Pure Appl. Geophys. 171 (2014), 835–855

DOI 10.1007/s00024-013-0693-7

Pure and Applied Geophysics

LiDAR and 2D Electrical Resistivity Tomography as a Supplement of Geomorphological Investigations in Urban Areas: a Case Study from the City of Wrocław (SW Poland)

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Abstract—In urbanized areas, particularly in lowland terrains and floors of large river valleys, the natural land configuration is often hard to recognize due to a long history of human activity. Accordingly, archaeological works in cities, which supply knowledge on settlement conditions, are usually accompanied by geological and geomophological research. Lately, data from light detection and ranging (LiDAR) have become a valuable source of information on urban land configuration. Geophysical methods are also becoming increasingly popular in background studies. The paper presents a method of using and linking these sources of spatial information about landforms in such areas. The main aim is to identify to what extent these complementary sources of data and the proposed method can be used in such a specific environment to reconstruct natural, buried terrain morphology. The city of Wrocław in Central Europe serves as an example. To this end geomorphometric studies were conducted with the use of digital elevation models (DEMs) based on LiDAR scanning and derivated land-surface parameters—SAGA Wetness Index, Channel Network Base Level and Altitude above Channel Network. The study also involved determining morphological edges and measurements of the meanders of the Odra, as well as expanding information on the spatial distribution of alluvia and the structure of slope breaks. To this end, geophysical measurements were conducted using the Two-Dimensional Electrical Resistivity Tomography method. Additionally, five typical sequences of man-made ground present within the perimeter of the city were distinguished. As a result, a map of the main landforms of Wrocław is presented. Finally, we argue that although high resolution DEM and derivate land-surface parameters are very useful in terrain analysis, places with thick man-made ground or strongly levelled areas must be recognized by geoarchaeological excavations or geological bore holes. The geophysical survey is useful to identify buried morphological edges and older relief elements in open areas.

Key words: Urban geomorphology, geomorphometry, LiDAR, 2D ERT, Odra river, Wrocław city.

1. Introduction

Geomorphological studies in urban areas are difficult to carry out due to dense development and artificial transformations of natural surfaces involving, among others, the formation of man-made ground and modifications of the drainage system (ROSENBAUM *et al.* 2003; SZABÓ 2010). As a result, the natural land configuration, especially in lowland areas, is obscured and hard to identify. This often prevents an unequivocal identification of initial landforms and the correct analysis of the local palaeogeographic development. Such difficulties accompany detailed geomorphological studies conducted during archaeological works (KVAMME 2006). These studies are greatly supported by digital elevation models (DEMs) and geophysical methods of ground penetration (KAMPKE 1999; CHALLIS 2006; PAPADOPOULOS *et al.* 2006; TSOKAS *et al.* 2011). Unfortunately, DEM analysis for flat, urbanized areas causes many errors associated with a model's accuracy, impact of land cover, existence of buildings and artificial transformations of ground surface (SITHOLE and VOSSELMAN 2004; BONK 2007; LIU 2008; REUTER *et al.* 2009). In addition, the analysis of terrain morphology in urban areas based on DEMs are rarely supported by results of other investigations. This article presents a method to use and link multiple sources of spatial information for determining boundaries of natural landform units in relatively flat (low relief gradients) urban areas, heavily altered by human activities. The investigation is based on GIS landform parameterization based on high resolution DEM, geophysical surveys and geological or geoarchaeological documentation. The main aim of the study is to identify to what extent these

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complementary sources of data and the proposed method can be used in such a specific environment for the reconstruction of natural terrain morphology.

The land-surface parameterization using the submeter DEM is the first approach of this type in the study area—the city of Wrocław. The DEM analysis draws on the existing knowledge about changes in the drainage system and information about natural and man-made sediments collected from various sources (archaeological excavations, geomorphological and archaeological literature). Due to the scarcity of information concerning the spatial variation of alluvial deposits outside of the city center and the structure of valley escarpments, geophysical profiling was conducted using the Two-Dimensional Electrical Resistivity Tomography method (2D ERT). The obtained results allowed for the reinterpretation of previous geomorphological and geological views and data. Among others, five typical sequences of made grounds and the range of the main landform units within the perimeter of the city were identified.

The proposed method is suitable for medium and large-sized cities of Central Europe, located in valley floors. Wrocław, selected as a test area, has a history closely related to the development tendencies of other cities of Central Europe (Piekalski 1999) e.g., Cracow, Leipzig, Dresden or Frankfurt; hence, it serves as an example as to how these new data sources add to the current state of knowledge on the natural configuration of urban land.

2. *Methods*

In this paper the combination of geomorphological research methods was used. Data obtained in the traditional way (field mapping, analysis of archaeological outcrops and geological bore holes) were linked with an analysis of high resolution DEM and results of geophysical surveys. This comprehensive aggregation of research methods, rarely seen in the literature, was attempted for an urban area, where many factors interfere with the recognition of natural landforms. The flow chart in Fig. 1 illustrates the course of investigation.

The basis for this study was the spatial analysis of the area of Wrocław, based on DEM provided by the Municipal Office of Wrocław. The original resolution of DEM is 1 × 1 m and it was created based on light detection and ranging (LiDAR). The airborne scanning was conducted in May 2006. The scanning point density was 2 points per sq metre, and the vertical measurement accuracy amounted to 15 cm. LiDAR data underwent pre-processing (You *et al.* 2003) by the supplier: the land surface (bare Earth model) was extracted from the point cloud—information about

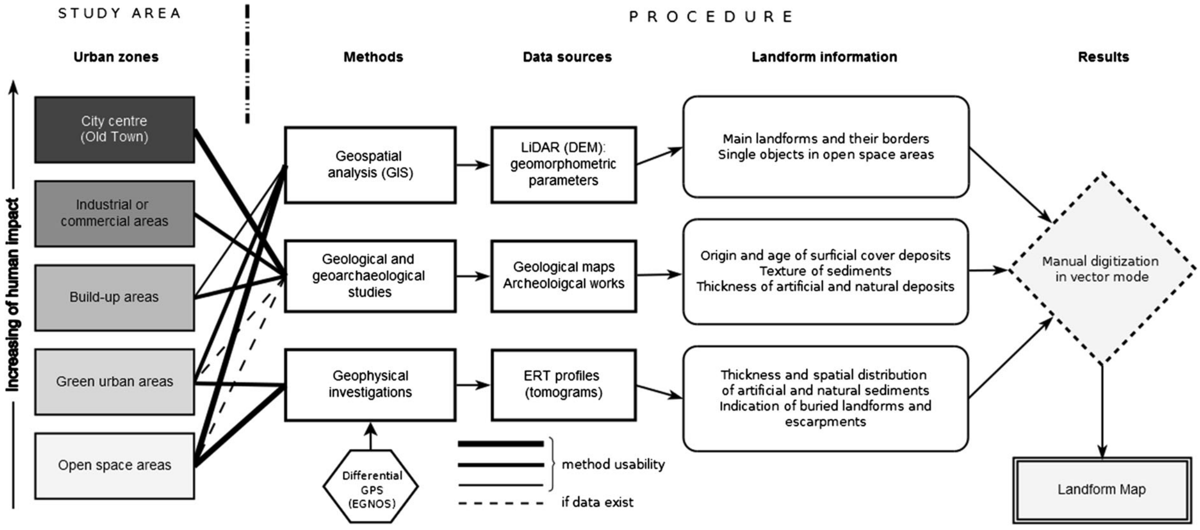


Figure 1
Scheme of research and use of data

the natural land cover, buildings and man-made elements that obstruct the view of waters (bridge fragments) were removed.

Light detection and ranging (LiDAR) data are one of the most accurate sources about land configuration, surpassing in precision global DEMs obtained from satellites, using radar system (SRTM) or stereo-pair images (Aster GDEM) and existed models from digitization of topographic maps contours (DTED) (Gamba *et al.* 2002; Hirano *et al.* 2003; Large and Heritage 2009; Rayburg *et al.* 2009; Höfle and Rutzinger 2011). In geomorphology, such data are widely used to study the fluvial environment (e.g., Charlton *et al.* 2003; Cavalli *et al.* 2008; Thorndycraft *et al.* 2008; Notebaert *et al.* 2009; Vetter *et al.* 2011), which is of particular importance in lowlands featuring flow directions that are difficult to identify correctly (Jones *et al.* 2008). The potential of this source of knowledge has also been realized in geological, hydrological, archaeological studies or visualization of urbanized areas (Palmer and Shan 2002; Afonso *et al.* 2006; Bathrellos 2007; Lasaponara *et al.* 2010).

In this paper the DEM obtained from LiDAR data was processed for geomorphological analysis using SAGA GIS software, while preparation and visualization of GIS layers involved the use of Global Mapper and MicroDEM software. The relief of Wrocław was determined based on derived land-surface parameters recalculated from the DEM. The DEM was re-interpolated to a resolution of 5 × 5 m or 10 × 10 m, in order to eliminate information noise. Among many land-surface parameters implemented in SAGA GIS, the *Topographic Wetness Index* (TWI, in modification *SAGA Wetness Index*), *Channel Network Base Level* (ChNBL) and *Altitude Above Channel Network* (AACN) were used. As opposed to basic parameters such as *Hypsometry*, *Slope*, A*spect* or *Curvature* usually used for geomorphometric analyses (Olaya 2009), the selected derived parameters allowed for the determination of poorly distinguishable morphological edges and fluvial morphology on a relatively flat surface. Other parameters were too sensitive to a network of roads and railway embankments and many small edges created by removing land cover layer (including buildings) during LiDAR data filtering. This study does not discuss in detail the assumptions behind each parameter. Consequently, below is a collection of essential information about each parameter only, with a reference to sources of information and the manner they were used.

According to theoretical assumptions, TWI indicates the dependency between the size of the surface participating in surface outflow and the value of its inclination (Beven and Kirkby 1979). Accordingly, this parameter shows the theoretical level of saturation with wetness of the earth surface and is one of the basic elements of hydrological modelling (Sørensen *et al.* 2005). The *SAGA Wetness Index* is a modification of TWI. The difference between the two lies in a different method of calculating the basic surface. As a result, DEM rasters representing valley bottoms within a small distance from channels are assigned a greater value of moisture than in the traditional TWI approach (Boehner *et al.* 2002). At the scale of Wrocław, SAGA WI allows for distinguishing potentially dry areas (elevations isolated morphologically) and places of potential moisture concentration (local terrain depressions). The ChNBL parameter is based on the determination of a local base level of erosion in nodes of the drainage network (Bugosh 2006) and in relation to the remaining surface of terraces and uplands. This parameter allows for the reproduction of floors of river valleys, indicating also the potential river flow and flood water concentration directions. The AACN parameter calculates the vertical distance to the channel network base level (Conrad 2003). The algorithm consists of two major steps: interpolation of a channel network base level elevation and subtraction of this base level from the original elevation. In the analysis, the parameter was used to automatically detect valley escarpments within the perimeter of the city.

Based on the analytical hill shading map of DEM the authors have categorized the meanders of the Odra located within the perimeter of the city in terms of a size. This involved the measurement of radiuses of particular meanders by inscribing properly-sized circles within them. This study employed meanders evident on DEM visualization. It does not take into account the elements of the meander system known exclusively from geological and archaeological studies and covered by man-made ground or younger fluvial sediments.

Conclusions on the morphology of valley floor using GIS analysis were related to the existing geological information (Assmann *et al.* 1912; Barsch *et al.* 1912; Barsch and Tietze 1912; Tietze and Behr 1932; Winnicka 1987; Łabno 1988; Goldsztejn 2009) about the occurrence of Holocene fluvial sediments and floodplain area, naturally affected during culmination of flood waters in July 1997 (*Culmination of Flood-Wave…*), what indirectly determines the boundaries between the Odra valley and the upland surface. Based on published (Chmal *et al.* 1993; Chmal and Traczyk 1998, 2001; Traczyk 2003) and unpublished materials collected during archaeological studies, the authors have supplemented the extensive inventory of bore holes and sites compiled earlier by Badura (2010), concerning the thickness of artificial sediments and the depth of natural ground (without any artefacts) in the city centre. This led to the creation of a database containing information on 297 spatially oriented sites within the old part of Wrocław (.shp file). The alluvial deposits in the valley bottoms and the Odra river valley escarpments are still rather poorly recognized in local geological structure. This mainly applies to areas outside of the city centre which were not subject to detailed archaeological works in the past. For this reasons geophysical profiles using the 2D Electrical Resistivity Tomography method were made. The ERT profiling allowed to detect the thickness of Holocene deposits and their spatial relations with other Quaternary sediments, which may be helpful in reconstructing past geomorphological processes. The procedure was mainly useful to confirm or deny the occurrence of landforms buried under younger sediments, especially morphological edges.

