Zeitschrift für Geomorphologie, Vol. 61/1 (2017), 000–000
Stuttgart, March 2017

Article

Quantification of bank erosion of artificial drainage networks using LiDAR data

Rosalie Vandromme[1,*], Anthony Foucher[2], Olivier Cerdan[1], Sébastien Salavador-Blanes[2]

[1] Département Risques et Prévention, Bureau de Recherches Géologiques et Minières, 3 avenue Claude Guillemin, 45060 Orléans, France. E-mails: r.vandromme@brgm.fr; o.cerdan@brgm.fr
[2] E.A. 6293 GéoHydrosystèmes COntinentaux, Université François Rabelais de Tours, Parc de Grandmont, 37200 Tours, France. E-mails: anthony.foucher@outlook.com; salvador@univ-tours.fr
* Corresponding author: r.vandromme@brgm.fr

With 7 figures

Abstract: Following the shift towards more intensive agriculture in cultivated lowlands in Europe, field sizes have increased and stream valley meanderings have been suppressed and realigned along new straight field borders. These modifications have led to profound alterations of the hydromorphology of the streams. To test the importance of these modifications, the objective of this study is to assess the potential of using high resolution DTM (Digital Terrain Model) to quantify the current volume of small drainage ditches at catchment scales and to assess the evolution of these ditches using archival data. The method has been applied to a small agricultural catchment drained by an artificial stream network. A specific 1400 m long ditch was chosen to estimate the capacity of a DTM (0.5 m) and to evaluate the actual topography and volume of stream. Forty-four channel cross sections measured with a centimeter DGPS (Differential Global Positioning System) have been compared with the same profiles measured with the DTM. The average DTM error in estimating stream depth is approximately 13% and is less than 12% for stream width detection. Estimates of the ditch volume using DTM sections instead of DGPS sections produces a result of 3100 m^3. An average error of 11% can be ascribed to the difference in the estimated ditch volume between the DGPS and DTM approaches, which was principally caused by under-estimates of bottom ditch morphology by the DTM. This study highlights the ability of airborne instruments to quickly and robustly detect and estimate the volume occupied by small-width stream networks (1.5 to 4 m) over large areas. This approach has opened new perspectives for the study of current and past bank activities at catchment scales to quantify bank erosion contributions to the overall sediment budget.

Keywords: Drainage ditch, airborne LiDAR data, digital elevation model, bank erosion, sediment transport

1. Introduction

Rural landscapes have been completely modified by human activities in Western Europe since the beginning of the 20th century. These modifications are mainly due to the shift towards more intensive agriculture, with land reallocation leading to increased field sizes that necessitate adaptations of modern practices and heavier machinery. As a consequence of this landscape standardization, stream valley meanderings have been suppressed and realigned along new straight field borders. Cultivated areas also expand into wetlands located in valleys traditionally used as grassland (De Groot et al. 2002). The expansion of cultivated areas into wetlands necessitated the set-up of a new drainage networks to artificially create gravity drainage of excess water present in soils. These new drainage ditches (and drains) were connected to the modified and re-aligned stream valleys which were also redesigned to allow more water to be evacuated. All these modifications resulted in increased drainage network density (in relatively flat cultivated areas of the Loire Valley, drainage density can reach more than 1.5 km/km^2).

However, these modifications led to profound sedimentary and morphological alterations (channel bed incision, deposition of fine sediment, bank erosion, etc.), which make it difficult to achieve good water quality status (Arts et al. 2004). Currently, several decades after

DOI: 10.1127/zfg/2017/0348
www.borntraeger-cramer.de
0372-8854/zfg/2017/0348 $ 0.00

these landscape modifications, major alterations of the hydromorphology of streams are being observed (Mizugaki et al. 2006). This is the expression of a progressive return to an equilibrium state (Foucher et al. 2014) (Le Gall et al. 2015). Problems that are most commonly reported concern either an increase of bank erosion rates and/or an increase in the amount of sediment deposited in the riverbed. Siltation is often due to insufficient sediment transport capacity of flowing water and has strong adverse effects on river habitats and biodiversity. This phenomenon is of major concern with respect to the implementation of the EU Water Framework Directive (2000). Bank erosion phenomena can lead to an overproduction of sediments which result in ponds and lake siltation. At catchment scales, some authors have shown that bank erosion can constitute an important contribution to the overall sediment budget of a stream (Russell et al. 2001). For example, in many Australian and Norwegian basins, bank erosion can be the dominant source of sediment flux with a contribution usually exceeding 90% (Caitcheon et al. 2012, Laceby 2012, Kronvang et al. 2013). Conversely, particles from the banks can be a minimal part of the sediment flux, such as in rivers of the United Kingdom, where they account for between 5 and 15% of the material flow (Walling & Collins 2005).

More recently (Foucher et al. 2015), have shown that during low flow periods, bank erosion can represent from 51% to 60% of sediment export. It is therefore of major importance to quantify this erosion process to make appropriate decisions on sediment transfer management practices.

Drainage ditches can represent a significant proportion of the total stream linear distance. However, their relatively small dimensions render the quantification of bank erosion time-consuming and cost-prohibitive as it cannot be detected by using commonly available satellite or aerial images. Recent remote-sensing technologies, especially airborne laser altimetry (Light Detection And Ranging, LiDAR) allow the acquisition of high-resolution topographic information (Tarolli et al. 2009). A valuable characteristic of this technology is the capability to derive a high-resolution Digital Terrain Model (DTM) from the last pulse LiDAR data by filtering the vegetation points (Slatton et al. 2007). Hence, LiDAR Digital Terrain Models are now used in many disciplines concerned with earth-surface representation and modeling hydrologic and geomorphologic properties and changes including landslides, river morphology and channel network structures.

