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HIGH RESOLUTION DEMS FOR THE ANALYSIS OF FLUVIAL AND ANCIENT ANTHROPOGENIC LANDFORMS IN THE ALLUVIAL PLAIN OF PADUA (ITALY)

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The alluvial plain around Padua results from the sedimentary activity of the Brenta and the Bacchiglione rivers since the last glaciation to the modern times. The inner and oldest part of the city developed on the banks of a former meander of the Brenta River, later occupied by a minor course, the Bacchiglione. Early archaeological evidence dates back to the final Bronze Age and the first urban settlement started in the Iron Age. The underground of the city centre consists of alluvial sediments overlaid by Iron Age, Roman, and Medieval archaeological deposits. A comparison of high-resolution DEMs, built from different datasets (CTR, CTR-n, CTC maps; LiDAR), is presented. This comparison shows how the accuracy and density of spot heights influence the derived geomorphological interpretations. LiDAR data have the potential to generate a very accurate DEM, even if it is very sensitive to local topographic anomalies and the specific conditions of acquisition. Only the CTC DEM can really be compared to LiDAR in terms of resolution: whereas the CTR DEM provides a good approximation of the mean surface of the alluvial plain, it also tends to «over-smooth» both natural and ancient anthropogenic landforms. The CTR-n DEM has higher resolution than the CTR but it is less suitable for geomorphological analysis. The LiDAR and the CTC DEMs, integrated with remote sensing data, provided new insights on the geometry of fluvial landforms at different scales, from single levees and bars to large alluvial ridges and interfluves. Moreover, these allowed for a high detailed investigation of the morphology of the archaeological mound in the city centre for geoarchaeological purposes.

KEY WORDS: DEM, LiDAR, Palaeochannel, Fluvial ridge, Archaeological mound, Venetian alluvial plain.

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INTRODUCTION

The geomorphological investigation of alluvial plains experienced a major improvement in Italy since the beginning of the 1980s, following the first release of the Regional Technical Maps (CTR - *Carta Tecnica Regionale*) at scale 1:10,000 and 1:5000. In these maps, the contour lines are not drawn in the low relief sector of the alluvial plain and the altimetry is represented through spot heights with a precision of ± 1.2 m and a density of 20-70 points per km². This setting allows a fairly detailed description of the main alluvial landforms (Castiglioni & *alii*, 1987; Zangheri, 1990; Castiglioni, 1995; Castiglioni, 1997a; 1997b; Tellini, 2001). DEMs (Digital Elevation Models) derived from CTR maps have been widely applied in the study of fluvial landforms (Guzzetti & *alii*, 1997; Mozzi, 2005; Ferrarese & *alii*, 2006). A new milestone in the production of DEMs in low-relief terrain is represented by LiDAR (Light Detection and Ranging). LiDAR's application on the study of alluvial environments has been increasing in the last 10 years (French, 2003; Jones & *alii*, 2007), as in the study on the Rhine-Meuse Delta (Berendsen & Volleberg, 2007; Possel, 2009).

In high-detail geomorphological investigations, it is of paramount importance to define the degree of accuracy attained by different DEMs in relation to the scale of the source dataset and the effectiveness of processing algorithms. The same observation could be said when DEMs are used for other applicative tasks, for example, in hydrological modeling, river channel monitoring, and mapping of flood hazard.

In this paper we present and compare the DEMs of the city of Padua and the surrounding alluvial plain (fig. 1) obtained from different cartographic datasets (fig. 2) and LiDAR. Due to its alluvial evolution during the Holocene

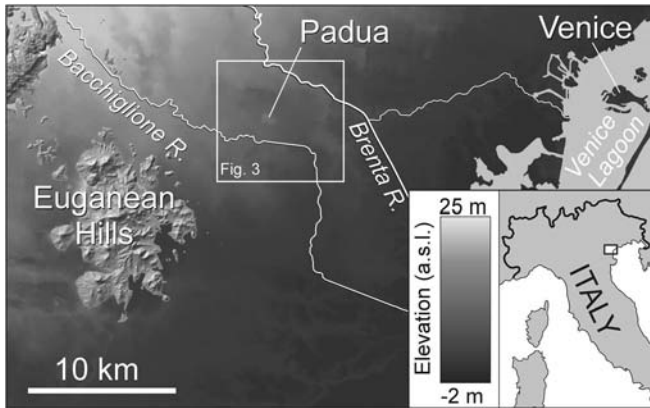


FIG. 1 - DEM of the central portion of the Venetian Plain with indication of Padua and its surroundings. The square indicates the area represented in fig. 4.

and the fairly continuous archaeological layering since the 1st millennium BC, Padua and its surroundings represent an interesting area to test the validity of DEMs produced from different sources, highlighting DEMs role in the investigation of natural and archaeological landforms. The aim is to provide a comparative evaluation of the results that can be obtained through the analysis of different DEMs in geomorphological and geoarchaeological research.

