget using airborne LiDAR data

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ABSTRACT

Sequential airborne LiDAR surveys were used to reconstruct the sediment budget of a 7-km-long braided river channel in southeastern France following a 14-year return period flood and to improve its accuracy step by step. Data processing involved (i) surface matching of the sequential point clouds, (ii) spatially distributed propagation of uncertainty based on surface conditions of the channel, and (iii) water depth subtraction from the digital elevation models based on water depths measured in the field. The respective influence of each processing step on sediment budget computation was systematically documented. This showed that surface matching and water depth subtraction both have a considerable effect on the net sediment budget. Although DEM of difference thresholding based on uncertainty analysis on absolute elevation values had a smaller effect on the sediment budget, this step is crucial for the production of a comprehensive map of channel deformations. A large independent data set of RTK-GPS checkpoints was used to control the quality of the LiDAR altimetry. The results showed that high density (7–9 points/m^2) airborne LiDAR surveys can provide a very high level of detection of elevation changes on the exposed surfaces of the channel, with a 95% confidence interval level of detection between 19 and 30 cm. Change detection from LiDAR data revealed that 54% of the pre-flood active channel was reworked by the flood. The braided channel pattern was highly disturbed by the flood owing to the occurrence of several channel avulsions.

1. Introduction

Braided gravel-bed rivers have long been recognized as very active geomorphic systems, but until recently, the lack of techniques to fully reconstruct the complex morphology of multithread river corridors have hindered our understanding of their dynamics. Until the mid-1990s, the topographic monitoring of braided channels was restricted to regularly spaced and fixed cross sections revisited after significant flow events (Ashworth and Ferguson, 1986; Carson and Griffiths, 1989; Ferguson and Ashworth, 1992). The main problem was the insufficient spatial resolution in the longitudinal direction, which fails to provide a clear picture of the complex assemblage of macroforms constituting these channels. Another issue was the high level of uncertainty for the computation of erosion and deposition volumes used in sediment budgets. These problems were partially solved with the application of techniques delivering spatially distributed topographic data that can be used to construct a digital elevation model (DEM) of the channel. The first DEMs of braided channels were produced by ground-based analytical (Lane et al., 1994, 1995) or airborne digital (Westaway et al., 2000) photogrammetry coupled with tacheometry for the survey of submerged areas and with real-time kinematic global positioning systems (RTK-GPS) (Brasington et al., 2000). These pioneering studies were followed by a considerable number of works using a wide variety of techniques: oblique digital photogrammetry (Chandler et al., 2002), airborne light detection and ranging (LiDAR) (Charlton et al., 2003; Lane et al., 2003; Hicks et al., 2008; Höfle et al., 2009; Bertoldi et al., 2011; Legleiter, 2012; Moretto et al., 2012), short-wavelength green LiDAR, capable of penetrating through the water column for mapping bathymetry (Kinzel et al., 2007; Bailly et al., 2010), and terrestrial laser scanning (TLS) (Milan et al., 2007; Williams et al., 2011; Brasington et al., 2012). Each of these techniques presents specific advantages explaining why they continue to be widely used in the braided river research community. However, airborne LiDAR seems more attractive given its prevalence in recent studies.

The popularity of airborne LiDAR is explained by its ability to cover large areas with high resolution and high precision DEMs, including ground surfaces covered by vegetation (Wehr and Lohr, 1999). Sequential airborne LiDAR surveys have been successfully

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deployed in large gravel-bed braided rivers to produce detailed maps of erosion and deposition. The first published study concerns the Waimakariri River in New Zealand, where a LiDAR-derived DEM of a 3.3-km reach was compared with a DEM obtained with airborne digital photogrammetry (Lane et al., 2003). The level of detection (LoD) of significant elevation change (68% confidence interval) was between 16 and 33 cm, depending on the wet or dry conditions of the channel during both surveys. However, braided channel responses exclusively derived from sequential airborne LiDAR data are still rare. Hicks et al. (2008) reported the case of the Waimakariri River, where two 1-m resolution LiDAR DEMs in 2000 and 2003 were compared, with a spatially averaged LoD of about 20 cm. A more recent study on the Brenta River in Italy showed similar results, with a LoD between 22 and 29 cm using two LiDAR DEMs of a 4.5-km-long braided channel (Moretto et al., 2012). Other studies based on airborne LiDAR in braided environments include: (i) quality control of the LiDAR altimetry with ground-based topographic surveys (Charlton et al., 2003); (ii) estimation of bank erosion (Surian and Cisotto, 2007); (iii) development of procedures for the automatic extraction of water surfaces from LiDAR point clouds (Höfle et al., 2009), which can be coupled with spectrally-based bathymetry (Legleiter, 2012); (iv) quantification of long-term incision rates from terraces (Turitto et al., 2010); and (v) analysis of the topographic signature of vegetation establishment in braided channels (Bertoldi et al., 2011).