Hence, methods of geomorphic change detection (GCD) with LiDAR can be a solution to understand and estimate bank erosion quantitatively. In addition, these methods may be applied to a wide range of time periods when gridded data is available at different times. For example, a study produced DEMs of Difference (DoD) with 5 years of high resolution survey data from a 1 km long braided reach of the River Feshie in the Highlands of Scotland (Wheaton et al. 2009). The authors developed techniques to estimate uncertainty methods to produce DoD maps and estimate the net change in terms of storage for morphological sediment budgets. Other examples at different scales (space and time), used Terrestrial Laser Scanning (TLS) to measure bluff erosion (Day et al. 2013) or peat ditch erosion in drained forest areas (Stenberg et al. 2016).

Most DoD studies have been concerned with temporal scales less than decades based on field surveys or remote sensing data (Heritage et al. 2007). Historical reconstructions of greater durations require historical imagery or the use of cartographic data. James et al. 2012 listed the potential sources of error in digitized topographic maps and DEMs and their consequences, applying GCD using DoD constructed from data extending over periods ranging from 70 to 90 years.

As noted by Notebaert et al. (2009) while studying fluvial geomorphology in Belgium, pixel resolution is an important factor in the identification of small landforms: only features with a width equal to or larger than the LiDAR resolution can be detected. With respect to the application of LiDAR techniques in the recognition of small channels, the study of James et al. (2007) has proven the capability of LiDAR data in identifying and mapping gullies and headwater streams, even under forest cover. Bailly et al. (2008) proposed a methodology that uses LiDAR data in several steps to detect artificial drainage networks in Mediterranean vineyard landscapes. They obtained a high omission rate (50%) in ditch detection due to the presence of dense vegetation over ditches and the low density of LiDAR sampling points. This observation confirms that in the context of cultivated landscapes, drainage algorithms used on DTMs are unable to accurately represent anthropogenically modified overland flow paths (Duke et al. 2006, Garcia & Camarasa 1999). Cazorzi et al. (2013) have succeeded in automatically detecting and characterizing the channel network in a floodplain in north-east Italy with a 1 m DTM derived from a LiDAR survey (planned to be highly affordable and to be easily repeatable in the future). These studies have demonstrated the potential of using LiDAR to assess bank erosion in large rivers or to detect and give 2D dimensions of smaller channel networks. However, estimating the precise depth and, therefore, the 3D geometry of ditches whose dimensions are on approximately the same order as the DTM resolution remains to be explored.

This is particularly important in order to perform an integrated hydromorphological evaluation following the modification of rural landscapes in the second part of the 20th century. As such, the aim of this study is to test the possibility of using a high-resolution DTM to detect and quantify the current volume of drainage ditches at catchment scales and to assess the evolution of these ditches using archival data. This method was tested in a small agricultural headwater catchment, the Louroux pond catchment, of the Loire Valley, France, with a very flat topography and where agricultural drainage has been highly developed since 1944.

2. Materials and methods

2.1. Study site

The Louroux pond catchment is a small agricultural headwater catchment (24 km^2) of the Indre River that drains into the Loire River and is located approximately 30 km south of Tours, France (Fig. 1A). This catchment is characterized by lowland topography with very gentle slopes (0.44%). Most of the catchment (95%) is cultivated, and there are only a few fields occupied by permanent pasture.

There are at least 220 drain tile outlets in the catchment and it is estimated that at least 50% of the catchment is drained (Fig. 1B). The total length of referenced stream reaches 45.5 km in this catchment (BDTOPO, IGN). The drainage density is approximately 1.8 km/km^2. Drainage ditches and streams widths range between 1 and 5 m and their depth can reach up to 3 m.

2.2. Control ditch

An airborne LiDAR survey was carried out on March 2013 with a Leica LAS70 embedded on a BN2T plane. The flight plan was made with a density of 7 pts/m^2. The trajectory calculations were made with the IGN French RGP network stations (Permanent Global Navigation Satellite System Network). The LiDAR cloud points were calibrated by measuring points and homologous segments. Calibration residuals showed a vertical accuracy of approximately 5 cm and a horizontal accuracy of approximately 12 cm (RMSE approximately 2 times the standard deviation, which leads to good precision). The points were then classified with Terrasolid suite® to distinguish ground points, vegetation points, overlapping points and inconsistent points. The classification methodology is organized based on several steps. The first step consists of manual detection of outliers and false measurements points. The second step concerns the automatic determination of the soil surface by deleting the vegetation cover. The principle of this soil identification method is to take