GEOMORPHOLOGICAL AND ARCHAEOLOGICAL SETTING

Padua lies in the distal plain of the Brenta River, a major Alpine river with a mountain catchment of 1800 km², which drains the southwestern portion of the Dolomites. The Brenta alluvial plain underwent several geomorphic changes during the last 20 ka, in response to changing climatic conditions (Mozzi, 2005; Fontana & *alii*, 2008). A major aggradation phase occurred during the LGM (Last Glacial Maximum, 30-17 ka cal. BP) when an alluvial megafan formed, fed by the meltwater of the glacier hosted in the Brenta valley. In the distal portion of the megafan, approximately between the Sile River to the East and the Astico River to the West, the LGM alluvial sequence consists of 15-20 m of fine-dominated deposits; in Padua, medium sands are the coarsest LGM sediments (Iliceto & *alii*, 2001). Following glacial decay an erosive tendency characterized the whole Venetian Plain, between Lateglacial and middle Holocene, when river activity funneled along few directions; this led to the formation of fluvial incisions (Mozzi, 2005; Fontana & *alii*, 2008). Traces of meandering, incised channels have been identified in the alluvial plain NW and SW of Padua (Castiglioni, 1982a; 1982b; Baggio & *alii*, 1992; Balista & Rinaldi, 2005; Mozzi & *alii*, 2010). Radiocarbon datings of some channel-fills NW of the city center indicate a middle Holocene de-activation of these meanders, between 8-6 ka cal. BP (Castiglioni & *alii*, 1987). Considering their direction and typology, Holocene channel

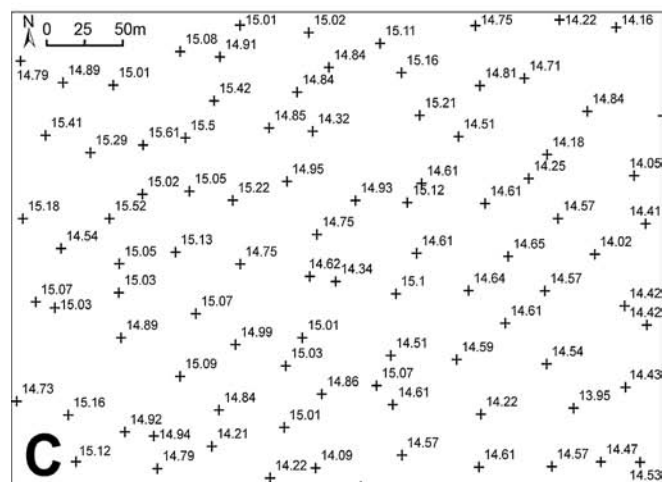
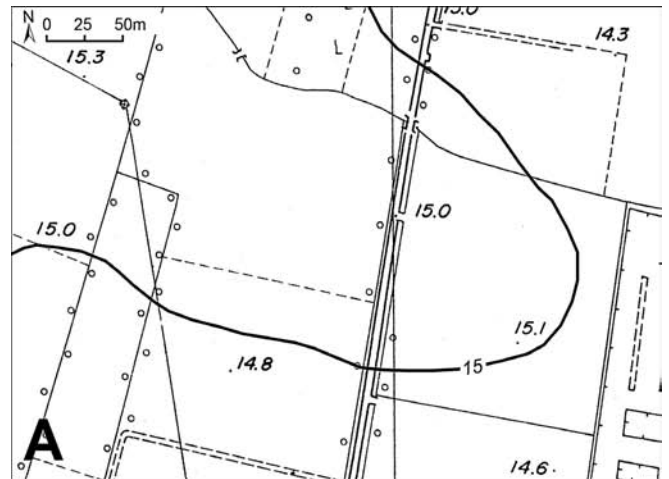


FIG. 2 - The original datasets used to produce the CTR, CTR-n and CTC DEMs, relative to the same sample area (128330 m²) in the alluvial plain NW of Padua. CTR sample (A) shows a contour line derived from manual interpolation of spot heights; CTR-n sample (B) shows the spot heights and the selected *z* features; the CTC sample (C) shows distribution of spot heights (topographic map is omitted due to problems of representation at this scale).

belts of the Brenta River are likely to continue beneath the city center.

The Padua plain is crossed also by another river, the Bacchiglione. This river is fed by springs located in the plain, at the transition between the gravelly piedmont plain and the clay-silty-sandy lower plain, about 30 km NE of Padua. It also receives water from the Astico River, which has a mountain catchment of 623 km² in the Venetian Prealps. The alluvial system of the Brenta River is larger than that of the Bacchiglione River. While the Brenta deposits form the majority of the plain, the sedimentary and geomorphic activity of the Bacchiglione seem to be restricted along its present meander belt.

Padua developed along the banks of opposing eastward and westward bends of two large meanders (Balista, 2004; Balista & Rinaldi, 2005), probably formed by the Brenta (Castiglioni, 1982a; 1982b). This river presently flows several kilometers NE of the city, and it is likely that the Bacchiglione River had already occupied the former channel of Brenta in Antiquity. Nevertheless, it is not yet settled whether the *Meduacus* River, which crossed the Roman city of *Patavium* as reported by Roman written sources, was the Brenta or the Bacchiglione. This latter has been crossing the city center since the Middle Ages, and only in the 19th century has it been artificially confined out of the city in order to prevent flood events. In the 1950s, long tracts of the relict meander in the center of Padua were partly filled and covered by roads.

The archaeology of Padua is very complex. Following scattered settlements of the final Bronze Age (1150-1000 BC) (De Min & alii, 2005), Padua experienced major growing phases during the Iron Age and then a new significant expansion since the 2nd century BC, when *Patavium* became a Roman *Municipium*. After a period of crisis in early medieval times, the city flourished again since the 12th century AD. This brought important changes in the urban structure such that large sectors of the present city date back to the 12th-15th century (Bonetto, 2009). The stacked layering of different cultural periods resulted in a very complex archeological stratigraphy, with a maximum thickness of 7 meters. It created the mound in the core of the city center, along the two meanders, which rises 5-6 m higher than the surrounding alluvial plain (Ferrarese & alii, 2006).