The application of electrical resistivity methods in soil surveying is fairly common (e.g., Samouëlian *et al.* 2005; Chambers *et al.* 2006; Schrott and Sass 2008; Van Dam 2012). They are successfully used in studies of the periglacial environment (Kneisel 2006; Kneisel *et al.* 2008; Harris *et al.* 2009; Kneisel 2010), slope dynamics (Sass 2007; Marescot *et al.* 2008; Migoń *et al.* 2010; Pánek *et al.* 2011; Carpentier *et al.* 2012), river valleys (Bersezio *et al.* 2007; Bowling *et al.* 2007; Škarpich *et al.* 2010), and in geoarchaeological studies (Domenico *et al.* 2006; Brown 2008). However, the detailed 2D ERT profiling method was never used before in Wrocław.

The basis of the 2D Electrical Resistivity Tomography method is to obtain a two-dimensional resistivity model of the surveyed geological formation. To this end, several measurements of the apparent resistivity in a specific array of electrodes along the surveyed profile are conducted. Next, these automatic measurements are subject to the inversion process. Inversion consists in solving a math for the assumed rock body model, followed by an iterative adaptation of the initial model to the measured data (Reynolds 1997; Samouëlian *et al.* 2005; Loke 2012). The ARES (GF Instruments, Brno, Czech Republic) instrument with an array of 40 electrodes, spaced every 2, 3 or 5 m was used in the study. The Wenner-Schlumberger array was used in each iteration and some measurements were repeated using the Wenner-Alpha method. These methods vary in a distance between pairs of current (C_1, C_2) and potential (P_1, P_2) electrodes. In practice the Wenner-Schlumberger method is used to 15 % deeper measurements than the Wenner-Alpha and is recommended for horizontal and quasi-horizontal (declined) layers (Milsom 2003; Loke 2012). By default, resistance results (in Ω/m) are compared to a range of values for various rock/sediments presented in a literature (e.g., Telford *et al.* 1990; Milsom 2003), although the final outcome was influenced by groundwaters (Saad *et al.* 2012). Data were processed and visualized in RES2DINV software (Geotomo Software, Malaysia).

Although electrical resistivity profiling was conducted in places representative with respect to the geological structure and landforms, the location of the profile itself was strictly dependent on the development on the land. Geophysical measurements were not conducted in the direct vicinity of power lines, gas and sewage networks, in private areas and developed areas with a hardened surface. A review of available literature confirms that except for isolated examples (e.g., Papadopoulos *et al.* 2009; Boudreault *et al.* 2010; Ayolabi *et al.* 2013) the ERT method is rarely used in city centres. All ERT profiles were marked by high accuracy GPS (Trimble GeoXH) with real-time corrections from EGNOS (European Geostationary Navigation Overlay Service).

Based on the DEM analysis and the collected geological and geomorphological information, a synthetic map of the main landform units of Wrocław was created by manual digitization in vector mode. Additionally, typical sequences of man-made sediments within the perimeter of the Old Town were distinguished according to our own geoarchaeological observations carried out over the last 25 years and their thickness was visualized.

3. *Area of Investigation*

Wrocław is a mid-size city in south-western Poland (area 293 km^2, 630,000 citizens) whose development was determined by its unique geographical location and tumultuous historical events. The city was founded over 1,000 years ago in an anastomosing section of the Odra river valley in the Silesian Lowland. The lowland character of the city is reflected both in the flatness of the terrain, as well as in absolute heights −120 m a.s.l. on average in the centre and 148 m a.s.l. at most in its westernmost part (Fig. 2; Table 1). The highest culminations (up to 155 m a.s.l.) are a man-made waste dump (40 m of relative height), partly reclaimed. The city is cut through by a network of channels and waterways of the Odra and its tributaries. In this location the main channel of the Odra is approx. 26 km. Among its tributaries, the longest distance within the city is covered by the Widawa (approximately 20 km), Ślęza (16 km), Bystrzyca (15 km) and Oława (8 km) rivers. The drainage network of Wrocław is complemented by over 1,000 km of channels of smaller

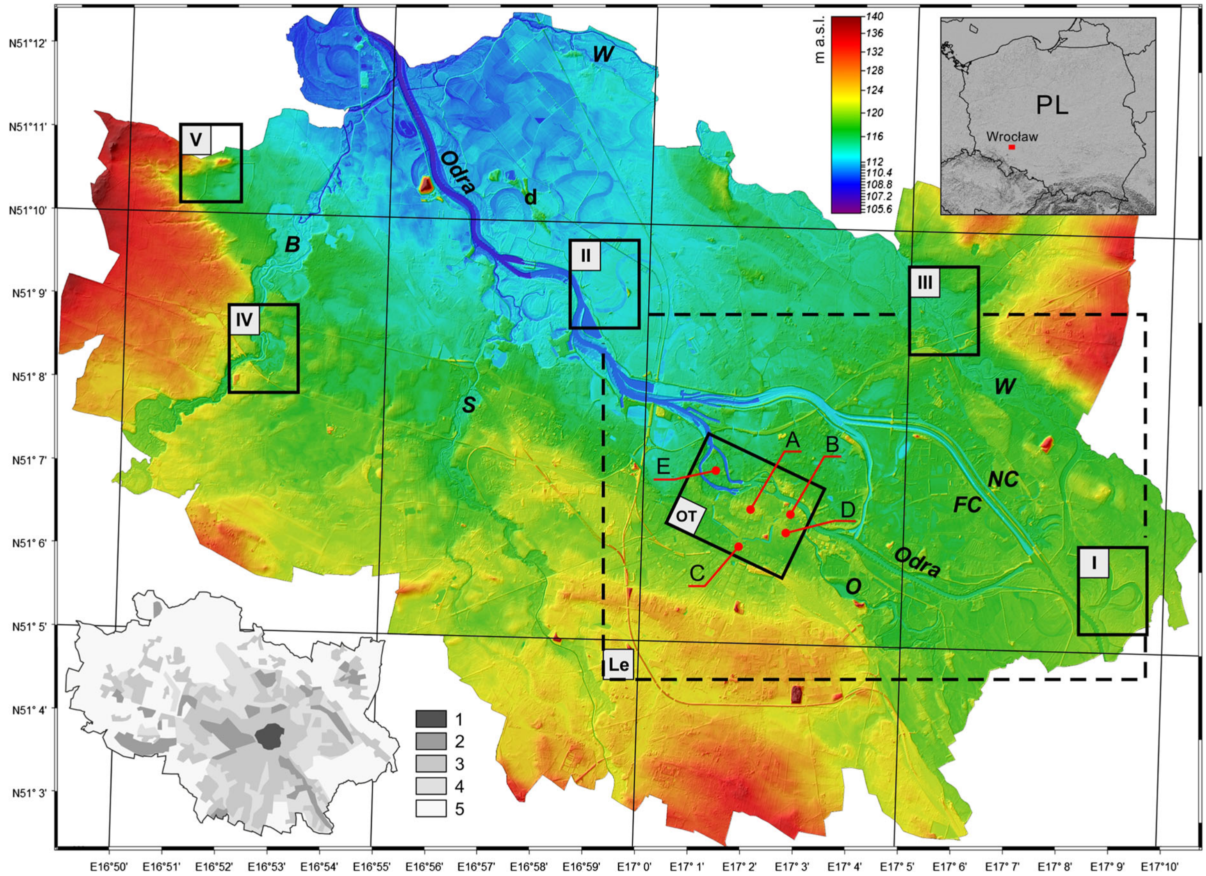


Figure 2

Hypsometry and land configuration of Wrocław: *I–V* areas subject to electrical resistivity investigation presented on Fig. 8, *Le* area presented on Fig. 4. *OT* Old Town area presented on Fig. 7. *A–E* points with characteristic artificial sediments from Fig. 6. *B* Bystrzyca river, *FC* Flood Canal, *NC* Navigable Canal, *O* Oława river, *S* Ślęza river, *W* Widawa river, *d* dunes; urban zones (land-use): *1* city centre (Old Town), *2* industrial or commercial areas, *3* build-up areas, *4* green urban areas, *5* open space areas

Table 1

Altitudes distribution of Wrocław area

Altitude (m a.s.l.)	Area (km^2)	% of area
104–110	4.43	1.5
110–115	68.77	23.4
115–120	118.79	40.5
120–125	66.67	22.7
125–130	21.89	7.5
130–135	11.13	3.8
135–156	1.86	0.6
Total	293.53	100.0

watercourses, canals and drainage ditches. The natural channel of the Odra on the section of the Silesian Lowland is meandering, with a tendency for lateral migration and meander cut-off. However, in the centre of Wrocław the river flows in many channels forming an anastomosing system (Czerwiński 1998) with permanent river islands (Fig. 3). Their current number and shape is however largely affected by human activity. One excellent example of how the drainage network of the Odra river valley changed in the Wrocław section was given by Leonhard (1901) (Fig. 4).

Within the perimeter of the city, Early Paleozoic and Mesozoic rocks are completely covered with Neogene and Quaternary sediments (Żelaźniewicz 2005). The Neogene is represented by Late Miocene formations of the total thickness of 85–170 m, sometimes visible near the surface, primarily in the western part of the city (Przybylski *et al.* 2004; Goldsztejn 2009). This area is situated within the Middle-Odra Fault Zone and the constant subsidence tendency of this area prevails until today (Grzempowski *et al.* 2009). The Quaternary sediments within the city are of glacial, fluvioglacial, fluvial and aeolian origin. The triple transgression of the Pleistocene Scandinavian ice-sheet during the Elestrian and Saalian glaciations left a sequence of petrographically-varying tills (Czerwonka and Krzyszkowski 1992; Badura and Przybylski 1998). The thickness of Quaternary sediments, excluding inland dunes, ranges from 1.5 to 10 m in south-western Wrocław, up to 40–50 m and more in the north, centre and southeast of the city (Goldsztejn 2009).