Uncertainty assessment in DEMs of difference (DoD) and sediment budget computation is a key issue for geomorphic interpretation of topographic changes. In fact, it is crucial to distinguish real morphological changes from noise. Uncertainty in DoD application has already received considerable attention (Brasington et al., 2000; Lane et al., 2003; Wheaton et al., 2010; Milan et al., 2011). Recent studies with conventional terrestrial survey techniques (RTK-GPS, total station) highlighted the spatial variability of uncertainty. Greater uncertainty is found in areas of high topographic variability (high grain and/or form roughness) and low point density (Heritage et al., 2009; Wheaton et al., 2010; Milan et al., 2011). The precision of altimetric data is also recognized to decrease significantly with the density of the vegetation cover and the slope steepness (Bowen and Waltermire, 2002; Hodgson and Bresnahan, 2004). These findings have not yet been incorporated in airborne LiDAR data processing for river environments, as the only factor of uncertainty that has been taken into account in the sediment budget computation is the wet or dry condition of the channel (Lane et al., 2003; Hicks et al., 2008; Erwin et al., 2012; Moretto et al., 2012). Recently, Carley et al. (2012) tested different DoD uncertainty procedures and showed that LoD subtraction from the raw DoD was the correct method to achieve a physically sound sediment budget compared to LoD exclusion (discarding DoD cells with values below the LoD).

A persistent problem with LiDAR data is that classically used near-infrared laser pulses (NIR, 1064 nm) are strongly absorbed by water and fail to provide the relief of submerged areas (Reusser and Bierman, 2007; Notebaert et al., 2009), even if for very shallow water conditions (typically <5 cm), some bed detection can be obtained from NIR laser (Milan et al., 2007). A common way to solve this problem is to derive the flow depth from multispectral (RGB) imagery acquired simultaneously with laser scans (Lane et al., 2003; Bertoldi et al., 2011; Legleiter, 2012; Moretto et al., 2012). The DEM of the submerged relief is obtained by subtracting optically derived water depths from the water surface, which can be automatically extracted from LiDAR point density and/or LiDAR intensity images (Höfle et al., 2009; Legleiter, 2012). This method requires calibrating a rating curve between water depth and a spectral predictor using data collected in the field concomitantly with the LiDAR survey. The performance of this procedure is contingent to the hydraulic and substrate properties of the channel during the survey. The best conditions for obtaining an accurate bathymetry are shallow clear water with highly reflective substrate (Legleiter, 2012). However, even under optimal conditions, the optical-bathymetric approach fails to capture deep water depths (>50 cm in the case study reported by Legleiter, 2012). This can be solved using green LiDAR systems (532 nm), which are more suitable for deep water and which do not give realistic data for water depths <30–40 cm (Kinzel et al., 2007; Bailly et al., 2010).

Although airborne LiDAR data is still expensive and not adapted for submerged channel conditions, these data are becoming increasingly available, notably in the context of regional and local water resources management plans (Cavalli and Tarolli, 2011). During the last 5 years in France, most of the large alpine rivers have been surveyed for the implementation of sustainable management of channel morphology and sediment transport, with the financial support of the French Water Agency. Therefore, requests from river managers are increasing concerning the potential of LiDAR data for the monitoring of channel changes. This is particularly true for braided rivers, which are recognized as endangered aquatic ecosystems highly sensitive to the preservation of active morphodynamics (Piégay et al., 2009). Given the constraints associated with the use of optical bathymetric mapping of the submerged part of river channels (availability of orthorectified multispectral imagery simultaneously acquired with the LiDAR survey, data acquisition of water depth in the field during the survey), there is a need to evaluate what can be achieved in terms of morphological change reconstitution and sediment budgeting when only LiDAR data are available (without aerial imagery), a situation which is very frequent in the operational context.

This paper addresses the issue of assessing errors in the quantification of morphological changes of a braided channel after the occurrence of a 14-year return-period flood in 2009, using exclusively airborne LiDAR data acquired in 2008 and 2010. A method for estimating geomorphic changes in the aquatic zones is proposed in a context where no airborne images are available, as frequently seen in operational studies. A complementary objective was to produce spatially distributed uncertainty from data collected in the field for different surface conditions. This data set gave insights into the quality of LiDAR altimetry for typical channel conditions of gravel-bed braided channels. Finally, data are used to characterize the flood effect on the braided channel pattern, by identification of the most active morphological processes and by quantification of the braidplain turnover.

2. Study site

2.1. The Bès River

The Bès River is a gravel-bed braided river located near Digne-les-Bains in the Southern French Prealps, with a 234-km^2 drainage area. It is the main tributary to the Bléone River in the Durance River basin (Fig. 1A). The geology of the catchment consists of sedimentary rocks, mainly limestone, marls, and marly limestone. Elevations range from 640 to 2700 m asl. The catchment is 70% covered by forest, 25% by grassland, and 5% by agricultural land. The climate is Mediterranean and mountainous, with snow in winter and high intensity rainfall in summer and autumn. The mean annual precipitation is 930 mm. The analysis of the historical long-profile of the Bès revealed an aggradation trend (+1.11 m between 1911 and 2009) during the twentieth century, which can be linked to the high sediment supply from active torrents in the catchment (Liébault et al., 2013).

The study reach covers the last 7 km of the Bès River (midpoint at 44°09′32.89″ N., 6°14′36.49″ E.; Fig. 1B). Here, the Bès is braided with a channel slope of 0.014, a surface median grain size (D_{50}) of 40–50 mm (derived from gravel surface photographs processed with Digital Gravelometer software), and a mean active channel width of 130 m (Fig. 1C). 'Active channel' refers here as the unvegetated gravel bars and low-flow channels. The braided channel is composed of a