METHODS

DEM production

Here we present the methods of DEM construction from different datasets (fig. 2): CTR, CTR-n (numerical release of CTR maps), CTC (Technical Map of the Municipality of Padua, scale 1:1000) and LiDAR.

DEM from CTR

The first tool that allows for a fairly good analysis of floodplain features was the CTR, printed in paper version at scales 1:10,000 and 1:5000 since 1984. The majority of

the spot heights (> 90%) of CTR derive from analog stereo restitution of aerial images acquired between 1981 and 1983 (scale of flight 1:18,000). The declared range of error is ± 1.2 m; in the interpolation of the DEM, this corresponds to an error of about ± 2 m at 1σ . The first step has been the creation of contour lines (1 m interval). Due to the high urbanization of the area and the low density of z values (spanning from 20 to 70 points/km²), a manual interpolation was preferred over other automatic methods in the drawing of the contour lines. This procedure allows the operator to discard all those points on modern artifacts that are regarded to be not representative of the surrounding topographic surface, for example, roads and railway tracks on embankments, bridges, dikes, farm yards, and others. The CTR derived contour lines were drawn from over 70 geodetic benchmarks, nine second-order vertices, and more than 4000 spot heights. The DEM (fig. 3a) was built with a specific version of the TIN interpolation for contour lines (Zhu & alii, 1999). This work is a part of a major project that stemmed from the collaboration between the University of Padua's Department of Geography and ARPAV (Regional Agency for Environmental Protection in Veneto) for the realization of a DEM (20 m cell size) of the natural surface of the entire alluvial plain of Veneto.

DEM from CTR-n data

In 1990, the cartographic services of the Veneto Region started to produce the numeric format of 1:5000 CTR-n, using APIC CAD software, exportable in DXF format. CTR-n has Z-features in many objects on its tiles: vertices of polygons and polylines have height attribute. To build the DEM of the city center and its surroundings, 14 maps of the more updated version (1997) were used (fig. 3b). A total of ~15,000 height spots exist within that area; moreover, to recreate the base level of break-lines in a separate layer, the most relevant anthropic objects were selected (e.g., roads, streets, artificial hydrographic networks, and ground level of buildings). A long pre-elaboration was needed to remove wrong objects and to manage missing values. Altimetry errors were detected through visual analysis of DEM derivatives (i.e., hillshade, slope, and curvature), which are very sensitive to the propagation of errors (Wood, 1996; Florinsky, 2005). Linear exact methods of interpolation (Delaunay TIN) were applied to the database; the derived TIN was converted in raster DEM, with a cell size of 5 m. The most evident problem is the incoherence in the z measurement of objects belonging to adjacent tiles (fig. 3b). It seems that every CTR series of tiles have its geodetic height plain reference that is not collinear. The effect is the formation of little and rectilinear scarps along some map tile edges. One or more low-pass filters cannot help to avoid this effect.

CTR-n DEM ranges from 0.5 to 25.5 m a.s.l., while CTR DEM has heights ranging from 6 to 18 m a.s.l. This difference between the two datasets (fig. 3a, 3b) is mainly due the general smoothing of the CTR DEM, characterized by the cutting of tops and the filling of depressions

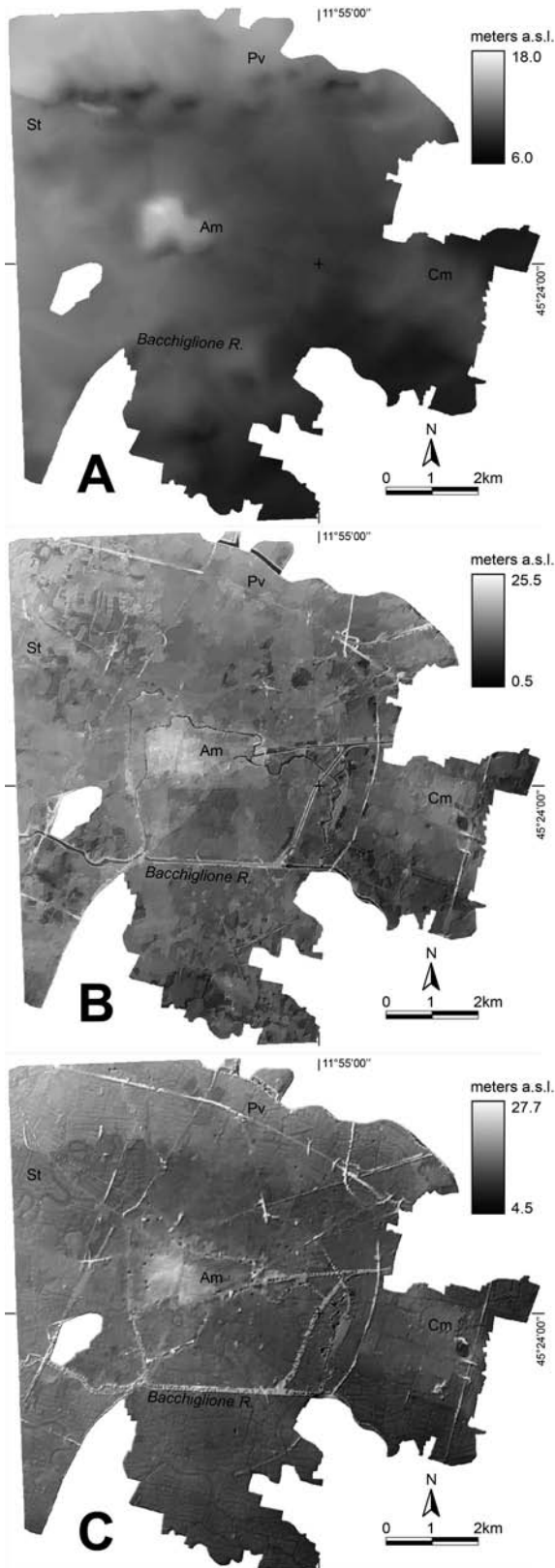


FIG. 3 - Greyscale DEMs with hillshading, obtained from: A) CTR; B) CTR-n; C) CTC. Main landforms described in the text: Pv) Pontevidarzero fluvial ridge; St) La Storta palaeochannel; Am) Anthropic mound; Cm) Camin fluvial ridge.

during the manual drawing of contours and the absence of anthropic breaklines.