We may assume that the formation of the Odra valley with the shape and direction resembling the current one started in the region of Wrocław at the

Figure 3
View of dense developments of the Old Town of Wrocław and Odra channel separated with river islands (photographed by M. Kasprzak)

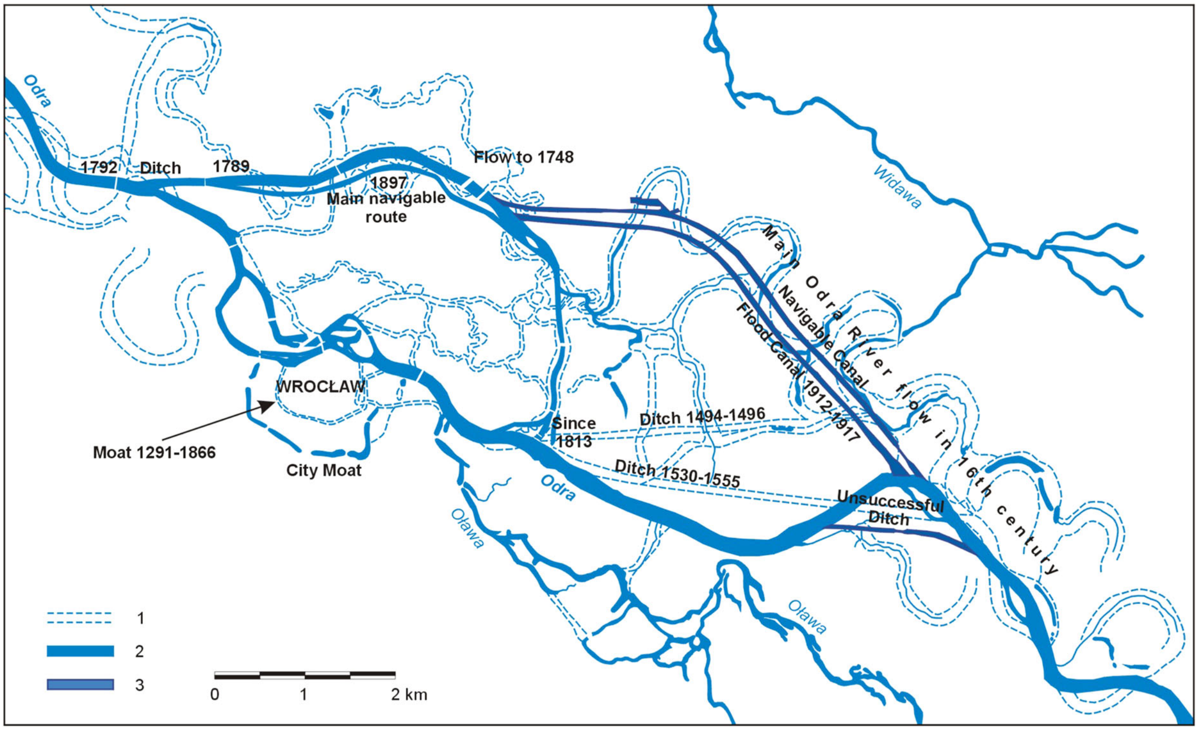


Figure 4
Channel changes in the Odra valley on Wrocław section: *1* paleochannels, *2* hydrographic system from turn of 19th and 20th century. *3* ditches dug in 20th century. According to: Leonhard's (1901) map, original scale: 1:50,000, modified

end of the Odranian Stage of the Saalian Glaciation, along with the deglaciation of this area (Przybylski *et al.* 2004). The valley adopted a different course than an earlier late Neogene and early Pleistocene drainage, when the pre-Odra turned towards the northeast of Wrocław (Badura and Przybylski 2004). During the last stage of the Saalian Glaciation, the Warta Stage, the ice-sheet did not reach the area of the contemporary Wrocław and stagnated 20 km further north (Krzyszkowski and Łabno 2002; Marks 2004, 2005), while proglacial drainage formed an ice-marginal valley (Wrocław Urstromtal) before its front. At that time the formation of the highest Pleistocene terrace level (15 m terrace according to Szczepankiewicz 1989) occurred. The climate warming during the Eemian interglacial period caused an incision to a depth of 30 m (Szczepankiewicz 1959). During the Weichselian (Vistulian) glaciation, with an increased accumulation in periglacial conditions, the filling of the deepened Odra valley with sandy-gravel material occurred. The filling locally reached the level of an older glacial upland. As a result, in the northern part of the Wrocław Plain, a part of the lateral tributaries of the Odra flowed along the surface of the glacial upland and caused its modelling (Traczyk 2007). The period of the next, fairly quick erosional lowering of the bottom of the valley of the middle Odra is dated at the end of the early stage of the Weichselian (Vistulian) glaciation (Chmal *et al.* 1993; Szponar and Szponar 2008). Since then, accumulation of fluvial deposits occurred nearly continuously and its rate was dependent on climate oscillations and human activity (Notebaert and Verstraeten 2010). Currently this accumulation has reached the level of the slightly undulating moraine-fluvioglacial upland (Chmal and Traczyk 2001). Consequently, within the area of Wrocław, the system of terrace levels of the Odra valley is not easy to distinguish. According to Tietze and Behr (1932), the highest level in this section of the valley bottom is built from mud overbank deposits (silty-sandy deposits with organic material) accumulated after the development of agriculture in the Odra basin (Dumanowski *et al.* 1962; Klimek 2000; Starkel *et al.* 2005; Notebaert and Verstraeten 2010); accordingly, it is of late Holocene age. Although the *Geomorphological Map* 1:50,000 published in the *Geological Atlas of Agglomeration of Wrocław* (Goldsztejn 2009) distinguishes 5 terrace levels within the perimeter of the city, ranging from 0.5 to 15 m above river level, due to the small relative differences between them reaching as little as 1 m and the lack of sound recognition of age, lithological and sedimentological aspects, this concept requires verification. The existing edges of the possible terraces are often the result of the erosional trimming of banks during contemporaneous floods (Przybylski *et al.* 2004). The subsurface layer of the ground is formed by common man-made sediments whose thickness and location are closely correlated to the development of settlement.

The middle age foundations of the city lie on Odra river islands and local terrain elevations. The city centre of Wrocław was established on erosional outliers built from fluvioglacial sediments (Chmal and Traczyk 2001). The Old Town outlier is cut along a distinct erosional edge from the north and in the south it terminates against shallow depressions formed in the late Holocene by flood waters. In the past these depressions were used to build two moats. The natural depressions were deepened by 5.5 m in the case of the now-filled old city moat and approximately 4 m in the case of the younger moat (Chmal and Traczyk 1998, 2001).

In the current land configuration of Wrocław the dominant features are artificial sediments, the artificial drainage network, and the effects numerous city redevelopments (buildings, flood embankments, railways) related to, among others, the construction and demolition of defensive fortifications (1807–1810) and damage suffered at the end of World War II (1945). Despite the fairly robust geologic recognition (Szponar and Szponar 2008; Goldsztejn 2009; Badura 2010) numerous issues related to the initial land configuration of Wrocław and its Quaternary development have not been unequivocally resolved. An interest in the natural landform configurations has grown significantly following the large flood of July 1997, when the flood waters of the Odra and its tributaries took advantage of natural depressions and short-cut flood channels, reaching quite far from the river channels.

4. Results

4.1. LiDAR Analysis

The range of natural and artificial relief features was set based on LiDAR data. In particular, the course of morphologic edges related to the erosional activity of the Odra and its tributaries, zones of flood flows and Odra paleomeanders (Fig. 5) were identified. The obtained image does not always coincide with the existing information provided in historical sources. This is the case in the area between the Widawa valley and the Flood and Navigable Canals in the eastern part of the city. The map of Leonhard (1901; Fig. 4) marks the course of the Odra channel outlined herein with numerous meander loops from 16th to 17th century, i.e., prior to the construction of the Navigable Canal. Due to the convenient communication routes (new waterway, railways) in the first half of the 20th century, a vast industrial zone was created in this area. As a result, along a strip approximately 0.6 km wide and 4 km long, natural landforms were completely erased (levelling of the site for stacking yards, structural embankments, etc.). The scale of transformation was so significant that the DEM visualization in this part of the city does not reveal the old meanders of the Odra at all.

Light detection and ranging (LiDAR) data allow for distinguishing of an erosional depression formed as a result of the activity of flood waters. This depression was used to construct the outer town moat at the end of the 13th century and contributed to its final shape from the end of the 17th century. This depression was used by the joint waters of the Odra and Oława rivers during the catastrophic flood in July 1997. During the culmination of the flood, the water flowed around the Old Town from the south and reached to the town centre rail overpass (Fig. 5b).

Due to slight height differences and the abundance of artificial sediments, to distinguish even the basic elements of the relief of the city is somewhat difficult. Based on DEM (Fig. 2; Table 1) it was determined that within the bottom of the Odra valley

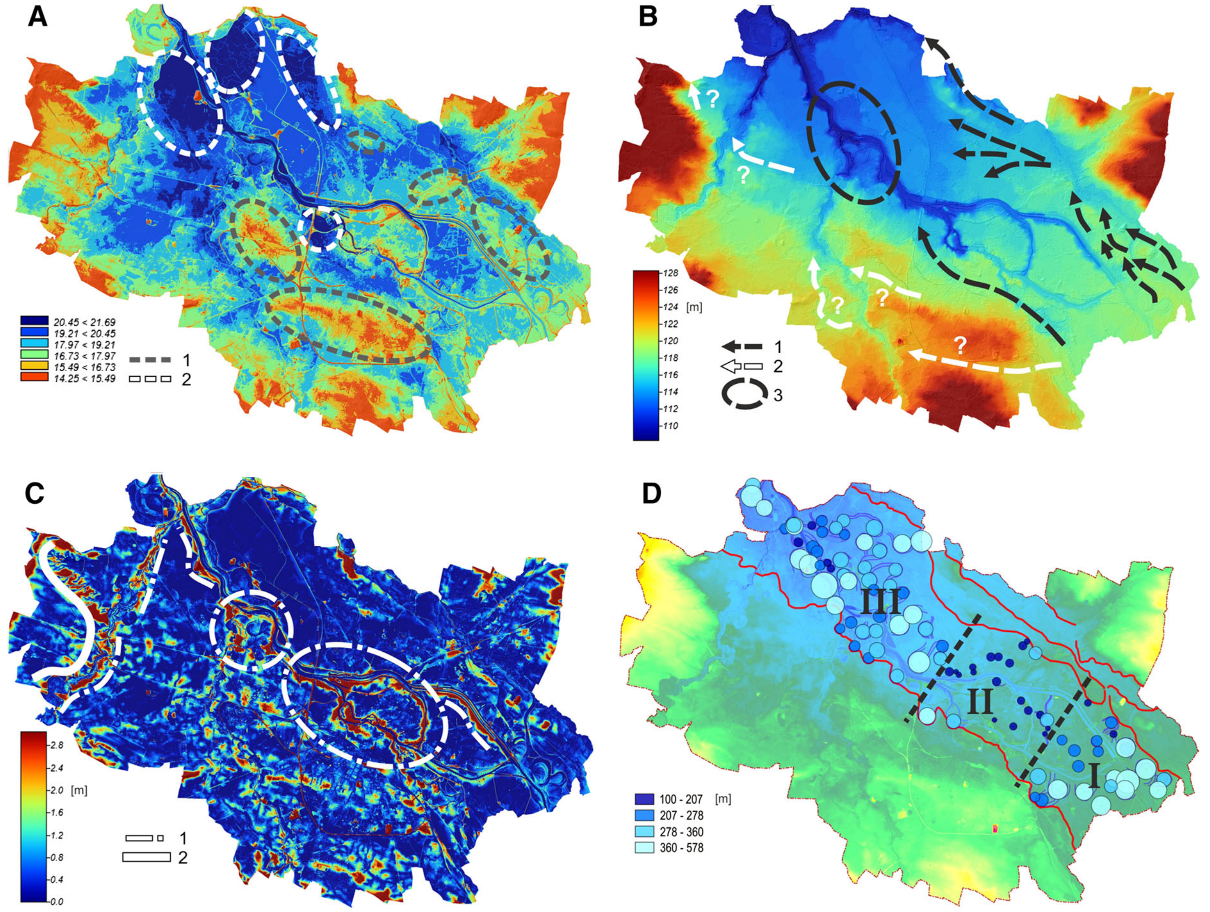


Figure 5

Output layers of GIS modelling and cartometric measurements based on DEM 10 × 10 m: **a** SAGA Wetness Index, not to scale; *1* potentially dry areas (isolated elevations), *2* potentially moist areas (local depressions); **b** Channel Network Base Level; *1* flood waters flow directions, *2* hypothetical flow of the Odra waters in Pleistocene, *3* river water concentration area; **c** Altitude Above Channel Network; *1* most distinct river levees and artificial embankments (flood banks, embankments accompanying communication routes and city developments), *2* edge of moraine upland; **d** *circles* inscribed into current and abandoned meanders of the Odra, values of radiuses provided; *I–III* zones varying in terms of meander sizes; *red lines* denote the boundaries of the valley of the Odra and Widawa

local height differences are related to the presence of natural morphologic edges (mainly erosional edges along the banks of river channels), reaching a maximum of 2–3 m. Larger differences, ranging from 5 to 8 m, are characteristic only for Pleistocene outliers located in the bottom of the valley and for dunes. The largest differences, 4–7 m, are visible in the edges of the Ślęza and Bystrzyca valleys, the left-bank tributaries of the Odra. Within watersheds, the average height differences do not exceed 2–4 m.

