Geodetic Fundamentals in the Development of a Voxel Model for the Subsoil of the City of Sevilla (Spain)

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Abstract: Current global challenges require a better understanding of the subsoil to optimise underground resources and plan for sustainable development. This is a key issue in anthropised metropolitan environments, where the high density of elements makes difficult to gain knowledge of this reality. The use of Geographic Information Systems (GIS) enables spatial management and visualisation of the underground data obtained from geotechnical surveys. The creation of 3D models in voxel format constitutes a pioneering and relevant line of research. This paper evaluates the main factors resulting from the integration of different topographic sources at a territorial level for the creation of surface models that efficiently adjust the geotechnical data collected, which usually lacks global height values. This task involved designing a coordinate system and a reference grid, as well as adjusting elevation data for the selected study case: the metropolitan area of Sevilla, Spain.

1 INTRODUCTION

The significance of understanding the underground reality in highly anthropised urban and metropolitan areas cannot be overstated. Accurate subsurface data is crucial to the design of new constructions, the conservation of existing ones and urban planning. Nevertheless, current information techniques are limited in their ability to provide detailed subsurface data through the use of remote sensors that capture information from the earth's surface on a massive scale. To address this issue, efficient strategies are required to collect data from geotechnical tests (such as boreholes and soil penetrometer) for the precise characterisation of the underground through the generation of 2D cartographies and 3D models by means of Geographic Information Systems (GIS). Regarding this approach, proposals that use vector and raster models to allow the visualisation of the distribution of underground geotechnical strata in a correlated way with the organisation of the urban infrastructure should be considered (Nonogaki et al., 2021; Soriano-Cuesta et al., 2023).

Given the interest of this line of work, the present research raises the need to develop models that can effectively manage detailed subsurface information using the voxel format. The accurate correlation of the subsurface information with the topographic configuration of the surface is essential in all the cases mentioned. Consequently, the current investigation presents the geodetic fundamentals that allow a rigorous adjustment of the relationship between

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surface information from different sources and subsurface data obtained from geotechnical tests of a spot nature. The study area chosen for this purpose is Sevilla, a city located in the south of Spain with a high heritage value and a metropolitan population of approximately one million inhabitants (Sanchez Fuentes et al., 2021) has been taken as a representative study area. The case study is based on a database of geotechnical tests that mostly lack geometric information on the absolute height of the test points, since they usually referenced their depth in relation to the surface level.

2 REFERENCE SYSTEM

The municipality of Sevilla covers an area of 142 km² and is located between 5°49'W and 6°02'W of Greenwich and between 37°18'N and 37°27'N of the equator. Since September 2012 the urban development department of Sevilla (Gerencia de Urbanismo y Medioambiente, 2023) has been using the "European Terrestrial Reference System 1989" (ETRS89), which is based on the GRS80 ellipsoid and in accordance with the INSPIRE guidelines. Coordinates are represented in the Universal Transverse Mercator projection (UTM), zone 30N.

However, Sevilla is located on the western periphery of UTM zone 30N and on the eastern periphery of the neighbouring zone 29N, causing distortions in distances, both in x and y direction, between 40 and 50mm per 100m (Figure 1). We chose the coordinate system of UTM zone 30N because the main part of the city falls east of the 6th degree of longitude west of Greenwich and thus in UTM zone 30N. The resulting distortions between ellipsoidal and projected distances had to be accepted to comply with Spain's official reference system, which also uses ETRS89 in conjunction with cartographic projections in UTM zones.

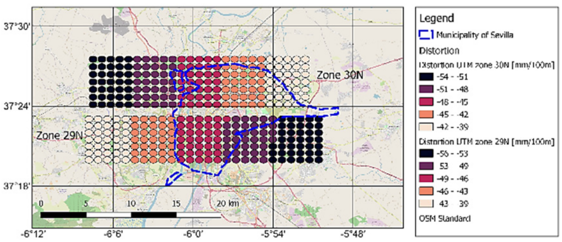

Figure 1: Distortion of UTM zones 29N and 30N at the city of Sevilla. Distortion values are given in mm per 100m and they are identical in x- and in y-direction at one location because of the conformal Transverse Mercator projection.