DEM from CTC

In 1996, the Municipality of Padua edited a topographic map of its territory at scale 1:1000. This map consisted of 251 tiles, and it was created in a CAD like proprietary format that was not compatible with the GIS software. Despite this problem, it was possible to export the CTC heights with correct z values and a relative geometric position in x and y that was later converted in geographic coordinates. Spot heights are ~240,000 in an area of 92 km², with a certified accuracy of 0.35 m in x-y positioning; z range of error is not declared, but normally it may be considered two to three times the planimetric error, that is, a value <1 m. Only 150,000 of these heights were useful for DEM generation (fig. 3c) because ~90,000 referred to the top of buildings and hence the selected points have a density of 1630 per km². Linear exact methods of interpolation (Delaunay TIN) were applied to the database, generating a first version of DEM in which the heights errors (mainly top building values not removed) were detected and removed with a visual survey of TIN and of its derivatives (slope, hill-shade, curvature). After these corrections, a DEM (5 m cell size) was produced. The dataset was then processed with a low-pass (mean) filter by a 3x3 kernel, obtaining a RMSE of 0.065 m from the data before the convolution. This model represents the ground level, except for some anthropic features like bridges, banks, railways, and highways. These have not been removed from the DEM because manual processing would have been too time-consuming and automatic procedures like filtering would over-smooth the whole DEM and lower its sensitivity. However, these modern artificial elements are so evident in the DEM that they do not represent a possible misleading factor in the visual interpretation of landforms for geomorphological and geoarchaeological purposes.

RMSE between CTC and CTR DEMs is 0.559 m in the whole area and 0.781 m in three sample areas, one within the city (3.4 km²) and two representing the surrounding alluvial plain (2.0 and 2.1 km² respectively). These values are remarkably low when compared to the significant difference of the two original datasets.

DEM from LiDAR

LiDAR data was acquired on September 2007 by CGR (*Compagnia Generale Riprese aeree*) for the Municipality of Padua. The dataset was acquired by an Optech ATLM Gemini at 70 kHz scan frequency at a fly height of 1500 m. The density of the altimetric sampling in the non-filtered point cloud is ~1.05 per m², with a mean distance of 0.97 m. The ground was obtained by CGR with a «default mask» processing obtained through the Terrascan software. Derived DEM is inevitably not smoothed, and it has many irremovable break lines. After some attempts at original point cloud, some of the infrastructures (e.g., viaducts, railroad tracks, etc.) became impossible to delete using

interpolation/filtering methods applicable on the entire area. The DEM (fig. 4) used in landform analysis derives from the rasterization of the «mean ground» 3D points averaged on a 5 m grid. This allows for the minimization of the influence of interpolation errors. The Z range of error was not declared by CGR, so altimetry was tested with DGPS ground survey of 25 points, acquired in RTK mode, in an open area of the city (Prato della Valle Square). These measures has a range of error <0.03 m and a total RMSE of 0.095 m with LiDAR DEM. In the whole area, there is a general error estimate of <0.2 m, but gross errors may be present locally especially in the urban area where vehicles, rubbish bins, and multipath effects on buildings can occur. Moreover, the LiDAR was acquired during late summer, when vegetation mass was still important and could mask fine morphological features outside and in the city.

Remote sensing data integration

The geomorphological interpretation of the landforms recognized on the DEM and the identification of elevation anomalies were checked through a comparison with the analysis of several series of aerial and satellite images of the studied area. Winter satellite images with a low geometric resolution (Landsat 5 e 7, ASTER) were useful to find analogies and differences of the soil reflectance in the whole area. Main vertical aerial images were analyzed: GAI flight (1955, scale 1:33,000), Veneto Region flights (1983, 1987, 1990, 1997; scale 1:17,000), and orthophotos (2000, 2003; scale 1:10,000), orthophotos with 8 cm resolution on visible and near-IR (2007). These images have high spatial resolution, allowing for a good control on geometry. The whole dataset is characterized by a good temporal resolution, which is useful for monitoring the anthropogenic changes related to the recent