Further conclusions result from derivate land-surface parameterization of DEM (Fig. 5a–c). Based on the SAGA WI parameter (Fig. 5a) it was established that places with the highest topographical predisposition for moisture/water concentration are located in the north-eastern part of the city, near the channel of the Odra, and near the Widawa valley. A similar, smaller area is located in the central part of the city, in the western part of the Old Town. Although this is an area of dense urban development, the analysis of historical plans reveals waterlogged areas that occupied the abandoned channel of the Odra. Potentially dry areas, elevated above the bottom of the Odra valley are, apart from the moraine upland by the boundary of the city, isolated areas in the southern and western part of the centre of Wrocław, between the Navigable Canal and the Widawa river. The area to the northeast of the Old

Town is also of interest due to its artificial elevation by the bank and flood protection system, bridgeheads, etc. The elements of flood banks and land elevations related to human activity are easily visible on the map presenting the local land elevation with respect to the valley network (Fig. 5c). The AACN parameter confirmed the presence of natural morphological edges limiting the glacial upland and the edges of the Bystrzyca valley in the western part of the city.

In relation to the course of the valley network and geological data (in particular: Assmann *et al.* 1912; Barsch and Tietze 1912; Barsch *et al.* 1912; Tietze and Behr 1932), ChNBL analysis produced particularly interesting results. Apart from depressions related to contemporary channels and watercourses (identified using the orthophotomap *Culmination of Flood-Wave…*), potential paths of Holocene flood flows were identified (Fig. 5b). In addition, depressions that cut through the area lying south of the Odra valley were identified. The origins of these depressions are probably related to the Pleistocene stage of the formation of the Odra valley and its tributaries (Traczyk 2003; Wiśniewski *et al.* 2013).

Based on the DEM analysis, 96 meanders of the Odra were identified (Fig. 5d). Their sizes and spatial arrangement are diverse and, consequently, three separate zones were isolated on the bottom of the valley (I–III on Fig. 5d). Most meanders (51) can be distinguished in the lower section of the valley, below the Old Town—zone III. Within the Old Town (II) and in the zone located east of the centre (I) 23 and 22 meanders were identified, respectively (Table 2). In the zones I and III meanders reach similar sizes with radiuses that may exceed 500 m, but the average values are, respectively, 316 and 306 m. In the zone II, the radiuses of the largest meanders reached 368 m, but for most of them they range from 180 to 190 m. This image may be connected with the development trend of the river. The zone II corresponds to the place that once housed the natural system of anastomosing channels presented on Leonhard's map (Leonhard 1901). Zones I and II feature meanders that were formed in relation to the free meandering of the Odra channel. Among traces of this meandering tract are the semicircular erosional edges visible along the southern perimeter of the Odra valley, west of the city centre (zone III).

Table 2

Dimensions of Odra river meanders in Wrocław

Zone (see Fig. 5d)	Number of meanders	Radius (R) of meanders (m)			Statistical parameters	
		R min	R max	R mean	Median	SD
I	23	151.1	512.4	316.1	285.2	99.0
II	22	100.5	368.2	180.4	170.7	72.7
III	51	161.2	476.0	306.7	294.0	80.5

4.2. *Geological and Geoarchaeological Data Interpretation*

Digital elevation model (DEM) analysis is equally inefficient in the case of the Old Town of Wrocław, inside the surviving outer moat. Here the initial relief was extensively covered by man-made ground—organic mud, sand and debris (concrete, bricks) sediments. Typical sequences of such sediments are presented in Fig. 6. The initial land configuration of this part of the city (Fig. 7) is known from bore holes (Goldsztejn 2009) and archaeological excavations performed during construction works related to the development boom in the last dozen years or so.

The visualization of the collected data (Fig. 7) confirms the hypothesis formulated by Chmal and Traczyk (2001) that the Old Town was situated on the Pleistocene terrace remnant. The highest-lying parts of this remnant are situated in the southern and south-western part of the Old Town. On the made ground thickness map these correspond to the zone where the ground thickness drops below 2 m (Fig. 7, mark A). The thickness of made ground is even smaller within the abandoned meander of the Odra within the western part of the Old Town (Fig. 7, mark B), as this area was under risk of flooding and remained undeveloped for a long time.

4.3. *2D Electrical Resistivity Tomography*

Geoelectrical studies were conducted on sites whose topographic features are presented in Fig. 8. On site I, profile A (Fig. 9a) was run along the abandoned channel of the Odra which is distinctive in morphology and was active before the regulation (straightening) of the Odra channel. The bottom of the abandoned meander is not filled with water, but

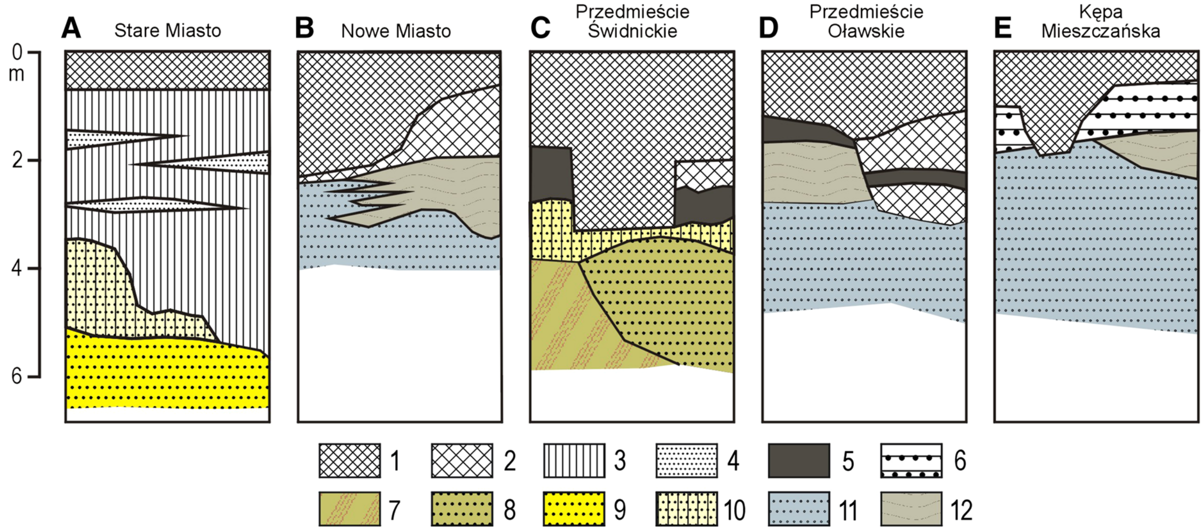


Figure 6

Typical structures of sediments (Old Town, names added): Artificial deposits (covers); *1* sandy rubble, *2* sands with rubble, *3* dumping ground (organic mud with rubbish), *4* sands, *5* humus (topsoil) sands, *6* bar sands and gravels with admixture of bricks, glass, ceramics, etc.; Natural deposits; *7* till, *8* fluvioglacial sands and gravels, *9* Pleistocene fluvial sands and gravels, *10* Pleistocene cover sands (river/periglacial origin), *11* Holocene river sands and gravels, *12* Holocene silty loams (flood deposits)

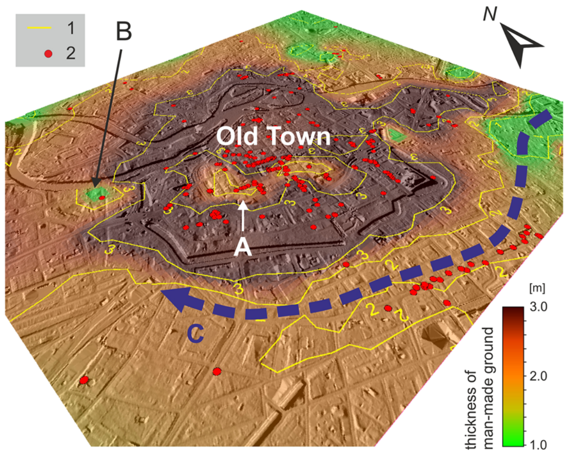


Figure 7

Thickness of artificial sediments within the Old Town: *1* thickness isolines based on the *Geological Atlas of Agglomeration of Wrocław* (Goldsztejn 2009), *2* archaeological sites inventoried with respect to man-made sediment thickness, *a* zones of the erosional remnant, *b* abandoned Odra meander, *c* floodwater flow direction (situation from July 1997)

its banks are locally strongly moisturized. Sediments with the highest resistivity representing scroll-bars were clearly outlined in the profile (No. 1). The abandoned meander is filled with an alluvial sediment up to the depth of 3.5–4 m (No. 2). Below this depth lies a sediment with the lowest, fairly homogeneously distributed resistivity (No. 3). It features an even/truncated floor. A good resolution of the result was achieved owing to the density of electrodes along the profile (every 2 m).

A more diverse situation was observed on the second site encompassing the meander channel of the Odra situated in the western part of the city (Fig. 8II). The profile B cuts through the abandoned meander used historically to cross the river, guarded by gords (from the Bronze Age to Iron Age) founded on local land elevations. Elevations in the period prior to channel abandonment were situated on the left bank on the river, i.e., on the side of Wrocław. Today it is the other way around. The larger of the elevations is a consolidated dune residing on a sandy-gravel foundation (Szponar and Szponar 2008). The elevation through which the beginning of profile B was run is considered an artificial embankment and its structure is unknown. The abandoned meander located beneath the elevation is clearly distinguishable in morphology. A drainage ditch filled with stagnant water runs along the axis of the abandoned channel. On the model (Fig. 9b), sediments forming the upper part of the elevation exhibit the highest electrical resistivity and are not homogenous (No. 1). The subsurface layers of the ground also exhibit high resistivity—this may be

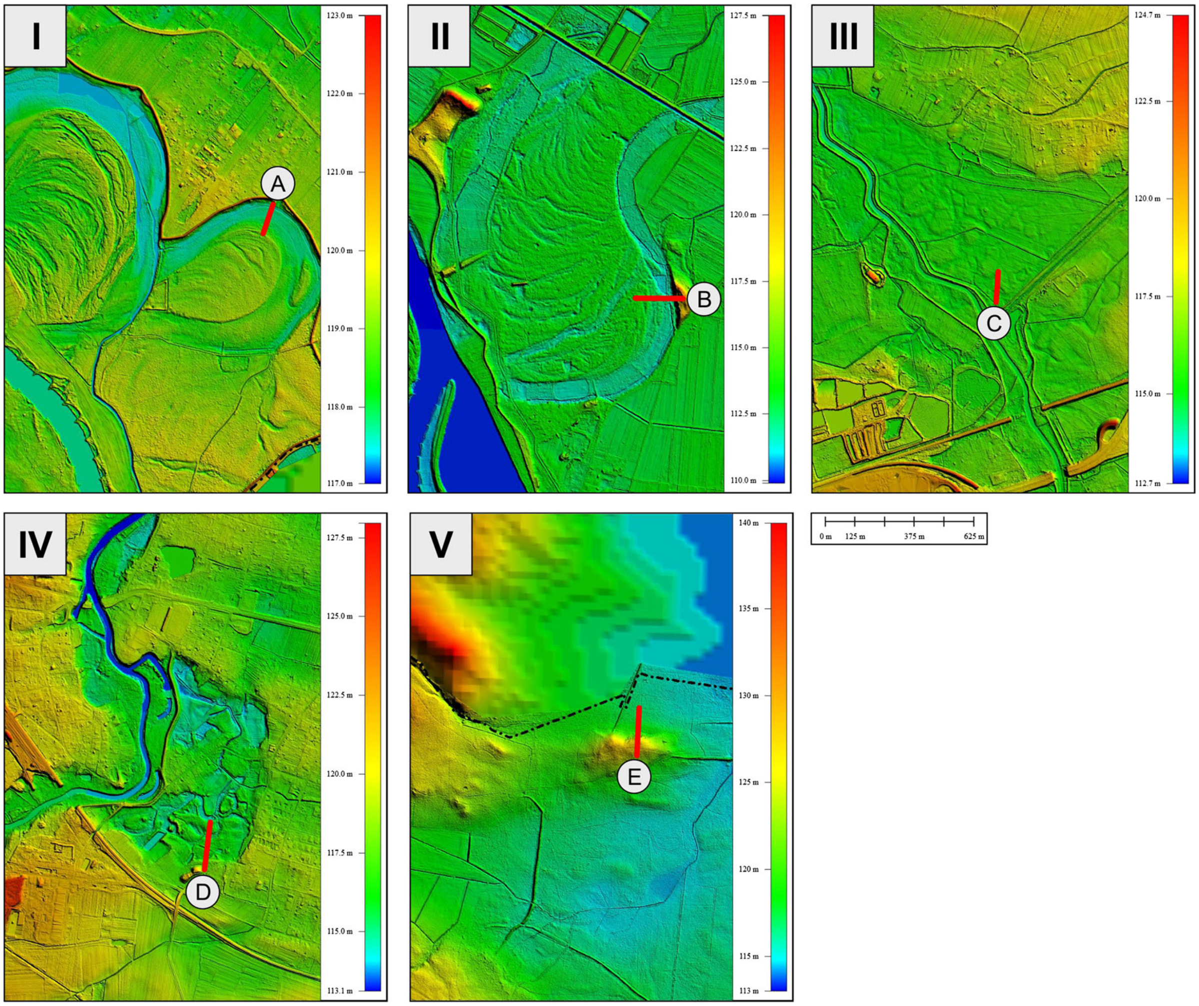


Figure 8

Sites selected for the electrical resistivity investigation, **a–d** profile lines denoted with a *red line* correspond to profiles on Fig. 9: *I* abandoned meanders of the Odra, *II* old meander of the Odra between dunes, *III* Widawa flood plain using the vast bottom of the Odra valley, *IV* Bystrzyca valley bottom, *V* elevations over the Odra valley, *dotted line* denotes the administrative boundary of the city