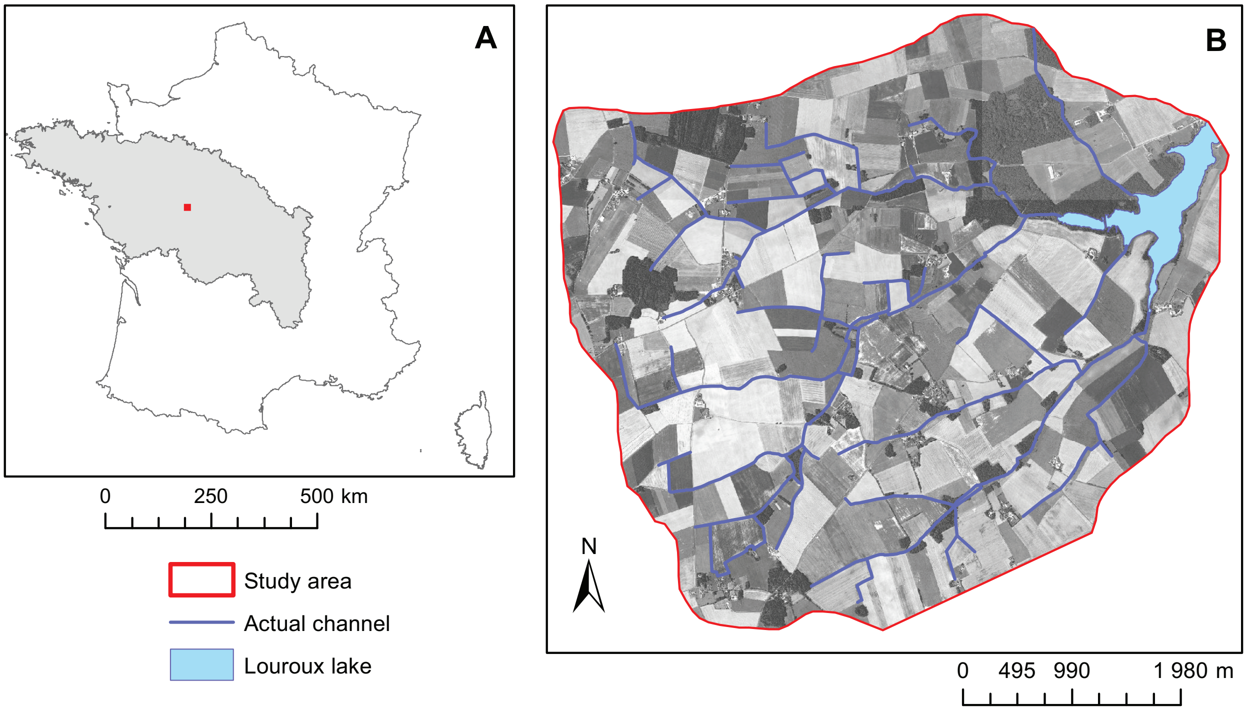

Fig. 1. **A** – Localization of the Louroux pond catchment in France and **B** – Current drainage network (adapted from BD TOPO 2.0 IGN).

the lowest point within a 60 to 100 cm radius, and then, by iterative calculations, the points are integrated as belonging or not to the soil depending on the angle and vertical distance criteria in relation to the DEM. The last step corresponds to a manual control which verifies areas where the slope classification is incomplete.

Using ground points, a triangulated model was created (TIN) and used to generate a 0.5 m point grid (point projection on triangulated surfaces) (Fig. 2A). On the survey day, there was approximately 10 cm of water in the ditches.

One specific 1400 m ditch was chosen to estimate the capacity of the DTM to evaluate its current 3D topography. This ditch was chosen because its history of redesign is quite well documented. A detailed topographic survey was performed November 2012 along this ditch (Fig. 2B) to provide accurate channel cross-sections. Forty-four channel cross-sections (one every 30–35 m

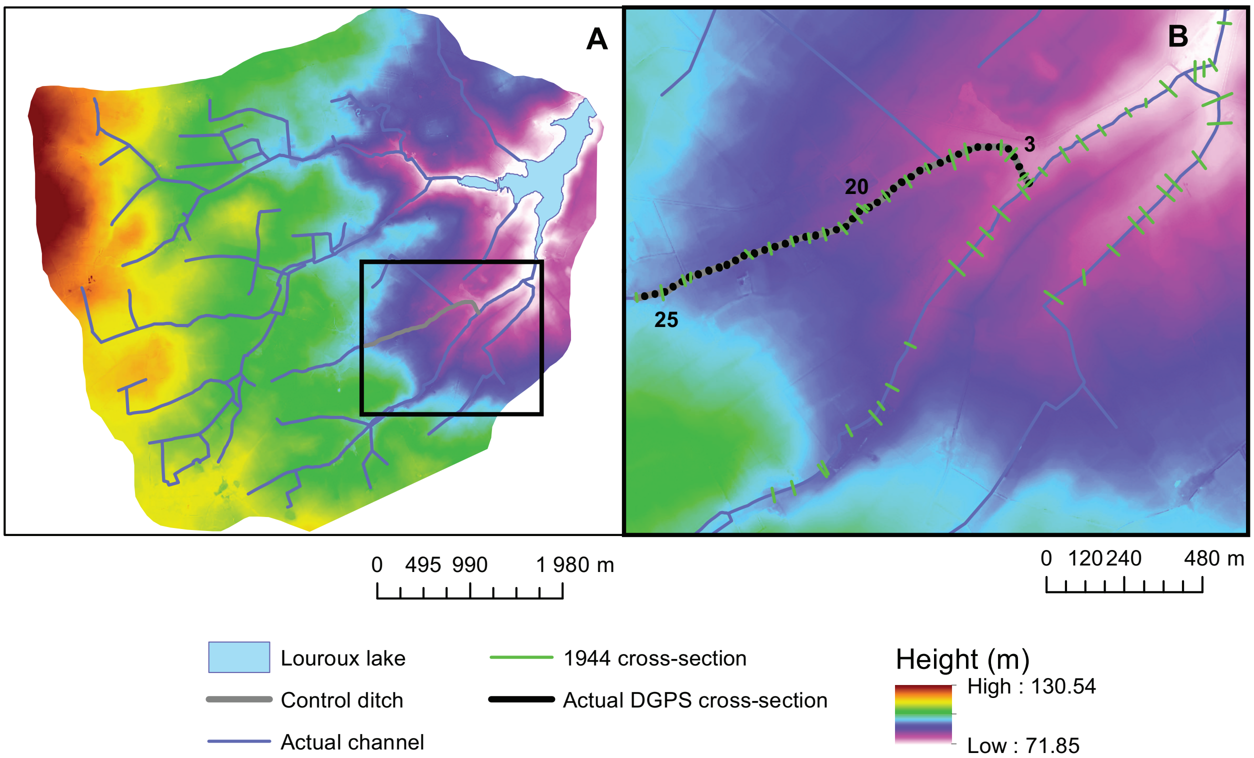

Fig. 2. **A** DTM and localization of **B**, the validation area.