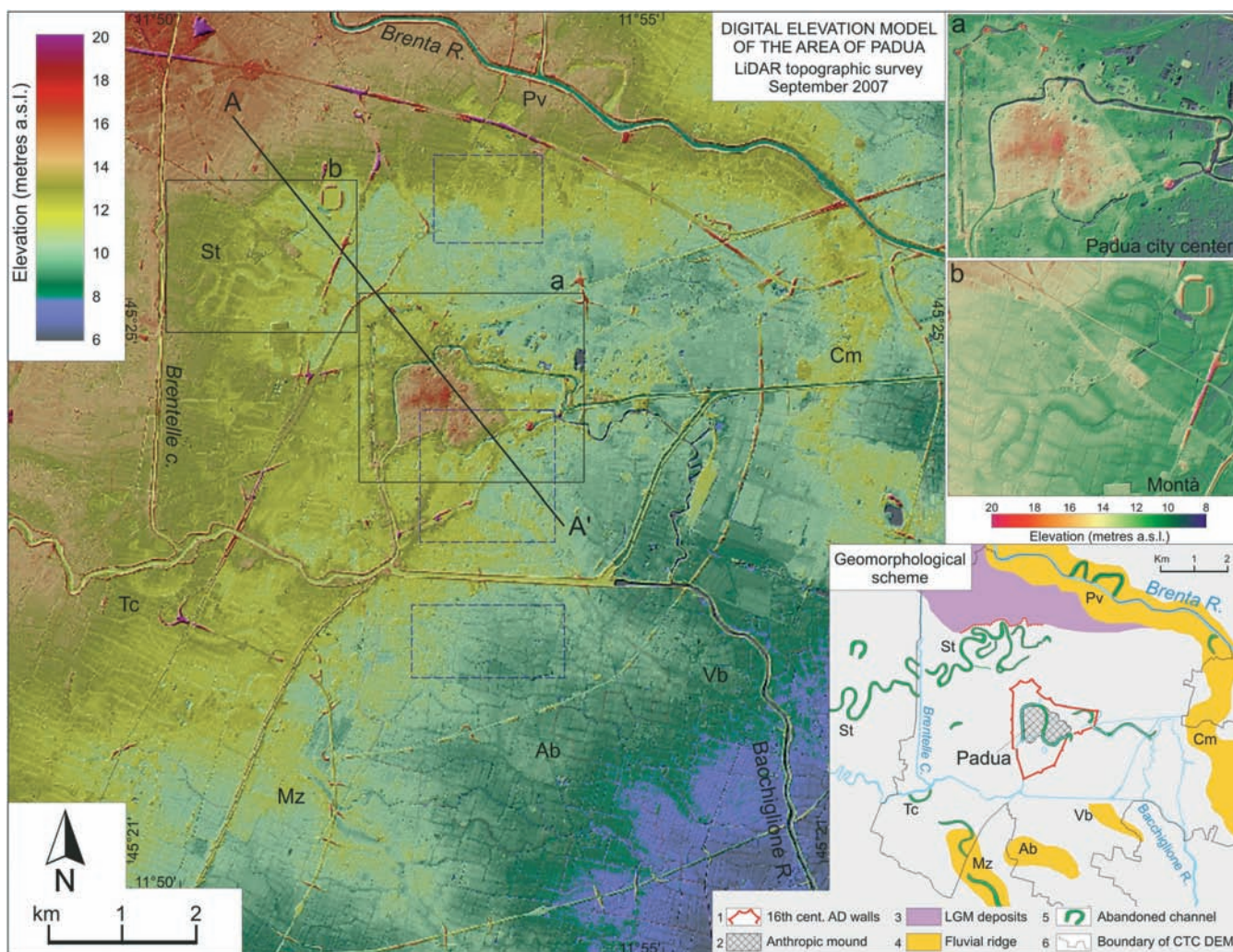


FIG. 4 - DEM of the municipality of Padua from LiDAR survey and sketch map of the main geomorphological features. The areas a) and b) are represented with an enlarged view on the right side of the figure. The line A-A' corresponds to the trace of the topographic profiles represented in fig. 6. The rectangles with blue dashed lines are the RMSE sample areas (table 1). Places cited in the text: Pv) Pontevedgarzere fluvial ridge; Cm) Camin fluvial ridge; Vb) Voltabarozzo fluvial ridge; Ab) Albignasego fluvial ridge; Mz) Mezzavia fluvial ridge; Tc) Tencarola meander; St) La Storta palaeochannel.

growth of the city. It also helps to avoid geomorphic misinterpretations. New indications were supported by oblique aerial images acquired at low altitude (about 300 m) in dedicated surveys. These were taken to identify paleohydrography and archeological features through cropmarks and soilmarks visibility (Mozzi & Ninfo, 2009). These oblique photos are characterized by a centimetric resolution; they allow the detection of small fluvial morphologies with high detail, e.g., crevasse channels, scroll bars, longitudinal bars, and natural levees (fig. 5) (Ninfo, 2009). Thus, these oblique photos were used to have a more accurate control on LiDAR DEM interpretation.

DISCUSSION

Errors and uncertainty of the DEMs

The different DEMs provided relevant information on the geomorphology of the study area, with varying details in terms of the modes of data acquisition and processing. LiDAR provides samples of altimetry with a uniform distribution and high accuracy in z-values; for this reason, it was used as a reference for comparison between DEMs (table 1). Mean Error (ME) and Error Standard Deviation (SD) were calculated following the indications of Fisher & Tate (2006). To be noted is the overall mutual consistency