interpreted to indicate the presence of dry sand of point bars (No. 2). Beneath them resides a material that also fills young abandoned channels (mark a) whose thickness at times exceeds 10 m (No. 4). These alluvia also cut into sediments found under the artificial sediment of the elevation (No. 3). These are most probably dune sands. Under the alluvial sediments of the generation of young paleochannels, lies the formation exhibiting the lowest resistivity (No. 5). Its structure, heterogeneous in terms of resistivity, resembles depressions of the generation of large paleochannels (mark b, turn of Pleistocene/Holocene, after Kozarski 1983). Without confirmation with drillings or using other geophysical methods, this shape cannot be unequivocally interpreted.

On the site III (Fig. 8), the Widawa flood plain was surveyed. From the north the Widawa uses the natural valley depression of the Odra. The ERT profile was run near the mouth of the right tributary of the Widawa on an undeveloped surface available to flood waters. The subsurface part of the obtained model (Fig. 9c) shows fillings of the migrating channels of the Widawa (No. 1). These reside on alluvia exhibiting slightly higher resistivity (No. 2, please note: the colour ramp is always adapted to the distribution of values), whose floor probably indicates a larger channel, now buried by sediments, and clear erosional surfaces truncating the older foundation (mark b). The thickness of the alluvia ranges from 3 to 10 m.

The next site (Fig. 8IV) is located in one of the parks of Wrocław, in a valley depression and system of channels of the Bystrzyca, a left tributary of the Odra, cutting into the fluvioglacial sediments of the surroundings. In this location the ERT profile (Fig. 9d) was run from the morphological edge through visible abandoned meanders. They had a waterlogged bottom and a width up to a few meters. On the obtained model, the fluvial sediments of the Bystrzyca represent a layer with a thickness up to 10 m (No. 3), with a moderately diversified floor. These reside on a ground exhibiting slightly lower resistivity (No. 4). Above them is a material with lower resistivity (wet mineral-organic aggradation, No. 1) or significantly higher resistivity (dry sand of point bars, No. 2).

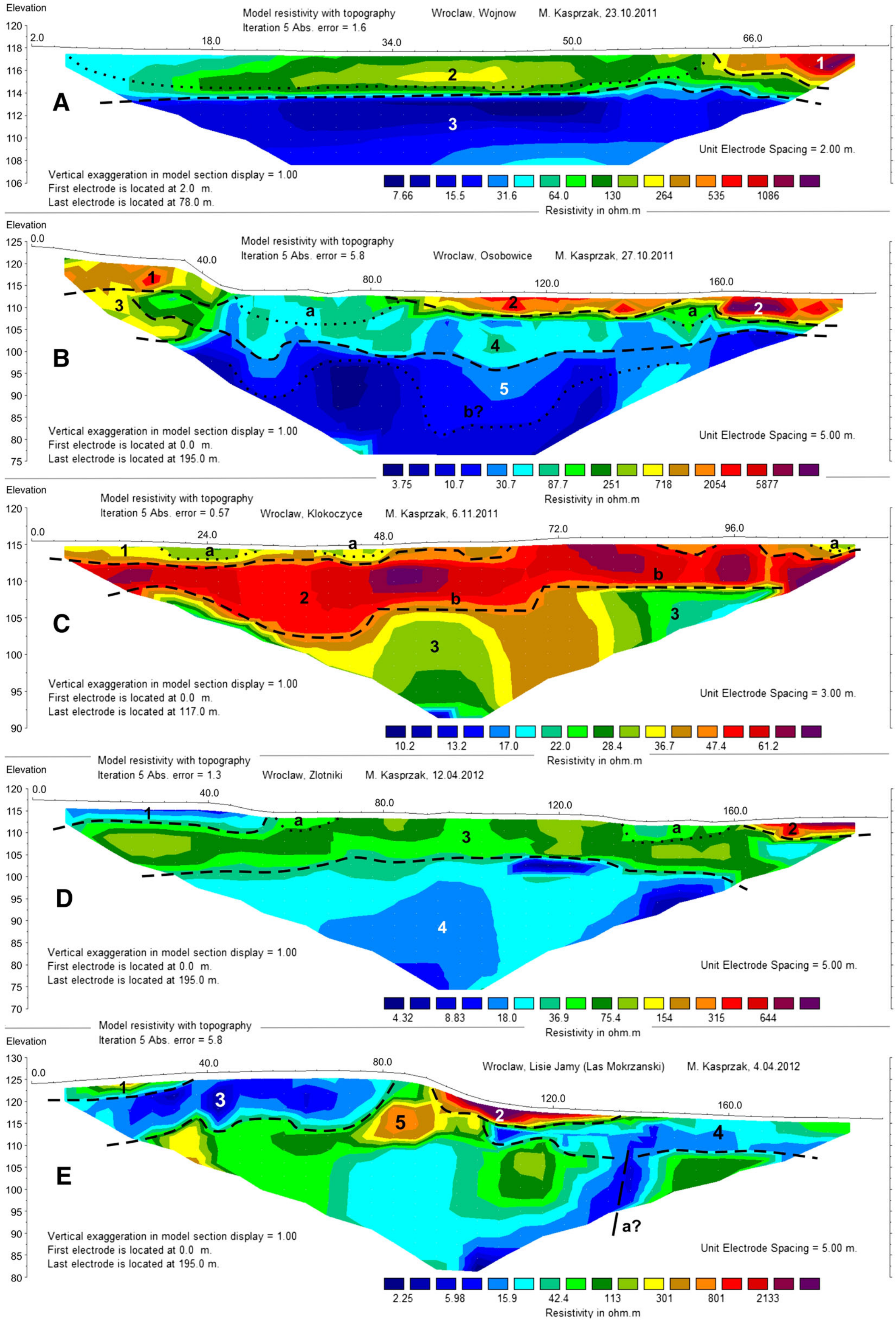
The last of the sites of electrical resistivity investigation was located at the western boundary of Wrocław—the location of the most clear morphological edge separating the bottom of the Odra from the fluvioglacial upland. This location features an isolated hill (129 m above sea level) and relative heights ranging from 7 to 11 m (Fig. 8v). The geomorphometric analysis (Fig. 5b) and the geological structure of this hill (sands and gravels, after Gizler 1982) indicate that this is probably a remnant separated from the rest of the upland by erosion. According to this assumption, it cannot be ruled out that during the Pleistocene phase of development of the Odra valley, its waters sporadically flowed around the hill from the west. The ERT profile was run through the culmination of the hill, its northern, steepest edge and a fragment of the valley bottom. On the obtained model, the highest resistivity was exhibited by slope deposits (No. 2). The highest point of the elevation contains a formation with high resistivity (No. 5) that may form an integral part of a deeper ground with heterogeneous resistivity. Below the hill, on a truncated surface, there are alluvia with a thickness of approximately 7 m (No. 4). A layer with a similarly low resistivity forms the southern hinterland of the hill (No. 3).

4.4. *Landform Map*

The analysis allows for distinguishing the main landforms within the perimeter of Wrocław (Fig. 10). These comprise: the Odra valley bottom and valley bottoms of its tributaries situated from 118 m a.s.l. at the eastern end of the city to 110 m a.s.l. at its north-western boundary. The bottom of the Widawa valley running in parallel to the Odra valley is located on a similar height. This allowed for the construction of a flood relief channel in the 20th century which is used to carry away excess water from the Odra channel to flood plains located in the Widawa valley. The bottom of the Odra valley is levelled. In morphological terms it is made from a terrace 3–4 m above river level. Only in the area of the undeveloped channel of the Odra, outside of the city centre, there are terraces 1.5–2 m high.

One important element of the geomorphic landscape of Wrocław are Pleistocene terrace levels located from 4 to 6 m above the water level in the Odra channel. In the centre of Wrocław, due to a strong distortion of natural height relations by human activity, the boundary between the Holocene bottom of the Odra valley and the Pleistocene terrace levels is now effectively undistinguishable. West of the centre of Wrocław, these are highlighted by the lateral erosion of meander banks. In the area between the bottom of the Widawa and Odra valley, within the Pleistocene terraces, there are small elevations built from glacial till and Neogene loam formations. These are erosional remnants of the upland which was transformed by fluvial processes in the Late Pleistocene.

In the north-eastern part of Wrocław, the Pleistocene terrace plains are directly adjacent to the glacial upland rising to 129–133 m a.s.l. On the southern side of the Odra valley, the Pleistocene terrace connects with slightly undulating denudation plains of the lower level of the glacial upland of the Wrocław Plain. Within this plain there are shallow troughs of secondary watercourses and traces of depressions formed by glacial ice-melting processes inherited from the Pleistocene. The geomorphological map (Goldsztejn 2009) also distinguishes sandur plains from the period of the Odra Stage of the Saalian Glaciation. The analysis of excavations made during


Elevation
Model resistivity with topography
Iteration 5 Abs. error = 1.6
Wroclaw, Wojnow
M. Kasprzak, 23.10.2011
120
118
116
114
112
110
108
106
2.0
18.0
34.0
50.0
66.0
A
1
2
3
Unit Electrode Spacing = 2.00 m.
Vertical exaggeration in model section display = 1.00
First electrode is located at 2.0 m.
Last electrode is located at 78.0 m.
7.66
15.5
31.6
64.0
130
264
535
1086
Resistivity in ohm.m
Elevation
Model resistivity with topography
Iteration 5 Abs. error = 5.8
Wroclaw, Osobowice
M. Kasprzak, 27.10.2011
125
120
115
110
105
100
95
90
85
80
75
0.0
40.0
80.0
120.0
160.0
B
1
2
3
4
5
a
b?
Unit Electrode Spacing = 5.00 m.
Vertical exaggeration in model section display = 1.00
First electrode is located at 0.0 m.
Last electrode is located at 195.0 m.
3.75
10.7
30.7
87.7
251
718
2054
5877
Resistivity in ohm.m
Elevation
Model resistivity with topography
Iteration 5 Abs. error = 0.57
Wroclaw, Klokoczyce
M. Kasprzak, 6.11.2011
120
115
110
105
100
95
90
0.0
24.0
48.0
72.0
96.0
C
1
2
3
a
b
Unit Electrode Spacing = 3.00 m.
Vertical exaggeration in model section display = 1.00
First electrode is located at 0.0 m.
Last electrode is located at 117.0 m.
10.2
13.2
17.0
22.0
28.4
36.7
47.4
61.2
Resistivity in ohm.m
Elevation
Model resistivity with topography
Iteration 5 Abs. error = 1.3
Wroclaw, Zlotniki
M. Kasprzak, 12.04.2012
120
115
110
105
100
95
90
85
80
75
70
0.0
40.0
80.0
120.0
160.0
D
1
2
3
4
a
Unit Electrode Spacing = 5.00 m.
Vertical exaggeration in model section display = 1.00
First electrode is located at 0.0 m.
Last electrode is located at 195.0 m.
4.32
8.83
18.0
36.9
75.4
154
315
644
Resistivity in ohm.m
Elevation
Model resistivity with topography
Iteration 5 Abs. error = 5.8
Wroclaw, Lisie Jamy (Las Mokrzanski)
M. Kasprzak, 4.04.2012
130
125
120
115
110
105
100
95
90
85
80
0.0
40.0
80.0
120.0
160.0
E
1
2
3
4
5
a?
Unit Electrode Spacing = 5.00 m.
Vertical exaggeration in model section display = 1.00
First electrode is located at 0.0 m.
Last electrode is located at 195.0 m.
2.25
5.98
15.9
42.4
113
301
801
2133
Resistivity in ohm.m