The official Spanish cadastre states that: "Cadastral mapping has a nominal precision of +/- 0.5 m in urban and +/- 2 meters in rustic. This precision is sufficient in most cases" (Dirección General del Catastro. Gobierno de España, 2023).

However, the development of a voxel model for the subsurface of the city of Sevilla (Spain) raises the question of whether such an accuracy requirement is adequate for geotechnical concerns. Volume calculations of the subsurface rely on the results of the area calculations on the surface and the strata depth data. Any distortions in distance measurements will inevitably lead to inaccuracies in area calculations. Furthermore, the depth values are provided without such a scale, which can cause a distortion between horizontal and vertical dimensions in the voxel model. For these reasons, a specific reference system was defined for the geotechnical project.

To ensure accurate area and volume calculations, an equal-area projection is necessary. The Lambert azimuthal projection was used for this purpose. The centre of the projection should be within the urban territory and was set to 37°24'N and 6°00'W (Figure 2). The GRS80 ellipsoid was used as the reference ellipsoid which aligns with Spain's official reference system.

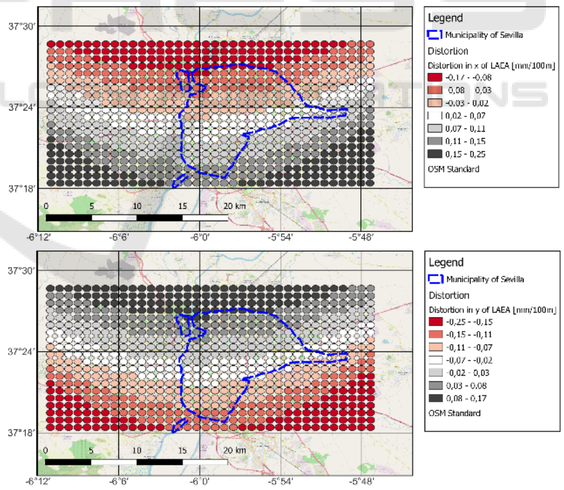

Figure 2: Distortion of the Lambert azimuthal equal-area (LAEA) projection in a) x-coordinates, b) y-coordinates. Distortion values are given in mm per 100m.

By using the Lambert azimuthal equal-area (LAEA) projection, distortions are minimized to less than 0.2mm per 100m distance (or 2mm per km) within the territory of Sevilla (Figure 2). The chosen projection therefore allows for the creation of an inherently true scale voxel model for the city of Sevilla.

3 REGULAR ANALYSIS GRID

A regular grid is frequently utilized in geotechnical analysis. In statistical analysis, for instance, point density is based on statistical units of equal size. Another application is the organization of tiles of a digital terrain model with equal sizes.

Based on the coordinate reference system LAEA-Sevilla described above, a regular grid with three zoom levels is defined. Zoom level 1 uses a 10 x 10 km cell size starting each cell at rounded coordinates (Figure 3: top). The numbering of each cell refers to the coordinate values of the upper left corner, rounded to 10 km. Grid cell 5030, for example, covers the range in x between 500000m and 510000m and in y from 290000m to 300000m. A coordinate-based numbering system is the most flexible option, as a 10km grid can be extended, without the need to rename existing cells if necessary.