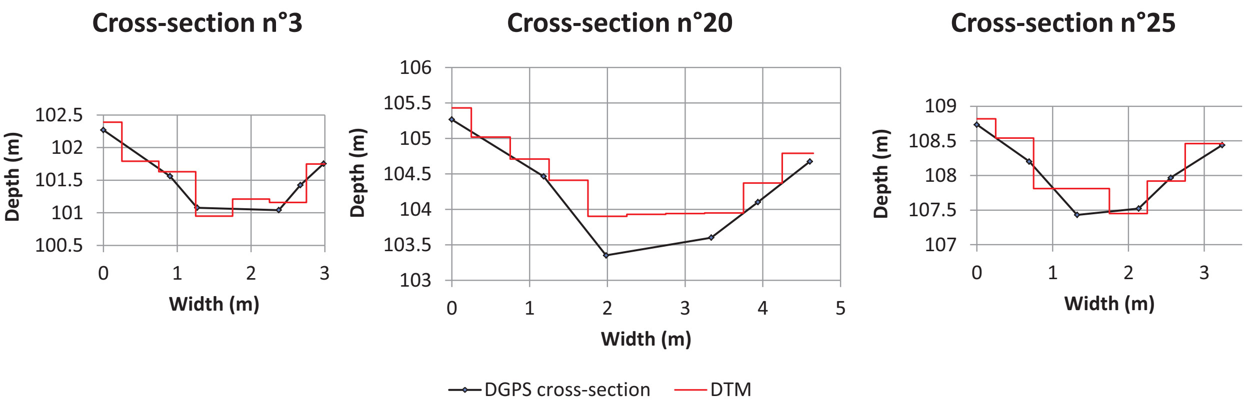

Fig. 3. Examples of cross-section geometry as depicted by 6 DGPS points (in black) compared to the DTM (in red) of the control ditch.

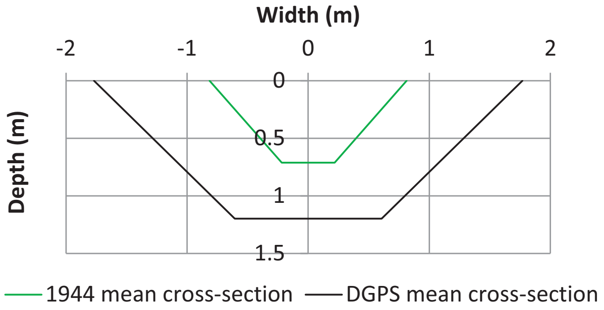

Fig. 4. Comparison between the mean 1944 cross-section along the control ditch (0.73 m²) (in green) and the mean cross-section obtained with DGPS points (2.84 m²) (in black).

on average) were measured with a DGPS (Differential Global Positioning System) Magellan pro flex® (centimetric accuracy). Most of the 44 profiles are composed of 6 measured points: 2 points at the top of the banks, 2 points at mid-height and the 2 last points at the base of the ditch to capture breaks in the slope (Fig. 3). These cross-sections were then compared to the geometries obtained with the DTM (Fig. 3).

Historical data were found in departmental archives for the south-eastern part of the Louroux pound catchment (Fig. 2B). The redesigned plans provided accurate geometrical information about these streams before and after management redesigned the stream in 1944. These archival data are composed of transverse profiles, which provide information about ditch depths and the bottom and top widths of banks. A compilation of these lateral and longitudinal punctual data was made to reconstruct the average geometry of the streams in 1944. Fig. 4 shows a comparison of the average DGPS profile of November 2012 with the average geometry in 1944. Within 69 years, the mean cross-section of this ditch increased by 350% (from 0.73 m² to 2.84 m²).

2.3. Calculation of ditch volume

The proposed morphological approach aims to evaluate the possibility of using a 0.5 m resolution DTM to estimate ditch volume automatically over the catchment area.

The method is composed of three main steps (Fig. 5):

1. Accurate detection of the ditch edges (two-dimensional localization of the top of the banks which delineate the horizontal surface in which the volume of the ditch is included).
2. Interpolation of a DTM not accounting for the ditch, DTM_{top}.
3. Calculation of the ditch volume (difference between the raw DTM and the DTM_{top}).

The first step requires special procedures to identify the subtle elevation changes in low relief topography. Indeed, drainage ditches are small scale forms and low "amplitude" elements. Amplitude is defined herein as the difference in elevation between points at the bottom of the ditch and the edges of the ditch. They are also topographically subtle in comparison to the surrounding plain, especially for areas where the landscape gradient is relatively low. The approach we present is based on the extraction of small amplitude objects from the DTM and the elimination of larger landscape forms. Similar approaches have been tested in other environments for landform characterization (Carturan et al. 2009) and for feature extraction (Hiller & Smith 2008, Passalacqua et al. 2010, Passalacqua et al. 2012 Cazorzi et al. 2013, etc.). The core idea shared by these studies is to apply a low-pass filter to the DTM, providing a smoothed elevation model representing an approximation of the larger landscape form. By subtracting the DTM from this smoothed map, an approximation of the local relief is achieved, where only small-scale topographic features are preserved and

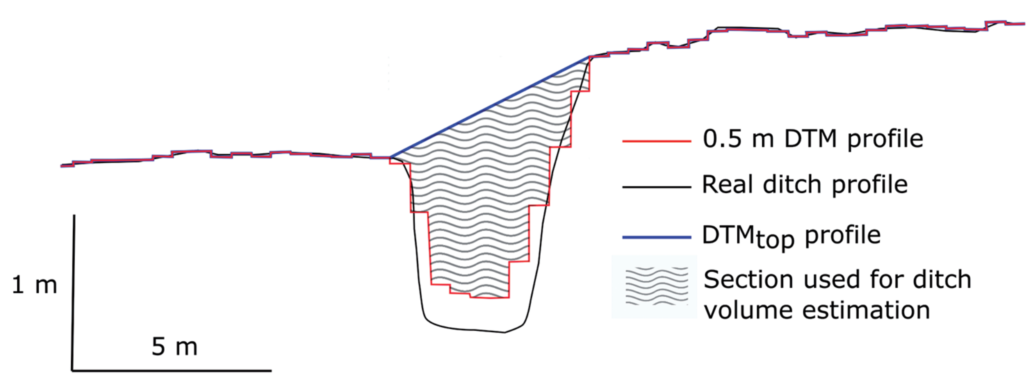

Fig. 5. Principle of ditch volume estimation.

not larger landscape forms. The derived model (Relative Elevation Attribute – *REA* – Carturan et al. 2009) represents a map of residual relief. This map is evaluated as:

$$REA_r = E_r - E_{DTM} \qquad (1)$$

where E_r is the average elevation of cells within a circular area with radius *r* (in meters) around the grid cell with elevation E_{DTM} (Carturan et al. 2009).

The raw DTM is shown in Fig. 6A and the REA for a moving circle analysis with a window of 7 meters radius is shown in Fig. 6B. REA clearly highlights drainage ditches (and other linear elements such as roads). Profile graphs of REA are shown in Fig. 6C.