◀

Figure 9
Electrical resistivity profiles and their interpretation: **a** profile through the abandoned meander of the Odra in the eastern part of Wrocław; *1* dry sand point bars of the Odra, *2* alluvia, *3* older ground truncated erosionally, *a* approximated cross-section of the abandoned meander; **b** profile through the meander of the Odra in the western part of Wrocław; *1* made sediment, *2* dry sand of point bars, *3* aeolian sands with alluvial build-up (*4*), *4* alluvia, *5* older alluvia, *a* approximated cross-section of the abandoned meanders, *b* bottom of older generations of Odra channels (?); **c** Widawa flood plain cross-section; *1* contemporary flood sediments, *2* alluvia, *3* older ground sediment, *a* current flood channels, *b* erosional truncation surface; **d** profile in bottom of Bystrzyca valley; *1* wet surface sediments with high content of organic substance, *2* dry sand of point bars of the Bystrzyca, *3* alluvia, *4* older ground sediments, *a* abandoned channel of the Bystrzyca; **e** cross-section through upland remnant towards the bottom of the Odra valley; *1* dry surface sediments, *2* slope deposits, *3* alluvia on remnant hinterland (?), *4* alluvia, *5* heterogeneous ground sediment, *a* glacitectonic line of discontinuity (?)

construction works indicates, however, that in most cases sandy-silty tills and silty-sandy cover deposits reside under the soil. Accordingly, this surface is polygenetic. Both weathering and aeolian transport processes in periglacial conditions contributed to its formation, as well as fluvial processes related to the activity of watercourses flowing down the surface of the Pleistocene upland towards the Odra valley (JARY *et al.* 2002; JARY 2010).

Upland areas are the last among the elements of the relief of the Wrocław area. The upland on the southern side of the Odra is split into several parts. Its surface reaches an absolute value, progressing away from the river, from 119 to 140 m a.s.l. South of the centre of Wrocław, within the upland, there is a morphological depression running in parallel to the

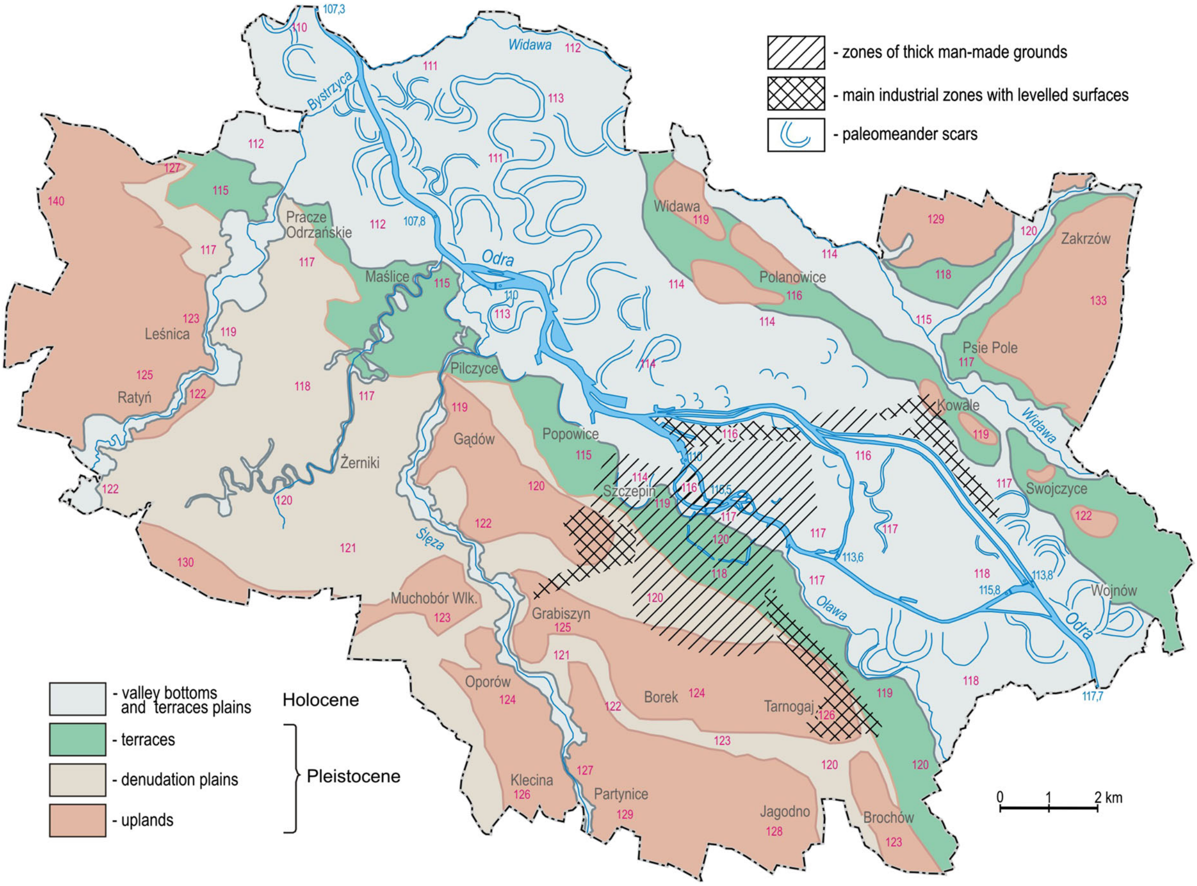


Figure 10
Map of main landforms in Wrocław. City district names and spot heights added

edge of the Odra valley. It is 400–600 m wide and its course is visible, among others, on SAGA WI and ChNBS maps (Fig. 5a, b—indicated by black arrow). This depression was probably active in the Late Pleistocene as an arm of the pre-Odra or the mouth of one of its tributaries (pre-Oława?), which was described based on geoarchaeological investigation by Chmal and Traczyk (2001). This was not a flow related to the local watercourse flowing along the surface of the upland (Fig. 5b—indicated by white arrow), as within the area of this depression, on the Palaeolithic site at Hallera street sandy-gravel fluvial sediments were uncovered (Wiśniewski *et al.* 2013). Their structural features indicate a high-energy depositional conditions. Similar depressions of the flow of the pre-Odra or its tributaries were also identified in other locations on the DEM model (Fig. 5b).

5. *Discussion and Conclusions*

The geomorphological investigations reported here follow the specific trend of urban geomorphology (Bathrellos 2007), that used evidence gained during archaeological and geo-engineering works. Performing a geomorphological analysis of the entire area of the city would not have been possible without high-resolution LiDAR data which, until recently, were largely unavailable in Poland. Properly processed and interpreted LiDAR data provide much better background for geomorphologic mapping than 1:10,000 topographic maps or ortophotomaps used earlier. This mainly applies to areas covered with vegetation whose image is filtered off during the processing of raw data. In the city, the areas of this type most difficult to analyze are vast areas of allotment gardens. LiDAR, however, cannot produce equally good results on areas subject to strong man-made transformations, subject to levelling, as, e.g., in the industrial zone between the Navigable Canal and the Widawa in the north of Wrocław or within the Old Town (Fig. 10). Detailed geomorphologic recognition of such areas is only possible during earthworks.

As the analysed DEM presents areas with fairly small height differences, the application of basic land-surface parameters (aspect, slope, curvature, etc.) failed to produce satisfactory results in the interpretation of landforms. For this reason, to survey urban areas with a high-resolution DEM, the authors propose to use derived land-surface parameters, implemented, among others, in SAGA GIS Free Open Source Software (Cimmery 2010) and in particular the *SAGA Wetness Index*, *Channel Network Base Level* and *Altitude Above Channel Network*. These parameters ensure robust patterning of morphologically isolated areas, the courses of river valleys and depressions determining flood flows and morphological edges. The obtained layers, as compared to prior geomorphological investigation of Wrocław, offer a completely new quality of spatial data.

In the proposed procedure, the analysis of high resolution DEM is the basis, but the picture may be significantly enriched through the use of 2D Electrical Resistivity Tomography. Although this method is popular, there are very few examples of its application in urban areas in literature (e.g., Meju 2000; Boudreault *et al.* 2010); though difficult to carry out in densely developed urban areas, these measurements provide good results in investigating valley bottom and valley sides sediments. Boudreault *et al.* (2010) also successfully applied this method to investigate man-made debris sediments; however, this requires cooperation during specific construction works.

The interpretation of electrical resistivity profiles must be treated with caution because the application of this method is burdened with several errors (Kearey *et al.* 2002; Milsom 2003; Schrott and Sass 2008). Such errors include the selection of an electrode array that does not correspond to the soil conditions, lack of distinct boundaries between the resistivity of different sediments on the output model, changing hydrogeological conditions of the soil and, primarily, over-interpretation of the obtained results. Despite such limitations, the obtained models serve as a valuable supplement to existing geological data obtained in drillings whose spatial interpretation is more time-consuming. Practice also shows that the interpretation of drillings made by various researchers in different periods carries a substantial burden of error.

The recognition of the geomorphological situation of Wrocław based on LiDAR and 2D ERT leads to new conclusions concerning the paleogeographic development of the city area. Measurements of the meander system allowed for mapping the range of the anastomosing section of the Odra, where the average radius of the meanders is smaller than in the case of the remaining sections. The tendency towards anastomosing of the Odra may be a result of not only the expected surface subsidence, but the accumulation of river sediment from mouth of the Oława, which provides a large bed load from the loess part of its catchment directly to a relatively narrow section of the Odra valley. There is also one visible tendency whereby the largest meanders with radiuses exceeding 400 m along the southern border of the valley bottom tend to group. As a result, the northern edge of the glacial upland forming a part of the Wrocław Plain is undercut. The direction of migration of the Odra channel, as well as the variation in its formation may be attributed to the neotectonic activity of the sub-Quaternary basement (Grzempowski *et al.* 2009). However, within the city area it is impossible to distinguish generation of paleomeanders of various age that would be different with respect to size, as was successfully attempted in other sections of the Odra (Ruszczycka-Mizera 1978).

Geoelectric investigation allowed for the separation of mineral-organic aggradations filling the abandoned meander from sands forming meander scroll-bars. These formations exhibit distinctly different electrical properties. The thickness of the fillings of the abandoned meanders of the Odra in the investigated profiles amounts to approximately 10 m. Fluvial sediments of large tributaries of this river (site on the Bystrzyca) have a slightly lower thickness. To date, these fillings were mainly investigated with respect to contamination with heavy metals (Ciszewski *et al.* 2008; Ciszewski and Turner 2009).

Light detection and ranging (LiDAR) data did not confirm that the Wrocław area features a morphologically legible terrace system of the Odra as presented by Goldsztejn (2009), a feature found in other sections of the river (Szczepankiewicz 1959, 1989). These levels have become indistinct as a result of erosional and denudation processes and the aggradation of Odra alluvia. Hence, their origin may not be distinguished without detailed sedimentological studies. We may assume that one remnant of the highest Pleistocene terrace is the depression formed by the flow of flood waters on the surface of the upland in the southern part of the city (Fig. 5b).

The remnants of the Pleistocene foundation survived within the bottom of the Odra valley, usually serving as locations for initial settlement. The best example of this type is the Wrocław Old Town (Buśko 1999; Chmal and Traczyk 2001; Badura 2010) which features an area with lower thickness of artificial sediments as compared to the surroundings (Fig. 7). Small in terms of absolute height elevations of Pleistocene outliers, these guaranteed safety during floods as evidenced during the high-magnitude events on the Odra, e.g., in 1854, 1903 or 1997. During historic floods, terraces elevated to 3–4 m above river level were shaped (built on or eroded). Contemporarily, the most intensely shaped is the level of 1–2 m above river level, but only outside of areas with channel reinforcements.