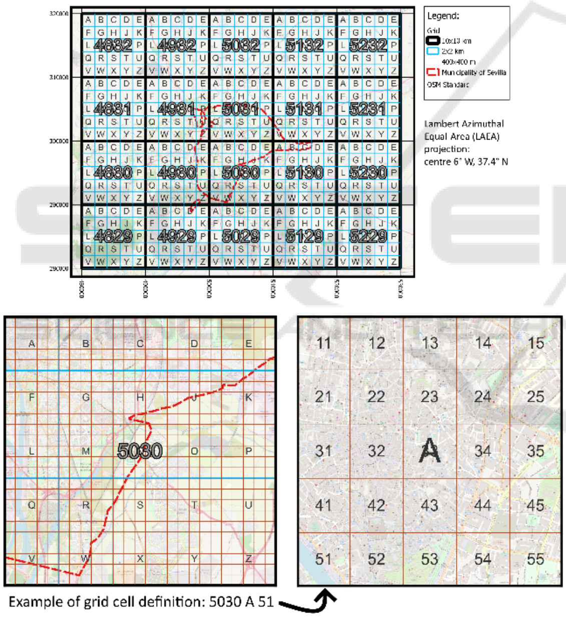

Figure 3: Definition of a regular grid with three zoom levels: Level 1 (10x10km), Level 2 (2x2km), Level 3 (400 x400m). The grid based on the coordinate reference system LAEA-Sevilla.

Each cell of Zoom level 1 is subdivided into 25 cells with a size of 2km x 2km (Zoom level 2). The cells labeled with characters starting with ‘A’ in the NW corner and continuing row by row from north to south until character ‘Z’. Character ‘I’ is not used to avoid any confusion with character ‘J’ (Figure 3: bottom left).

For large scale studies a third Zoom level 3 is used with a cell size of 400x400m. The 25 cells are labelled through numerical codes in such a way, that the first number refers to the relative cell position in the y-direction and the second number refers to the position in x-direction. Therefore, labelling of Zoom level 3 starts with ‘11’ and ends with ‘55’ (Figure 3: bottom right).

The combination of the label for each zoom level provides the complete information about the position of the cell. Grid cell 5030 A 51, for example, covers the square area from point (500000.00, 298000.00) in the SW corner to point (500400.00, 298400.00) in the NE corner.

Per definition, locations falling exactly between two cells are assigned to the eastern cell and the southern cell, respectively. This means, for example, that a point at location (500000.00, 300000.00) falls into cell 5030 A 11.

4 ELEVATION DATA

There are two primary sources of altitude information for the urban area of Sevilla and the surrounding countryside: cadastral survey points and LiDAR measurements taken from an airplane (Centro Nacional de Información Geográfica, 2020). Based on LiDAR measurements from 2012 to 2022 (containing UTM coordinates and ellipsoidal heights) a DTM has been created by the National Geographic Institute and the National Center for Geographic Information in Spain (*Instituto Geográfico Nacional (IGN) / Centro Nacional de Información Geográfica (CNIG) (Mº Fomento)*). Only filtered ground points have been used to calculate the DTM, interpolating the elevation values of areas covered by non-ground points. In addition, satellite measurements and the digital surface models derived from them are also available: SRTM (National Aeronautics and Space Agency -NASA-, 2013), ALOS AW3D (Japan Aerospace Exploration Agency -JAXA-, 2021) and MERIT (Global Hydrology Group, 2018). These measurements can be used to determine the elevation of boreholes (Table 1).

The vertical accuracy of global Digital Elevation Models (DEMs) is partially dependent on the slope (Uuemaa et al., 2020). For this reason, the MERIT DEM was also used as a data source, as it removes multiple error components and a comparison of global DEMs has shown that in flat terrain the MERIT DEM is more accurate than SRTM (Yamazaki et al., 2017) and AW3D (Uuemaa et al., 2020, p. 9). Comparing the LiDAR based DTM with MERIT DEM results into a standard deviation of ±3.2m (1-sigma range; total grid coverage); the range

Table 1: Data sources of elevation, their Coordinate Reference System (CRS) and reference ellipsoid, horizontal resolution, and accuracy of elevation for the area of the grid as well as for the city of Sevilla and in the rural area.