Tarolli & Dalla Fontana (2009) and Pirotti & Tarolli (2010) used a threshold identified as m-times the standard deviation of curvature as an objective method for channel network extraction from high resolution topography for

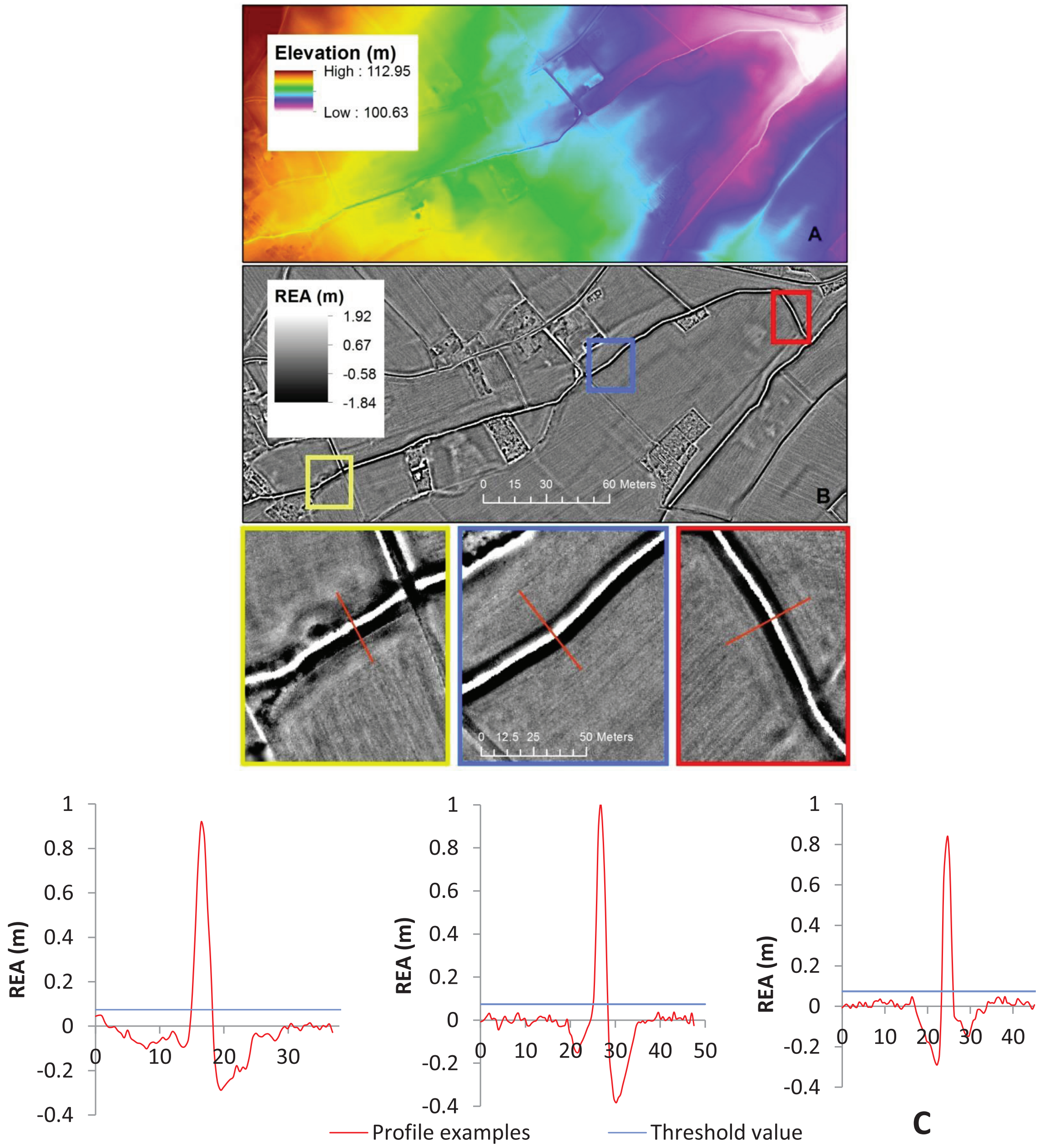

Fig. 6. **A** – raw DTM, **B** – REA on the control ditch (average elevation of cells evaluated within a circular area with a radius of 7 meters), **C** – examples of profiles graph of the REA.

mountainous contexts. For the proposed methodology, the chosen threshold is the standard deviation of REA as in Cazorzi et al. (2013) in a similar agrarian context.

Hence, the selected zones allow for extraction of ditch contours and their elevations to interpolate DTM_{top} (using the natural neighborhood method) (Fig. 5). It is then simple to estimate the volume between DTM_{top} and the raw DTM due to DTM subtraction. Before the interpolation, a 0.5 m buffer has been added to the ditch contours to account for the influence of each 0.5 m pixel and not to under-evaluate volume estimation: this over-estimation is regulated by the DTM subtraction because only positive volumes are kept.

3. Results

3.1. Comparison of cross-sections

The procedure described below was first applied to the control ditch (Fig. 3). The 44 DGPS profiles were used to reconstruct ditch geometry by linking them by segment. This operation was performed supposing straight trajectory between two profiles. Using these measurements, the control ditch volume was estimated as 3700 m^3. To understand and quantify errors made with the high-resolution DTM, each DGPS profile was compared to the equivalent profile obtained with the DTM (Fig. 3). Globally, ditch sections extracted from the DTM were under-evaluated because of a biased restitution of bottom ditch elevation. The average error made by DTM in estimating stream depth was approximately 13% and less than 12% for stream width detection. The ditch volume estimate using DTM sections instead of DGPS sections was 3108 m^3.

With this comparison, we can therefore estimate an average error on all the sections of 16%, principally caused by under-estimating bottom ditch morphology. One identified bias of bottom ditch elevation calculations is linked to the fact that 10 cm of water on average was present in the ditches at the time of the flight. This error is mainly present in the parts of the stream with the smallest sections: the DTM resolution is too coarse to faithfully capture the stream morphology of these small objects (Fig. 7).