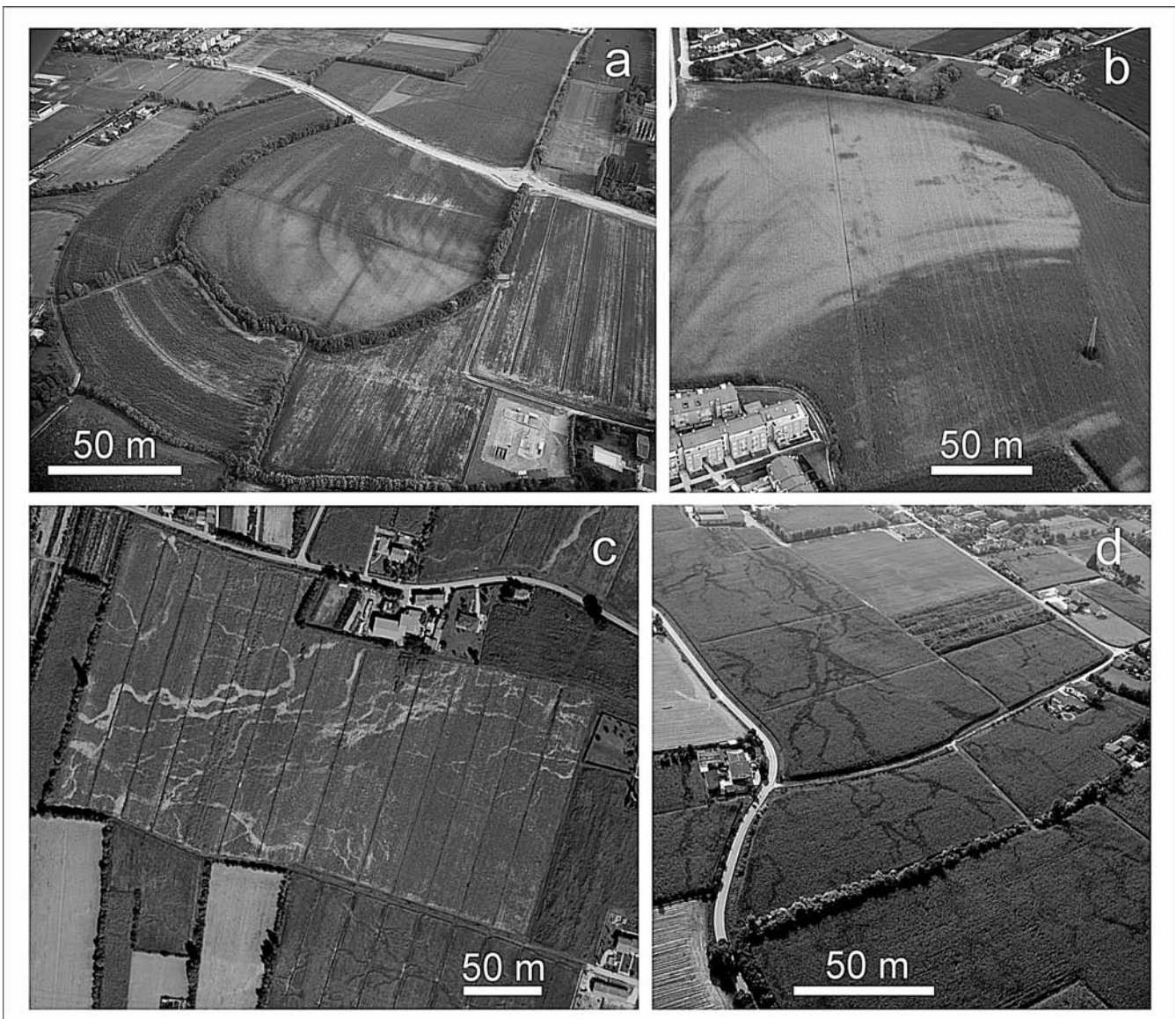


FIG. 5 - Selection of aerial images used to interpret the morphologies evidenced in the DEMs: a) oblique photo of La Storta middle Holocene abandoned meandering channel with the evident traces of the scroll bars; b) oblique aerial photo of La Storta middle Holocene meander point bar with the over imposed trace of an ancient road; c) vertical aerial photo of crevasse splay distributary channels related with the late Holocene fluvial ridge of Camin; d) oblique photo of late Holocene crevasse splay in the area of Saonara.

TABLE 1 - Main characteristics of the DEMs: RMSE, ME, and SD are calculated in comparison with LiDAR DEM; sample areas are visible in fig. 4

Origin of the data	Year	~ n° of spot heights	Cell size of DEMs (m)	Max-Min Altitude (m a.s.l.)	RMSE on whole area (m)	ME (m)	SD (m)	RMSE on sample areas (m)
LiDAR	2007	4300000	5	29.3 - 2.5	–	–	–	–
CTC	1996	150000	5	27.7 - 4.6	0.91	-0.01	0.88	0.52
CTRn	1997	15000	5	25.5 - 0.5	1.23	-0.50	1.16	1.12
CTR	1983	5000	20	18.0 - 6.0	1.43	-0.29	1.51	0.87

of the DEMs, as defined by low RMSE values reported in table 1. In spite of the limited number of spot heights, CTR DEM shows a rather low RMSE, which is even lower than CTR-n in sample areas.

As regards the capability of different methods to provide appropriate sampling of the topographic surface, it has to be recalled that in cartography-derived DEMs the majority of spot heights are located on stable surfaces. In the study area, spot heights mainly lie on artificial surfaces like roads, squares, embankments, and others. A lower number of spot heights is positioned on natural soil in open spaces such as fields, woods, and parks. The relative density per km² tends to be higher in urbanized areas, where the majority of surfaces are anthropogenic, and this is a drawback for the reconstruction of natural landforms.