Source (year)	Type of geometry	CRS	Ellipsoid	Horizontal resolution	Elevation accuracy
IDE Sevilla Redes Topo (2009)	point	UTM 30N	GRS 1980	accuracy ca. ±0.001m	accuracy ca. ±0.001m
Cadaster surveying (2001 to 2017)	point	UTM 29N, 30N	GRS 1980	accuracy ca. ±0.01m	accuracy ca. ±0.01m
LiDAR (from 2001 to 2015)	point	UTM 29N, 30N	GRS 1980	2.00m	±0.15m (max. error <=0.6m)
LiDAR (from 2015 to 2022)	DTM based on filtered ground points	UTM 29N, 30N	GRS 1980	2.00m	±0.15m (max. error <=0.6m)
SRTM GL1 (2000)	DEM	EPSG 4326	WGS 84	1 arcsec (ca. 30m)	±3.4m (city ±3.7m, rural ±1.8m)
AW3D30 (from 2006 to 2011)	DEM	EPSG 4326	WGS 84	1 arcsec (ca. 30m)	±3.1m (city ±4.3m, rural ±1.5m)
MERIT	DEM	EPSG 4326	WGS 84	3 arcsec (ca. 90m)	±3.2m (city ±2.8m, rural ±1.6m)

of the differences, however, falls between -206m because of gravel pits constructed after DEM data collection and +45m because of buildings not removed in the DTM but constructed after DEM data collection. The standard deviation inside the city of Sevilla is approximately ±2.8m due to the presence of the numerous buildings, but in the rural area the standard deviation is much smaller, around ±1.6m.

The AW3D30 DEM is a digital surface model that includes all buildings, bridges etc. This means, that men made features have not been removed in the DEM. As a result, its standard deviation is greater than for MERIT, especially inside the city of Sevilla (Table 1). The same observation can be made for elevation data of SRTM (Nikolakopoulos, 2020, p. 45).

To determine the local elevation for each borehole location, a terrain model of the same time the borehole was measured is required. The most precise elevation data come from altimeter points and LiDAR measurements. However, it is important to note that both sources of data are time-dependent. Additionally, a few building heights not recognized in the LiDAR based DTM as well as altimeter points not representing the terrain should be eliminated.

4.1 Filtering LiDAR Points

Only LiDAR points that are classified as ground should be used to calculate the terrain model. However, some LiDAR points are misclassified as ground although they represent other objects such as buildings or bridges. To eliminate misclassified ground points, the following filter operations can be performed:

1. Select only LiDAR points that are not located within water areas such as rivers, canals, lakes, artificial water tanks and pools. The elevation values of water have been set to ‘no data’.
2. Only select LiDAR points that are not located within huge buildings of unusual shape and roof type that are misclassified as ground points. There are 22 buildings that have been manually identified in the terrain model and their elevation values have been set to ‘no data’.

The result is a terrain surface with 2m horizontal resolution but only including the elevation of the terrain at the time of the LiDAR measurements.

4.2 Filtering Altimeter Points

In this research 504,818 surveying points fall within the above defined area of the grid, but not all of them represent the terrain. In order to filter altimeter points with correct values of the elevation of the terrain, the following filter operations must be performed.

1. Only select altimeter points with TTGGSS 028112.
2. Eliminate points with unknown elevation (height = 0).
3. Eliminate points with incorrect elevation values at surrounding towns that are placed very close to the city of Sevilla as Olivares (constant height = 160m) and Villanueva del Ariscal (constant height = 150m).
4. Eliminate surveying points on top of buildings with an elevation much greater

than the local trend surface based on filtered LiDAR ground points. In this case, the threshold equals 0.5m, which is about 2.5 times of the maximum elevation error of LiDAR.

The elevation of the surveying points can be checked for gross errors through the comparison with the LiDAR based DTM. The standard deviation of the height differences of 1,199 precise surveying points equals ±0.32m. There are 24 points that have a height difference greater than 1m. Most of these points are located on highways and bridges.

The standard deviation of the height differences of 292,926 altimeter points with a supposed precision of 1cm equals ±1.07m (Figure 4). This is due to several points that exhibit a height difference of up to 21m in relation to the LiDAR based DTM. Taking the time of measurement into account there seems to be a trend that the accuracy in the years 2001 to 2003 and 2011 is about ±1m, but much greater in the years 2004 (±1.96m) and 2005 (±1.51m). Most precise are 14 points measured in 2012 with an accuracy of ±0.25m. The reason for this is likely due to the fact that the LiDAR measurements were performed closer to that year than to other years.