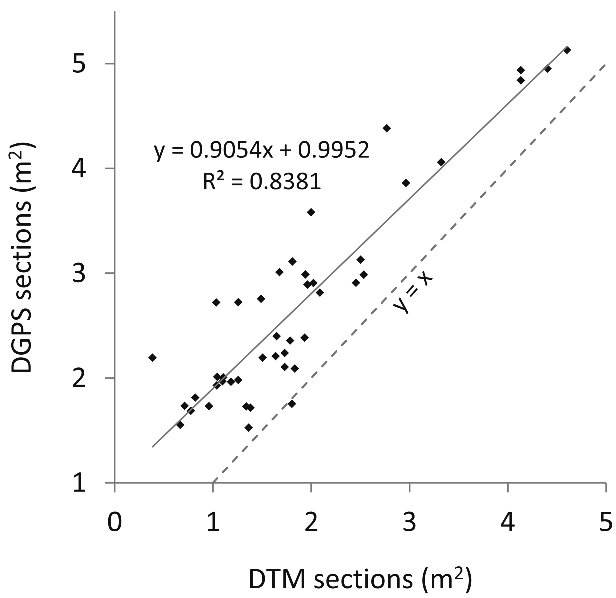

Fig. 7. Comparisons between all DGPS sections and the corresponding DTM sections.

3.2. DTM volume estimation

Continuous data obtained by the DTM allowed us to calculate the volume of the 1.4 km control ditch in 2013. Compared to the volume previously calculated using DTM cross sections, this estimation accounts for continuous evolution of stream morphology. With this technique, a volume of 3300 m^3 has been calculated for the control ditch. This result is higher than the previous value obtained using the LiDAR cross section estimation (3100 m^3) but it is in better agreement with that calculated with the DGPS data. The use of LiDAR cross sections induces an underestimation of 200 m^3 for this stream portion compared to the DTM approach. This slight underestimation (approximately 11%) may be attributed to the vegetation shadow effect that may have been present on the edges of the banks. The LiDAR cross sections were measured in accessible areas where there was no vegetation, interpolation between the different sections was carried out independent of the potential presence of vegetation, whereas LiDAR data take vegetation into account.

Overall, the results obtained on a small part of the hydrographic network confirm that the DTM calculated from LiDAR cloud points provides good results and allows for error estimation, even for ditches that are small (1.5 to 4 m width) morphologically. These results show that the LiDAR approach is a good alternative for estimating stream bank volumes. Unlike DGPS surveys, it allows large data sets to be rapidly obtained. A small DGPS campaign can help evaluate underestimations in the LiDAR approach. It does not require data preprocessing or permits to cover large areas with high resolution to identify ditch networks and quantify volumes in agricultural plains.

3.3. Comparison with the 1944 control ditch

Three-dimensional historical plans dating back to the redesign of the stream in 1944 have been compiled for the control ditch to reconstruct the volume it occupied at that time. Post-construction control with wooden templates suggests that streams were rectilinear and very geometric. Using the geometrical information given by the historical redesign plans and considering the ditch is made of sections that are represented by the nearest measured profile, the control ditch volume was 1000 m^3. The previous result obtained with DTM data suggests that the control ditch in 2013 occupied a volume of 3300 m^3. Considering an underestimation of 11% as calculated previously, the ditch volume can be brought back to 3700 m^3.

Therefore, within 69 years, more than 2700 m^3 of bank material has been exported, representing an average loss of sediment of 1900 $m^3.km^{-1}$ (28 $m^3.km^{-1}.yr^{-1}$). On this ditch section, we can estimate an average erosion/incision of bank faces at 36 $t.km^{-1}.yr^{-1}$ (with an average bank dry bulk density calculated in the catchment at 1300 $kg.m^{-3}$).

The results obtained from a small part of the catchment indicate a high level of erosion during the last 69 years in response to anthropogenic management practices during the post-war period.

3.4. Catchment scale

The LiDAR approach to catchment scale allows the current volume of the ditches to be estimated at 69100 m^3. Insofar as ditch dimensions are homogeneous within the catchment, the total volume can be estimated more precisely to approximately 76700 m^3 (considering an underestimation of 11%). To make a first rapid estimation of the total volume just after the stream redesign in 1944, the volume calculated for the 1400 m control ditch (1000 m^3) has been extrapolated to 45.5 km (total length of referenced stream). Hence, it is assumed that stream beds occupied a volume of 32500 m^3 over the entire catchment immediately after their redesign. By comparing the current volume occupied by the streams in 2013 with this 1944 volume, an approximate gross delivery of bank material to the streams can be evaluated to 44200 m^3 (assuming that all the current ditches existed in 1944). Within 69 years, this represents approximately 57400 t of bank material eroded that contributed to pond filling, representing a mean sediment delivery of bank material of 830 $t.yr^{-1}$ between 1944 and 2013 and a specific delivery approximately 35 $t.km^{-2}.yr^{-1}$.

4. Discussion

In this study, airborne LiDAR data have been used to estimate artificial drainage ditch volumes over a large area (24 km^2). Previous studies have used airborne LiDAR data over large areas to automatically detect artificial ditches. Cazorzi et al. (2013) have succeeded in automatically detecting and characterizing the channel network in a floodplain in northeast Italy with a 1 m DTM derived from a LiDAR survey. They highlighted the possibility of estimating network summary statistics (i.e., network length, drainage density and storage capacity) in an agrarian/floodplain context were flow-direction matrices are not applicable to extract the network, due to the low surface gradient. Other studies have been conducted to detect natural stream and channel heads, in mountainous contexts, by using different resolution grids deduced from airborne LiDAR data (Tarolli & Dalla Fontant 2009, Vianello et al. 2009, Cavalli et al. 2008). These approaches rely on hillslope morphology and drainage area analysis. Bailly et al. (2008) attempted to use LiDAR data for ditch volume estimates at catchment scales (2 km^2) with a similar LiDAR point sampling density but in a different context, notably in terms of vegetation density. In the Mediterranean context, where vegetation is concentrated along the water flow path, vegetation presents a strong limitation which impedes accurate detection. Overall, high-resolution LiDAR data are more often used to compute DoD to detect local erosion, such as cliff erosion (for example, e.g., Day et al. 2013, Stenberg et al. 2016).