One major feature of all cities of Eastern Europe is transformation resulting from the formation of made ground. In Wrocław these are characteristic of the city centre, flood banks and communication lines creating, among others, morphologically distinct oblong elevations of minimal height (Fig. 5c). Similar oblong forms are related to natural fluvial processes and formation of natural levees (as exemplified by the Bystrzyca in the western part of the city). The largest height differences are characteristic of dunes and edges of the upland, in particular their fragments in the western part of the city. It cannot be ruled out that glacitectonic deformations, presented on the geomorphological map by Goldsztejn (2009), contributed to the formation of this area. This may by attested by the line of discontinuity in the electrical resistivity of the deeper ground captured in the 2D ERT profile (Fig. 9e).

Although the analysis concerns specific environmental conditions, the proposed expansion of the traditional geomorphological investigation in the urban environment may be implemented in other areas too, in particular in cities located in the valleys of large rivers with a long history, where changes of the river network and formation of made ground have played a significant role in the development of relief.

Acknowledgments

The authors would like to thank the Municipal Office of Wrocław for providing LiDAR data for investigations and the students of the University of Wrocław for the involvement in electrical resistivity measurements and also reviewers for their valuable comments and suggestions.

References

Afonso, M.J., Chaminé, H.I., Gomes, A., Fonseca, P., Marques, J. M., Guimarães, L., Guilhermino, L., Teixeira, J., Carvalho, J. M., Rocha, F. T. (2006), *Urban hydrogeomorphology and geology of the Porto metropolitan area (NW Portugal)*, IAEG2006 Paper *92*, 1–9.

Ayolabi, A. A., Enoh I. J. E., Folorunso A. F. (2013), *Engineering Site Characterisation Using 2-D and 3-D Electrical Resistivity Tomography*, Earth Science Research *2(1)*, 133–142.

Assmann, P., Barch, O., Cramer, R., Quitzow, W., Soenderop, F., Tietze, O. (1912), *Geologische Karte von Preußen und benachbarten deutschen Ländern 1:25 000 Blatt Gr. Naedlitz*, Preußische Geologische Landesanstalt, Berlin.

Badura, J. (2010), *Geomorphological Conditions of Localization of the Left Bank Settlement of Wrocław* (in Polish), Wratislavia Antiqua *11*, 15–45.

Badura, J., Przybylski, B. (1998), Pleistocene *Ice Sheets Range and Deglaciation of the area between Sudetes and the Silesian Ridge* (in Polish), Biuletyn PIG *385*, 9–28.

Badura, J., Przybylski, B. (2004), *Evolution of the Late Neogene and Eopleistocene Fluvial System in the Foreland of the Sudetes Mountains, SW Poland*, Annales Societas Geologorum Poloniae *74*, 43–61.

Barsch, O., Tietze, O. (1912), *Geologische Karte von Preußen und benachbarten deutschen Ländern 1:25 000 Blatt Schmolz*, Preußische Geologische Landesanstalt, Berlin.

Barsch, O., Tietze, O., Michael, R., Schlunk, F., Schneider, O., Soenderop, F., Tornau, F. (1912), *Geologische Karte von Preußen und benachbarten deutschen Ländern 1:25 000 Blatt Kattern,* Preußische Geologische Landesanstalt, Berlin.

Bathrellos, G. D. (2007), *An overview in urban geology and urban geomorphology,* Bulletin of the Geological Society of Greece *XXXX*, Proceedings of the 11th International Congress, Athens, May, 2007.

Bersezio, R., Giudici, M., Mele, M. (2007), *Combining sedimentological and geophysical data for high-resolution 3-D mapping of fluvial architectural elements in the Quaternary Po plain (Italy)*, Sedimentary Geology *202*, 230–248.

Beven, K., Kirkby, N. (1979), *A physically based variable contributing area model of basin hydrology*, Hydro. Sci. Bull. *24(1)*, 43–69.

Boehner, J., Koethe, R., Conrad, O., Gross, J., Ringeler, A., Selige, T. Soil Regionalisation by Means of Terrain Analysis and Process Parameterisation. In: *Soil Classification 2001. European Soil Bureau, Research Report No. 7, EUR 20398 EN* (eds. Micheli, E., Nachtergaele, F., Montanarella, L.) (Luxembourg 2002), pp 213–222.

Bonk, R. (2007), Scale-Dependent Effect of Input Data Design on DEM Accuracy. In: *Digital Terrain Modelling* (eds. Peckham, R. J, Jordan G.) (Springer-Verlag Berlin Heidelberg 2007), pp. 83–98.

Boudreault, J.-P., Dubé, J.-S., Chouteau, M., Winiarski, T., Hardy, E., (2010), *Geophysical characterization of contaminated urban fills*, Engineering Geology *116*, 196–206.

Bowling, J. C., Harry, D. L., Rodriguez, A. B., Zheng, Ch. (2007), *Integrated geophysical and geological investigation of a heterogeneous fluvial aquifer in Columbus Mississippi*, Journal of Applied Geophysics *62*, 58–73.

Brown, A. G. (2008), *Geoarchaeology, the four dimensional (4D) fluvial matrix and climatic causality*, Geomorphology *101*, 278–297.

Bugosh, N. (2006), *Basic Manual for Fluvial Geomorphic Review of Landform Designs* (Draft), http://www.ai.org/dnr/reclamation/files/re-Basic_Manual_for_Fluvial_Geomorphic_Review_of_Landform_Designs_28APR06.doc.

Buśko, C. (1999), *Changes in configuration of terrain of pre–foundation and foundation Wrocław* (abs. in eng.), Mediaevalia Archaeologica *1*, 43–50.

Carpentier, S., Konz, M., Fischer, R., Anagnostopoulos, A., Meusburger, K., Schoeck, K. (2012), *Geophysical imaging of shallow subsurface topography and its implication for shallow landslide susceptibility in the Urseren Valley, Switzerland*, Journal of Applied Geophysics *83*, 46–56.

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

Challis, K. (2006), *Airborne Laser Altimetry in Alluviated Landscapes*, Archaeol. Prospect. *13*, 103–127.

Chambers, J.E., Kuras, O., Meldrum, P. I., Ogilvy, R. D., Hollands J. (2006), *Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site,* Geophysics *71(6)*, 231–239.

Charlton, M. E, Large, A. R. G., Fuller, I. C. (2003), *Application of airborne LiDAR in river environments: the River Coquet, Northumberland, UK*, Earth Surface Processes and Landforms *28(3)*, 299–306.

Chmal, H., Czerwiński, J., Czerwińska, I., Traczyk, A. (1993), *Geological and Geomorphological Characteristics of Archaeological Investigation Area in the Dominikański square in Wrocław* (in Polish), Silesia Antiqua *35*, 383–400.

Chmal, H., Traczyk, A. (1998), *Geological and Geomorphological Characteristics of Archaeological Investigation Area* (in Polish), Silesia Antiqua *39*, 275–280.

Chmal, H., Traczyk A. (2001), *Notes on the Geomorphology of the Marketplace in Wrocław* (in Polish), Wratislvia Antiqua, Studia z dziejów Wrocławia *3*, 7–14.

Cimmery, V. (2010), *User Guide for SAGA (version 2.0.5) Vol. 1.*, pp. 372.

Ciszewski, D., Czajka, A., Błażej, S. (2008), *Rapid migration of heavy metals and* ^{137}*Cs in alluvial sediments, Upper Odra River valley, Poland*, Environmental Geology *55(7)*, 1577–1586.

Ciszewski, D., turner J. (2009), *Storage of sediment-associated heavy metals along the channelized Odra River, Poland*, Earth Surf. Process. Landforms *34*, 558–572.

Conrad, O. (2003), *ChannelNetwork_Altitude.cpp. SAGA System for Automated Geoscientific Analyses, Module Library/ta_channels*, http://saga.sourcearchive.com/documentation/2.0.7plus-pdfsg-2/ChannelNetwork__Altitude_8cpp_source.html.

Culmination of Flood-Wave in the city of Wrocław, 1997-07-14, 7.04 AM–Orthophotomap in scale 1:25 000, *Head Office of Geodesy and Cartography, Warszawa* (in Polish).

Czerwiński, J. (1998), *Geological, geomorphological and anthropogenic factors of flood hazard in Wrocław* (in Polish), Czas. Geogr. *69(1)*, 43–63.

Czerwonka, J. A., Krzyszkowski, D. (1992), *Pleistocene stratigraphy of the central part of Silesian Lowland, southwestern Poland*, Bull. Pol. Acad. Sc. Earth Sc. *40(3)*, 203–233.

de Domenico, D., Giannino F., Leucci, G., Bottari, C. (2006), *Integrated geophysical surveys at the archaeological site of Tindari (Sicily, Italy)*, Journal of Archaeological Science *33*, 961–970.

Dumanowski, B., Jahn, A., Szczepankiewicz, S. (1962), *The Holocene of Lower Silesia in the light of results of the first radiocarbon dating*, Bull. d. l'Acad. Pol. d. Sci. Géol. Géogr. *10(1)*, 47–52.

Gamba, P., Dell'Acqua, F., Houshmand, B. (2002), *SRTM data characterization in urban areas*. International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences *34.3/B*, 55–58.

Gizler, H. (1982), *The Detailed Geological Map of Poland 1:50 000, sheet Oborniki Śląskie*, PIG.

Goldsztejn, J. (ed.) (2009), *Geological and Engineering Database with the Development of Engineering-Geological Atlas of Agglomeration of Wrocław* (in Polish), Przedsiębiorstwo Geologiczne Proxima S.A. we Wrocławiu, Państw. Inst. Geol., Wrocław, 90 p. and maps.

Grzempowski, P., Badura, J., Cacoń, S., Przybylski, B. (2009), *Recent Vertical Movements in the Wrocław Section of the Middle Odra Fault Zone*, Acta Geodyn. Geomater. *6(3)*, 339–349.

Harris, Ch., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, Ch., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M. A., Lehning, M., Matsuoka, N., Murton, J. B., Nötzli, J., Phillips, M., Ross, N., Seppälä, M., Springman, S. M., Mühll, D. V. (2009), *Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and geotechnical responses*, Earth-Science Reviews *92*, 117–171.

Hirano, A., Welch, R., Lang, H. 2003, *Mapping from ASTER stereo image data: DEM validation and accuracy assessment*. ISPRS Journal of Photogrammetry & Remote Sensing *57*, 356–370.

Höfle, B., Rutzinger, M. (2011), *Topographic airborne LiDAR in geomorphology: A technological perspective*, Zeitschrift für Geomorphologie *55(Suppl. 2)*, 1–29.

Jary, Z. (2010), *Loess–soil sequences as a source of climatic proxies: an example from SW Poland,* Geologija *52(1–4)*, 69–72.

Jary, Z., Kida, J., Śnihur, M. (2002), *Loess and loess-derived sediments in SW Poland* (in Polish), Czas. Geogr. *73(1–2)*, 63–100.

Jones, K. L., Poole, G. C., O'Daniel, S. J., Mertes, L. A. K., Stanford, J. A. (2008), *Surface hydrology of low-relief landscapes: Assessing surface water flow impedance using LIDAR-derived digital elevation models*, Remote Sensing of Environment *112*, 4148–4158.

Kampke, A. (1999), *Focused imaging of electrical resistivity data in archaeological prospecting*, Journal of Applied Geophysics *41*, 215–227.

Kearey, P., Brooks, M., Hill, I. The principles and limitations of geophysical exploration methods. In: *An Introduction to Geophysical Exploration* (eds. Kearey, P., Brooks, M., Hill, I.) (Blackwell Science 2002), pp 1–7.

Klimek, K. (2000), *The Sudetic tributaries of Upper Odra transformation during the Holocene*, Studia Geomorph. Carpatho-Balcanica *32*, 27–45.

Kneisel, Ch. (2006), *Assessment of subsurface lithology in mountain environments using 2D resistivity imaging*, Geomorphology *80*, 32–44.