Furthermore, it is important to stress that the degree to which each spot is representative of the surrounding areas may be highly variable. In the CTR DEM, this uncertainty is controlled by the operator who selects only reliable and relevant elevations during the manual interpolation of contour lines. The situation is more complex when all the spot heights available in the dataset are used. This was the case of DEMs derived from CTR-n, CTC, and LiDAR, which necessarily incorporated a part of this uncertainty even when processed with appropriate methods. As the total number of spot heights increases (table 1), the possibility that representative ones are present in the dataset becomes higher. On the other hand, the higher number of spots also increases the presence of local errors, as the probability of non-representative points to be incorporated is, for the same reason, higher. This constitutes a problem for automated and quantitative methods of landform extraction from DEM (Ninfo, 2009). When a visual geomorphological interpretation of the same DEM is carried out, misinterpretations are controlled by the expert operator. In this case, a higher resolution of the DEM, allowed by a larger dataset of z values, is definitely an advantage

Geomorphologic analysis of topographic outputs

Concerning this use of DEMs in visual geomorphological interpretation, it can be seen that only major landforms can be recognized in the CTR DEM (fig. 3a): the present Brenta River fluvial ridge; an abandoned Brenta ridge which stems from the previous one at the eastern margin of the study area (Camin ridge in fig. 4); a low alluvial terrace in the NW corner of the study area, with scarp height of <3 m; and large inter-ridge depressions in the SE cor-

ner. In spite of the low resolution, the anthropic mound in the historical city centre of Padua can be easily recognized.

All these features are also evident in the CTR-n DEM (fig. 3b), whose slightly higher resolution than the CTR DEM allows for a better understanding of the geometry of the alluvial ridges, as well as the anthropogenic mound. It must be noted that the CTR-n DEM incorporates modern artifacts, which in some places blur and mask the underlying landforms; particularly evident are highways, railway tracks, and dikes. A weakness of this DEM is represented by the systematic errors in altimetry of some tiles, presumably due to problems in the plane of reference. Consequently, some square areas in the DEM are higher or lower than the surrounding ones: this is the case of some tiles aligned N-S, south of the city, as evidenced in fig. 3b.

The CTC DEM (fig. 3c) provides a major improvement in landform detection: all the previously described elements are evident, as well as some new and smaller ones. Single fields can often be recognized, delimited by ditches, which show up as depressed linear features. The terrace scarp north of Padua is visible and the traces of major palaeochannels are extremely evident SW and NW of the city in the area of Montà. These latter palaeohydrographic features are evident in several aerial images and were partly studied by previous authors (e.g. Castiglioni, 1982a; 1982b; Castiglioni & alii, 1987; Baggio & alii, 1992; Balista, 2004), but its topographic relevance has been fully appreciated only after the first processing of the CTC DEM (Ferrarese & alii, 2006). The city mound reveals an inner articulation in higher and lower parts within the two meanders, with much more definite edges. This setting allowed specific geoarchaeological investigations on the structure of the ancient city and the quantitative assessment of the underground archaeological deposits (Ferrarese & alii, 2006).

In the LiDAR DEM (fig. 4) the fluvial ridges and scarps are evident and well outlined and new palaeochannels are detected. In the SW portion of the study area, two abandoned channels run on top of fluvial ridges, probably dating to middle Holocene (Mz and Ab in fig. 4). An abandoned meander, cut by the present Bacchiglione River, is also visible (Tc in fig. 4). The high resolution of the LiDAR DEM allows for the precise assessment of the large dimensions of this palaeochannel, supporting its attribution to a former course of the Brenta River. This observation suggests the existence of a late Holocene Brenta channel belt, partly masked and blurred by the later geomorphic activity of the Bacchiglione River (more details on the stratigraphy of these sedimentary units can be found in Mozzi & alii, 2010). In the meander belt NW of Padua, the DEM provides a good control on the downstream continuity of the palaeochannels. To be noted is the lack of palaeohydrographic traces west of the city, along an area elongated in W-E direction and ca. 2 km wide. In the LiDAR DEM, this is a slightly elevated zone and thus this area can be interpreted as an interfluvium between two Holocene Brenta channel belts; the field survey confirmed that it consists of LGM deposits (Mozzi & alii, 2010).

The LiDAR DEM relies on a terrain sampling which is at the scale level of the geomorphological complexity of

the alluvial plain (fig. 4b). It provides the three-dimensional morphology of abandoned meander bars and channels, such as those observed in low-altitude, high-resolution oblique aerial photographs in fig. 5a,b, pertaining to the Holocene channel belt NW of Padua (St in fig. 4). The LiDAR DEM shows the geometry of natural levees and crevasse splays, but it fails to show the intricate network of minor distributary crevasse channels, as the ones recognized with aerial images on the flanks of the Camin ridge (fig. 5c,d). Up-to-date higher density LiDAR acquisition (e.g., 4-7 point/m²), carried out on bare winter fields, could possibly allow the appreciation of these and other minor fluvial morphologies. The mound and the 16th century AD city walls are evident with great detail in the LiDAR data (fig. 4a).

The LiDAR DEM topographic profile in fig. 6 shows the fluvial scarp that cuts the LGM deposits. The middle Holocene fluvial channels, which cut this scarp through lateral erosion in the area of Montà (geomorphological scheme in fig. 4), are characterized by high sinuosity. The palaeochannel indicated as «St» shows a particularly well-preserved morphology and remarkable downstream continuity in the LiDAR DEM (fig. 4b). This palaeochannel, known as La Storta, probably formed between 8400 and 6300 cal BP (Castiglioni & *alii*, 1987; Mozzi & *alii*, 2010); it shows several analogies in terms of sinuosity, channel and meander widths with the largely coeval incised palaeochannels recognized in the Tagliamento (Fontana, 2006; Fontana & *alii*, 2008) and Piave systems (Bondesan & *alii*, 2008; Carton & *alii*, 2009). Fluvial ridges are well evidenced by LiDAR; the palaeochannels related to them are characterized by a considerably lower sinuosity when compared to the incised palaeohydrography at Montà.