We also made a volume comparison with historical plans for a single ditch (where recalibration plans were available) and we extrapolated the results to the catchment scale in order to estimate bank material contribution to sediment export for the last 69 years. James et al. (2012) have shown that it was also possible, in certain cases, to construct DEMs by extracting topographic data from historical maps (70 to 90 years old) where geomorphic (channel or river bed incision/migration) change has been substantial. Depending on the resolution and quality of the historical plans this methodology can produce even more detailed results. This type of comparison with historical plans has been carried out by Landemaine et al. (2015) in the Ligoire catchment on a natural river. The quality of the historical recalibration plans available for that study permitted them to analyze successive patterns of erosion and deposition along the stream.

Concerning catchment scale results, Foucher et al. (2014) estimated sediment export during the period from 1945–2013 with to seismic imagery and core dating in the lake: ca. 300 t. $km^{-2}.yr^{-1}$ between 1954 and 1980 and ca. 95 t. $km^{-2}.yr^{-1}$ between 1980 and 2013. Today, erosion rates recorded at the outlet of the Louroux catchment are approximately 90–102 t. $km^{-2}.yr^{-1}$. Therefore, the order of magnitude of the mean export rate is approximately 180 t. $km^{-2}.yr^{-1}$ for the last 70 years. Bank material contribution would be approximately 20% for the all periods and ca. 31% for the period between 1954 and 1980 when the ditches were constructed. Bank erosion seems to be one of the most important sources of material exported thought the river systems in these agricultural plain catchments, mostly in the years immediately following construction as there is a new created topographic dynamic and the river is attempting to reach a new equilibrium.

Moreover, these drainage features not only provide materials but also facilitate the transfer of particles that originate from surface erosion or tile drain erosion. In these environments, drainage contributes substantially to increasing catchment sediment connectivity.

5. Conclusions and perspectives

The intensification of agriculture in the second half of the 20th century has led to an increase in artificial drainage network densities of cultivated catchments in lowland areas. As a result, these streams and ditches are eroding, transferring sediments to rivers (Kronvang et al. 2013, Olley et al. 2013), and degrading their ecological status. Since quantification of these processes at catchment scales by field measurements is time consuming, we investigated the potential of airborne instruments to map and quickly estimate the volume occupied by ditch networks over large areas, using a 0.5 m DEM.

Although, drainage ditches are relatively small objects (1.5 to 4 m width), we could detect them and estimated a ditch volume. A comparison with terrestrial DGPS profiles shows an average of 11% under-estimation of the volume.

This method can be relatively easily applied and can be repeated or compared to historical plans to assess ditch profile evolution and its contribution to the river sediment budget. In this study, the volume estimated at the catchment scale was compared to the ditch originally designed 69 years ago by extrapolating historical plans to the entire catchment. Hence, it was possible to assess that more than 44200 m^3 of bank material has been exported, representing an average sediment loss of 35 $t.km^2.yr^{-1}$. These new quantifications allude to high erosion, mainly induced by anthropogenic land use changes, of the landscape despite having a very flat topography.

The underestimation of DTM ditch volume detection corresponds to the limitations of this method and is directly linked to DTM resolution and ditch size. The high-resolution DTM technique does not allow for good resolution of the bottom ditch width, since it can be smaller than 0.5 m. Moreover, the vegetation cover along the banks can slightly affect the results, however in case of an extrapolation of this method over large areas, the presence of vegetation can locally induce an underestimation of ditch volume or even prevent stream detection. A simple way to overcome this problem is to calculate the stream depth where the vegetation is present by extrapolating the stream depth of the upstream and downstream sections around this vegetated area. Stream depth near vegetated areas seems to have little consequence on long-term estimates of these values averaged over time.

Acknowledgements: We gratefully acknowledge Xavier Bourrain, Jean-Noel Gautier and Anne Colmar and the financial support of the Agence de l'Eau Loire Bretagne.

References

Arts, M.J.T., Haenen, G.R.M., Voss, H.-P. & Bast, A. (2004): Antioxidant capacity of reaction products limits the applicability of the Trolox Equivalent Antioxidant Capacity (TEAC) assay. – Food Chem. Toxicol. 42: 45–49.

Bailly, J.S., Lagacherie, P., Millier, C., Puech, C. & Kosuth, P. (2008): Agrarian landscapes linear features detection from LiDAR: application to artificial drainage networks. – Int. J. Remote Sens. 29: 3489–3508.

Caitcheon, G.G., Olley, J.M., Pantus, F., Hancock, G. & Leslie, C. (2012): The dominant erosion processes supplying fine sediment to three major rivers in tropical Australia, the Daly (NT), Mitchell (Qld) and Flinders (Qld) Rivers. – Geomorphology 151–152: 188–195.

Carturan, L., Cazorzi, F. & Dalla Fontana, G. (2009): Enhanced estimation of glacier mass balance in unsampled areas by means of topographic data. – Ann. Glaciol. 50: 37–46.

Cavalli, M., Tarolli, P., Marchi, L. & Dalla Fontana, G. (2008): The effectiveness of airborne LiDAR data in the recognition of channel-bed morphology. – Catena 73 (3): 249–260.

Cazorzi, F., Fontana, G.D., De Luca, A., Sofia, G. & Tarolli, P. (2013): Drainage network detection and assessment of network storage capacity in agrarian landscape. – Hydrol. Process. 27: 541–553.

Day, S.S., Gran, K.B., Belmont, P. & Wawrzyniec, T. (2013): Measuring bluff erosion part 1: terrestrial laser scanning methods for change detection. – Earth Surf. Proc. Land. 38: 1055–1067.

De Groot, R.S., Wilson, M.A. & Boumans, R.M.J. (2002): A typology for the classification, description and valuation of ecosystem functions, goods and services. – Ecol. Eco. 41: 393–408.