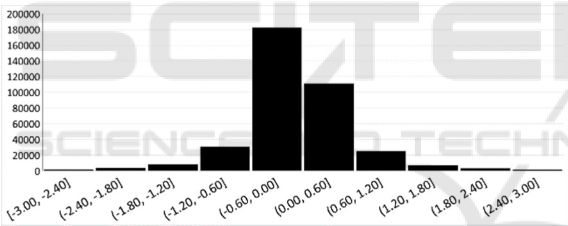

Figure 4: Histogram of height differences between surveying and altimeter points on one side and the LiDAR based DTM on the other (range from -3m to +3m, excluding outliers).

4.3 Correcting the LiDAR Based DTM

Finally, the filtered surveying and altimeter points can be used to calculate a correction for each pixel of the preliminary (LiDAR based) digital terrain surface. Since the elevation values of surveying and altimeter points are more precise than that of LiDAR points (Table 1), we should base the DTM on these elevation data. However, there are many areas without any surveying and altimeter point, especially in the rural areas outside of the city of Sevilla. In these "empty" areas we must rely on the LiDAR points with third highest vertical accuracy.

The cone model of DTM correction enables the calculation of elevation correction at a pixel location in the preliminary DTM using all exact elevation data of the survey points from the surrounding area (Figure 5a). The maximum sphere of influence is described by a cone whose radius depends on the ratio of the accuracy of the LiDAR heights (±15cm) to the measurement accuracy (±1mm and ±1cm).

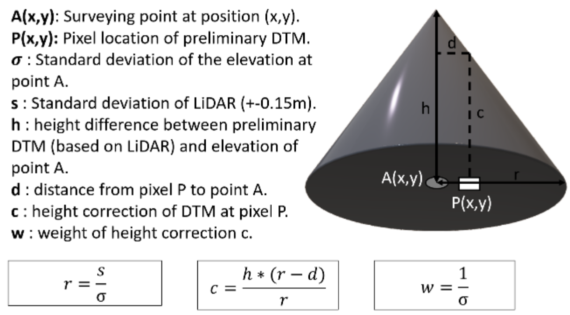

Figure 5a: Cone model of DTM correction describing the method of calculating the DTM correction of a pixel location in relation to a surveying point with a more precise elevation of the terrain. The greater the distance *d* between pixel and surveying point, the smaller is the correction *c*, which also depends on the ratio *r* between both standard deviations of the elevation values. The cone is defined through height difference *h* and ratio *r*. At the centre of the cone the correction equals *h* and is zero at the radius of the cone.

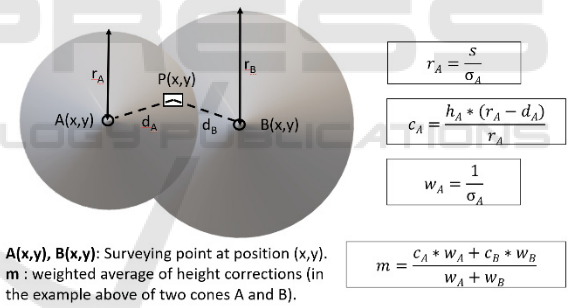

Figure 5b: Overlap of two cones and calculation of the weighted mean height correction *m*.

When cones from multiple survey points overlap, correction values are weighted and averaged based on the reciprocal of measurement accuracy of the measurement and the distance between the pixel and the survey point (Figure 5b). However, the interpolation between a pixel and a survey point should not be carried out across break lines. For this reason, all areas with a slope greater than 30° have been identified as potential breakline areas in the preliminary DTM. The areas surrounding these have been marked and vectorised as terrain zones. By checking whether the interpolation takes place within the same terrain zone and does not intersect any inner breakline zone or the outer boundary, it was possible to ensure that the interpolations do not take place across artificial unevenness in the terrain, such as the boundaries of rivers, lakes, bridges, ramps, docks, and steep ditches. This also includes areas with LiDAR points from buildings that were incorrectly identified as ground points, such as buildings with green roofs or unusual roof shapes.