Kneisel, Ch. (2010), *Frozen ground conditions in a subarctic mountain environment, Northern Sweden*, Geomorphology *118*, 80–92.

Kneisel, Ch., Hauck, Ch., Fortier, R., Moorman, B. (2008), *Advances in geophysical methods for permafrost investigations*, Permafrost and Periglacial Processes *19*, 157–178.

Kozarski, S. (1983), *River channel changes in the middle reach of the Warta Valley, Great Poland Lowland*, Quaternary Studies in Poland *4*, 159–169.

Krzyszkowski, D., Łabno, A. (2002), *Late Saalian (Wartanian) Glacial Paleography and Formation of End Moraines at the Northern slopes of Silesian Rampart, Southwestern Poland*, Ann. Soc. Geol. Pol. *72*, 67–87.

Kvamme, K. L. There and Back Again: Revisiting Archaeological Locational Modeling. In: *GIS and Archaeological Site Location Modeling* (eds. Mehrer, M. W., Wescott, K. L.) (Tylor and Francis 2006), pp 2–34.

Large, A. R. G., Heritage, G. L. Laser Scanning – Evolution of the Discipline. In: *Laser Scanning for the Environmental Sciences* (eds. Large, A. R. G., Heritage G. L.) (Wiley-Blackwell 2009), pp 1–20.

Lasaponara, R., Coluzzi, R., Gizzi, F. T., Masini, N. (2010), *On the LiDAR contribution for the archaeological and geomorphological study of a deserted medieval village in Southern Italy*, Journal of Geophysics and Engineering *7*, 155–163.

Leonhard, R. Die Entwickelung der Stromlage der Odra bei Breslau nach den Unterschungen. In: *Breslau. Lage, Natur und Entwickelung, Eine Festgabe dem XIII Deutschen Geographentage* (C. T. Wiskott, Breslau 1901), pp 39–47.

Liu, Xiaoye (2008), *Airborne LiDAR for DEM generation: some critical issues*, Progress in Physical Geography *32(1)*, 31–49.

Loke, M. H. Tutorial: 2-D and 3-D electrical imaging surveys. *Geotomo Software*, Malaysia 2012.

Łabno, A. (1988), *The Detailed Geological Map of Poland 1:50 000, sheet Leśnica*, PIG.

Marescot, L., Monnet, R., Chapellier, D. (2008), *Resistivity and induced polarization surveys for slope instability studies in the Swiss Alps*, Engineering Geology *98*, 18–28.

Marks, L. (2004), *Pleistocene Glacial Limits in Poland*, Developments in Quaternary Sciences, *2(1)*, 295–300.

Marks, L. (2005), *Pleistocene Glacial Limits in the Territory of Poland*, Przegl. Geol. *53(10/2)*, 988–993.

Meju, M.A. (2000), *Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: Model development with a genetic diagnosis approach*, Journal of Applied Geophysics *44*, 2–3, 115–150.

Migoń, P., Pánek, T., Malik, I., Hrádecký, J., Owczarek, P., Šilhán, K. (2010), *Complex landslide terrain in the Kamienne Mountains, Middle Sudetes, SW Poland*, Geomorphology *124*, 200–214.

Milsom, J. Resistivity Methods. In: *Field Geophysics* (ed. Milsom, J.) (Wiley, 2003), pp 97–116.

Notebaert, B., Verstraeten, G. (2010), *Sensitivity of West and Central European river systems to environmental changes during the Holocene: A review*, Earth-Science Reviews *103*, 163–182.

Notebaert, B., Verstraeten, G., Govers, G., Poesen, J. (2009), *Qualitative and quantitative applications of LiDAR imagery in fluvial geomorphology*, Earth Surf. Process. Landforms *34*, 217–231.

Olaya, V. Basic Land-Surface Parameters. In: Geomorphometry*: Concepts, Software, Applications*. Developments in Soil Science *33* (eds. Hengl, T., Reuter H. I.) (Elsevier 2009), pp 141–169.

Palmer, T. C., Shan, J. (2002), *A Comparative Study on Urban Visualization Using LiDAR Data in GIS*, URISA Journal *14(2)*, 19–25.

Pánek, T., Tábořík, P., Klimeš, J., Komárková, V., Hradecký, J., Šťastný, M. (2011), *Deep-seated gravitational slope deformations in the highest parts of the Czech Flysch Carpathians: Evolutionary model based on kinematic analysis, electrical imaging and trenching*, Geomorphology *129*, 92–112.

Papadopoulos, N. G., Sarris, A., Yi Myeong-Jong, Kim Jung-Ho (2009), *Urban archaeological investigations using surface 3D Ground Penetrating Radar and Electrical Resistivity Tomography methods*, Exploration Geophysics *40*, 56–68.

Papadopoulos, N. G., Tsourlos, P., Tsokas, G. N., Sarris, A. (2006), *Two-dimensional and Three-dimensional Resistivity Imaging in Archaeological Site Investigation*, Archaeol. Prospect. *13*, 163–181.

Piekalski, J. (1999), *Transformation of medieval towns of Central European interior. Spacial structure* (abs. in Eng.), Mediaevalia Archaeologica *1*, 21–42.

Przybylski B., Badura J., Krąpiec M. Geological Structure of the Odra Valley between Oława and Lubiąż (in Polish). In: *Geoekologiczne i środowiskowe problemy gospodarowania i ochrony doliny górnej i środkowej Odry. 18–19 XI 2004* (eds. Szymańska, H., Cwojdziński, S., Poprawski, L.) (PIG, Wrocław 2004), pp 9–32.

Rayburg, S., Thoms, M., Neave, M. (2009), *A comparison of digital elevation models generated from different data sources*, Geomorphology *106*, 261–270.

Reuter, H. I., Hengl, T., Gessler, P., Soille, P. Preparation of DEMs for Geomorphometric Analysis. In: *Geomorphometry Concepts, Software, Applications*. Developments in Soil Science 33 (eds Hengl, T., Reuter, H. I.) (Elsevier, 2009), 87–120.

Reynolds, J. M. Electrical resistivity methods. In: *An Introduction to Applied and Environmental Geophysics* (ed. Reynolds, J. M.) (John Wiley and Sons, 1997), pp 420–490.

Rosenbaum, M. S., McMillan, A., A., Powell, J. H., Cooper A. H., Culshaw, M. G., Northmore, K. J. (2003), *Classification of artificial (man-made) ground*, Engineering Geology *69*, 399–409.

Ruszczycka-Mizera M. (1978), *Interpretation of aerial photographs as a method of analysis of river valley bottom relief development in larger rivers such as the Odra river* (abs. in eng.), Acta Univ. Wratislaviensis *340*, Prace Inst. Geogr. Ser. A *2*, 115–151.

Samouëlian A., Cousina I., Tabbagh A., Bruandd A., Richard G. (2005), *Electrical resistivity survey in soil science: a review*, Soil and Tillage Research *83*, 173–193.

Saad, R., Nawawi, M. N. M., Mohamad, E. T. (2012) *Groundwater Detection in Alluvium Using 2-D Electrical Resistivity Tomography (ERT)*. Electronic Journal of Geotechnical Engineering *17(D)*, 369–376.

Sass, O. (2007), *Bedrock detection and talus thickness assessment in the European Alps using geophysical methods*, Journal of Applied Geophysics *62*, 254–269.

Schrott, L., Sass, S. (2008), *Application of field geophysics in geomorphology: Advances and limitations exemplified by case studies*, Geomorphology *93*, 55–73.

Sithole, G, Vosselman, G. (2004), *Experimental comparison of filter algorithms for bare-Earth extraction from airborne laser scanning point clouds*, ISPRS Journal of Photogrammetry & Remote Sensing *59*, 85–101.

Sørensen, R., Zinko, U., Seibert, J. (2005), *On the calculation of the topographic wetness index: evaluation of different methods based on field observations*, Hydrol. Earth Sys. Sci. Discuss. *2*, 1807–1834.

Starkel, L., Soja, R., Michczyńska, D. J. (2005), *Past hydrological events reflected in Holocene history of Polish rivers*, Catena *66*, 24–33.

Szabó, J. Anthropogenic Geomorphology: Subject and System, In: *Anthropogenic Geomorphology. A Guide to Man-Made Landforms* (eds. Szabó J. Lóránt D., Lóczy D.) (Springer 2010) pp. 3–10.

Szczepankiewicz, S. (1959), *The Odra valley between Wrocław and Brzeg Dolny* (in Polish), Czas. Geogr. *30*, 263–286.

Szczepankiewicz, S. (1989), *The lands of the South-Western Polish–Morphogenesis and Quaternary History* (in Polish), Acta Universitatis. Wratislaviensis, 1029, Studia Geogr. *47*, 137 p.

Szponar, A., Szponar, A. M. Geology and Paleogeography of Wrocław (in Polish) (KGHM Cuprum, Wrocław 2008), 164 p.

Škarpich, V., Tábořík, P., Hradecký, J. (2010), *Geomorphological interprettion of valley bottoms in the Moravskoslezské Beskydy Mts. based on geoelectrical measurement* (abs. in eng.), Zprávy o geologických výzkumech v roce 2010/Kvartér, inženýrská geologie, 87–91.

Telford, W. M., Geldard, L. P., Sherif R. E. Resistivities of Rock and Minerals, In: *Applied Geophysics Sec. Ed.* (eds. Telford, W. M., Geldard, L. P., Sherif R. E.) (Cambridge Univ. Press 1990) 289–292.

Thorndycraftm, V.R., Benito, G., Gregory. K.J. (2008), *Fluvial geomorphology: A perspective on current status and methods*, Geomorphology *98*, 2–12.

Tietze, O., Behr, J. (1932), *Geologische Karte von Preußen und benachbarten deutschen Ländern 1:25000, Bln. Deutsch-Lissa, Bl. Breslau (Nord)*, Preußische Geologische Landesanstalt, Berlin.

Traczyk, A. (2003), *Origin and chronology of Pleistocene deposits in the archaeological sites in the Sleza river valley in Wrocław Oporow*, (in Polish, abs. in Eng.), Acta Univ. Wratislaviensis 2485, Studia Archeologiczne *33*, 53–79.

Traczyk, A. (2007), *Late-Pleistocene and Holocene evolution of valleys of the Lower Silesia for example Ślęza valley in Wroclaw* (in Polish), Prace Instytutu Akademii Świętokrzyskiej w Kielcach *16*, 125–140.

Tsokas, G. N., Tsourlos, P. I., Vargemezis, G. N., Pazaras, N.T. (2011), *Using surface and cross-hole resistivity tomography in* *an urban environment: An example of imaging the foundations of the ancient wall in Thessaloniki, North Greece*, Physics and Chemistry of the Earth *36*, 1310–1317.

Van Dam, R.L. (2012), *Landform characterization using geophysics—Recent advances, applications, and emerging tools*, Geomorphology *137*, 57–73.

Vetter, M., Höfle, B., Mandlburger, G., Rutzinger, M. (2011), *Estimating changes of riverine landscapes and riverbeds by using airborne LiDAR data and river cross-sections*, Zeitschrift f. Geomorphologie *55(2)*, 51–65.

Winnicka, G. (1987), *The Detailed Geological Map of Poland 1:50 000, sheet Wrocław*, Państw. Inst. Geol., Warszawa.

Wiśniewski, A., Adamiec, G., Badura, J., Bluszcz, A., Kowalska, A., Kufel-Diakowska, B., Mikołajczyk, A., Murczkiewicz, M., Musil, R., Przybylski, B., Skrzypek, G., Stefaniak, K., Zych, J. (2013), *Occupation dynamics north of the Carpathians and Sudetes during the Weichselian (MIS5d-3): the Lower Silesia (SW Poland) case study*, Quaternary International *294*, 20–40.

You, S., Hu, J., Neumann, U., Fox, P. (2003), *Urban site modeling from LiDAR*. Computational Science and Its Applications—ICCSA 2003, 579–588.

Żelaźniewicz, A. The geological history (in Polish), In: *Nature of the Lower Silesia* (ed. Fabiszewski, J.) (Pol. Acad. of Science, Korab., Wrocław, 2005), pp 61–134.

(Received July 3, 2012, revised May 31, 2013, accepted June 24, 2013, Published online July 9, 2013)