Duke, G.D., Kienzle, S.W., Johnson, D.L. & Byrne, J.M. (2006): Incorporating ancillary data to refine anthropogenically modified overland flow paths. – Hydrol. Process. 20: 1827–1843.

European Environment Agency (2000) EU Water Framework Directive (http://ec.europa.eu/environment/water/water-framework/info/intro_en.htm).

Foucher, A., Salvador-Blanes, S., Evrard, O., Simonneau, A., Chapron, E., Courp, T., Cerdan, O., Lefèvre, I., Adriaensen, H., Lecompte, F. & Desmet, M. (2014): Increase in soil

erosion after agricultural intensification: Evidence from a lowland basin in France. – Anthropocene 7: 30–41.
Foucher, A., Laceby, P.J., Salvador-Blanes, S., Evrard, O., Le Gall, M., Lefèvre, I., Cerdan, O., Vignesh, R. & Desmet, M. (2015): Quantifying the dominant sources of sediment in a drained lowland agricultural catchment: The application of a thorium-based particle size correction in sediment fingerprinting. – Geomorphology 250: 271–281.
Garcia, M.J.L. & Camarasa, A.M. (1999): Use of geomorphological units to improve network extraction from a DEM drainage Comparison between automated extraction and photointerpretation methods in the Carraixet catchment (Valencia, Spain). – JAG 1: 187–195.
Heritage, G., Hetherington, D. & Wiley, J. (2007): Towards a protocol for laser scanning in fluvial geomorphology. – Earth Surf. Proc. Land. 32: 66–74.
Hiller, J.K. & Smith, M. (2008): Residual relief separation: digital elevation model enhancement for geomorphological mapping. – Earth Surf. Proc. Land. 33: 2266–2276.
James, L.A., Hodgson, M.E., Ghoshal, S. & Latiolais, M.M. (2012): Geomorphic change detection using historic maps and DEM differencing: The temporal dimension of geospatial analysis. – Geomorphology 137: 181–198.
James, L.A., Watson, D.G. & Hansen, W.F. (2007): Using LiDAR data to map gullies and headwater streams under forest canopy: South Carolina, USA. – Catena 71: 132–144.
Kronvang, B., Andersen, H., Larsen, S.R. & Audet, J. (2013): Importance of bank erosion for sediment input, storage and export at the catchment scale. – J. Soil. Sed. 13 (1): 230–241.
Laceby, J.P. (2012): The Provenance of Sediment in Three Rural Catchments in South East Queensland, Australia. – Thesis (PhD Doctorate), Griffith University, Brisbane.
Landemaine, V., Gay, A., Cerdan, O., Salvador-Blanes, S. & Rodrigues, S. (2015): Morphological evolution of a rural headwater stream after channelisation. – Geomorphology 230: 125–137.
Le Gall, M., Evrard, O., Thil, F., Foucher, A., Salvador-Blanes, S., Cerdan, O. & Ayrault, S. (2015): Tracing Sediment Sources Using Strontium Isotopes in a Pond Draining an Agricultural Catchment (Loire River Basin, France). – Procedia Earth Planet. Sci. 13: 30–34.
Mizugaki, S., Nakamura, F. & Araya, T. (2006): Using dendrogeomorphology and 137 Cs and 210 Pb radiochronology to estimate recent changes in sedimentation rates in Kushiro Mire, Northern Japan, resulting from land use change and river channelization. – Catena 68: 25–40.
Notebaert, B., Verstraeten, G., Govers, G. & Poesen, J. (2009): Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology. – Earth Surf. Proc. Land. 34: 217–231.
Olley, J., Burton, J., Smolders, K., Pantus, F. & Pietsch, T. (2013): The application of fallout radionuclides to determine the dominant erosion process in water supply catchments of subtropical South-east Queensland, Australia. – Hydrol. Process. 27 (6): 885–895.
Passalacqua, P., Belmont, P. & Foufoula-Georgiou, E. (2012): Automatic geomorphic feature extraction from LiDAR in flat and engineered landscapes. – Water Resources Research 48: 1–18, W03528.
Passalacqua, P., Do Trung, T., Foufoula-Georgiou, E., Sapiro, G. & Dietrich, W.E. (2010): A geometric framework for channel network extraction from LiDAR: Nonlinear diffusion and geodesic paths. – Journal of Geophysical Research 115: 1–18, F01002.
Pirotti, F. & Tarolli, P. (2010): Suitability of LiDAR point density and derived landform curvature maps for channel network extraction. – Hydrol. Process. 24: 1187–1197.
Russell, M., Walling, D. & Hodgkinson, R. (2001): Suspended sediment sources in two small lowland agricultural catchments in the UK. – J. Hydrol. 252: 1–24.
Slatton, K.C., Carter, W.E., Shrestha, R.L. & Dietrich, W. (2007): Airborne Laser Swath Mapping: Achieving the resolution and accuracy required for geosurficial research. – Geophys. Res. Lett. 34: 1–12, L23S10.
Stenberg, L., Tuukkanen, T., Finér, L., Marttila, H., Piirainen, S., Kløve, B. & Koivusalo, H. (2016): Evaluation of erosion and surface roughness in peatland forest ditches using pin meter measurements and terrestrial laser scanning. – Earth Surf. Proc. Land. 41 (10): 1299–1311.
Tarolli, P., Arrowsmith, J.R. & Vivoni, E.R. (2009): Understanding earth surface processes from remotely sensed digital terrain models. – Geomorphology 113: 1–3.
Tarolli, P. & Dalla Fontana, G. (2009): Hillslope-to-valley transition morphology: New opportunities from high resolution DTMs. – Geomorphology 113: 47–56.
Vianello, A., Cavalli, M. & Tarolli, P. (2009): LiDAR-derived slopes for headwater channel network analysis. – Catena 76 (2): 97–106.
Wheaton, J.M., Brasington, J., Darby, S.E. & Sear, D.A. (2009): Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. – Earth Surf. Proc. Land. 35: 136–156.

Manuscript received: February 18, 2016
Accepted: December 16, 2016