The aggrading tendency of fluvial channels brought the formation of the Albignasego, Voltabarozzo, Camin, and Pontevigodarzere ridges (respectively Mz, Ab, Vb, Cm, and Pv in fig. 4). The Pontevigodarzere - Camin di-

rection has probably been active since the final part of the 1st millennium BC until the Middle Ages (Castiglioni & *alii*, 1987). The LiDAR DEM also outlines the mound and several details on present-day (roads, railway tracks, entrenched parking lots) and medieval-to-modern (city walls and canals) artifacts. In order to allow a direct comparison, the topographic profiles based on the LiDAR and other DEMs are also reported in fig. 6.

It can be seen how the CTR DEM provides a good approximation of the mean natural surface of the alluvial plain along its NW-SE regional dip, but it underestimates the elevation and the complexity of the anthropogenic mound. The CTC profile is generally coherent with the LiDAR profile but, in certain places, it fails to provide correct information; for example, the Piovego Canal is higher than the canal banks because the profile falls on a bridge that has not been removed by the dataset. The problem of incorrect elevation of entire tiles of the CTR-n is evident at the SE end of the profile, where an anomalous ca. 2 m deep and 1 km long depression is shown.

CONCLUSIONS

DEM are powerful tools for geomorphological research in low relief areas, such as the city of Padua and the surrounding alluvial plain. The LiDAR and CTC DEMs provided new insights on the geometry of fluvial landforms at different scales, from single levees and bars to large alluvial ridges and interflaves. Moreover, they allow for the detailed investigation of the morphology of the archaeological mound in the city centre for geoarchaeological purposes.

LiDAR data have the potential to generate a very accurate DEM, but it has to be recalled that the number of possible sources of error is larger in comparison to traditional methods (Fisher & Tate, 2006); these errors are more dependent on specific conditions of acquisition (e.g.,

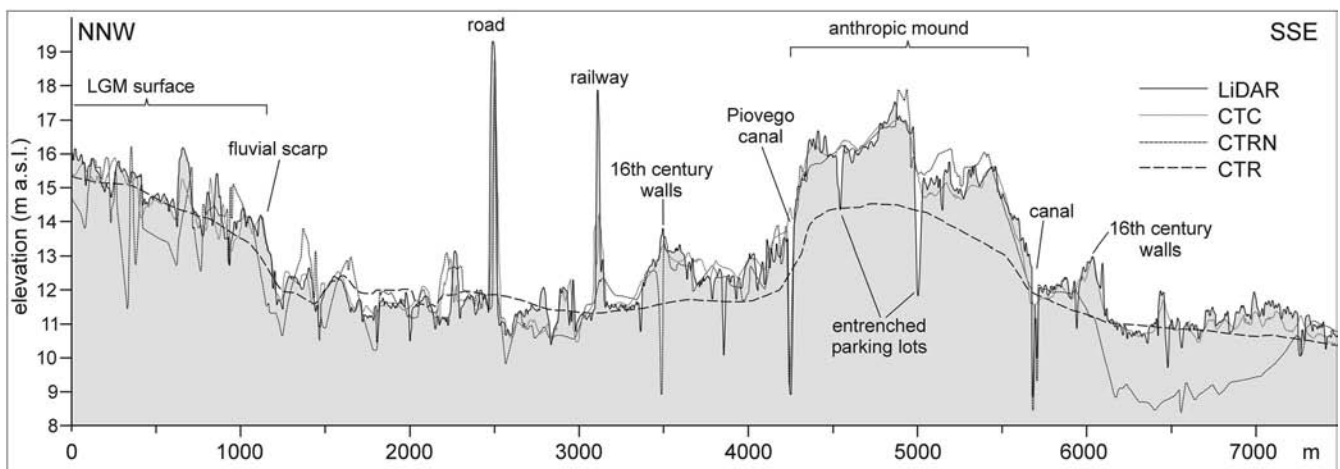


FIG. 6 - Comparison of the topographic profiles extracted from the different DEMs. An average value every 30 m was taken in the CTR-n, CTC and LiDAR profiles.

seasonal vegetation growth in the countryside and in parks; presence of cars, people, dust bins, and other small objects in the urban environment). The LiDAR DEM is very sensitive to local topographic anomalies that may be difficult to remove.

Only the CTC DEM can really be compared to the LiDAR DEM in terms of resolution. In spite of the fact that the CTC DEM is based only on 3.5% of the elevation spots used in LiDAR DEM, it shows a very good level of coherence in terms of errors. The CTR DEM provides a good approximation of the mean surface of the alluvial plain, but it should be mentioned that the contour lines were manually drawn with the apposite aim of representing the natural surface. The CTR DEM tends to «over-smooth» both natural and ancient anthropogenic landforms. The CTR-n DEM has a higher resolution than the CTR DEM; still, it is the worst one for geomorphological investigation. This is due to the presence of a large amount of systematic errors and heights not representative of natural topography, without counterbalancing this drawback with a significant increase in the total number of spot heights.

Generally, the visual geomorphological interpretation of DEMs strongly benefits from the use of high-resolution data sets such as LiDAR, even if non-representative values (e.g., present day roads, embankments, bridges, are systematically incorporated. This is because the interpretation of a skilled operator is able to pinpoint relevant landforms and discard «modern anthropogenic disturbance». It must be noted that these effects are present also in natural areas, i.e., dense arbustive vegetation on hillslopes (Ninfo, 2008).

When automated and quantitative methods of landform extraction from DEMs are applied (Ninfo, 2009), it is of utmost importance that the DEM only contains relevant geomorphic information, that is, information strictly related to the topography of the landforms to be investigated. Otherwise, even DEMs based on large datasets will not provide effective outputs, as the more dense sampling of altimetry increases, by the same ratio, the probability that non-representative features are incorporated in the DEM.

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