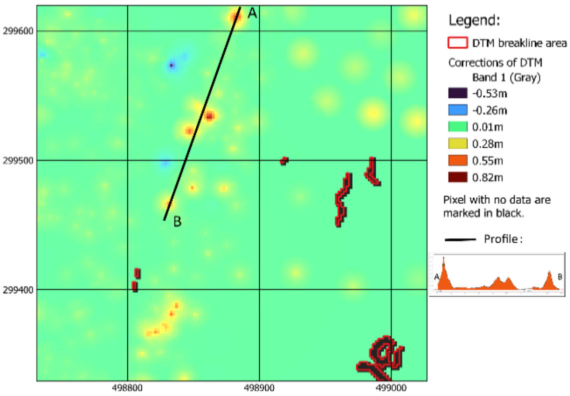

Figure 6: Map of a test area representing the height correction of the LiDAR based DTM.

In a final step the height corrections can be applied to the elevation of the DTM (Figure 6). The result is a digital terrain model with elevation values of mixed accuracy. To address this, the estimated accuracy of each elevation is stored in a second band of the raster file.

4.4 Temporal Aspect of Elevation Data

The ground surface undergoes permanent changes, especially in urban areas with numerous construction projects. Therefore, it is necessity to take the temporal aspect into account when developing a digital terrain model (Figure 7).

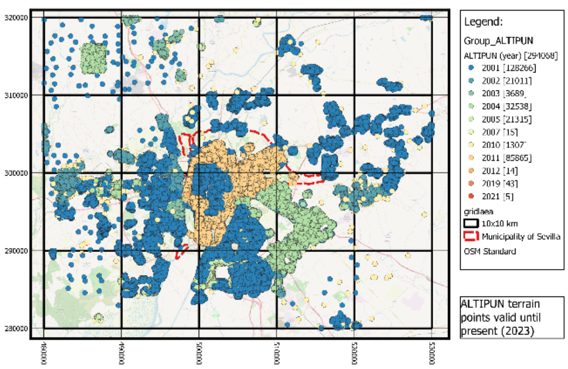

Figure 7: Surveying points with a valid elevation until present (year 2023).

However, the exact time of measurement is in most cases unknown, and we can only provide a temporal range at which measurements were performed. LiDAR data are based on flights between 2015 and 2021, but the surveying work to obtain elevation data was carried out between October 2001 and June 2022. Most of the elevation points, however, were measured from 2001 to 2005 and 2011, making them older than the LiDAR data.

Most of the points at the old city center of Sevilla were surveyed in 2001, but points at the modern part of the city were measured as late as 2011. Surveying points at the towns and villages outside of the municipality of Sevilla were collected between 2001 and 2005. Any gaps without points must be filled up with elevation data derived from LiDAR data to calculate a continuous DTM. The temporal aspect, however, has not been covered in this paper due to its complexity which will be considered in future analyses.

5 CONCLUSIONS

The paper presents a rigorous evaluation of the main factors that affect the problems derived from the creation of a voxel model at a territorial level based on data from the primary sources of height information. In this case, the paper has focused on aspects related to topographic adjustment, but the findings can be applied to future issues related to the integration of subsurface information. In this sense, the definition of a working grid at different scales enables the evaluation of the quality and quantity of the information collected by sector, and the establishment of an efficient work plan. This approach identifies areas with common characteristics and problems that can be solved with shared methods and strategies.

Regarding the creation of a voxel model of the subsurface from the borehole data, an accurate Digital Terrain Model (DTM) is required, which allows us to determine the surface elevation of boreholes. Height information of varying accuracy is available for the area of Sevilla and its rural surroundings, which is used to correct a DTM based on LiDAR measurements. LiDAR data of bridges and buildings often misidentified as ground points must be eliminated in order to improve the preliminary DTM, which is partially representing a Digital Surface Model (DSM) instead of a Digital Terrain Model (DTM) (Figure 8). The challenge here is to develop a suitable method to determine DTM corrections from

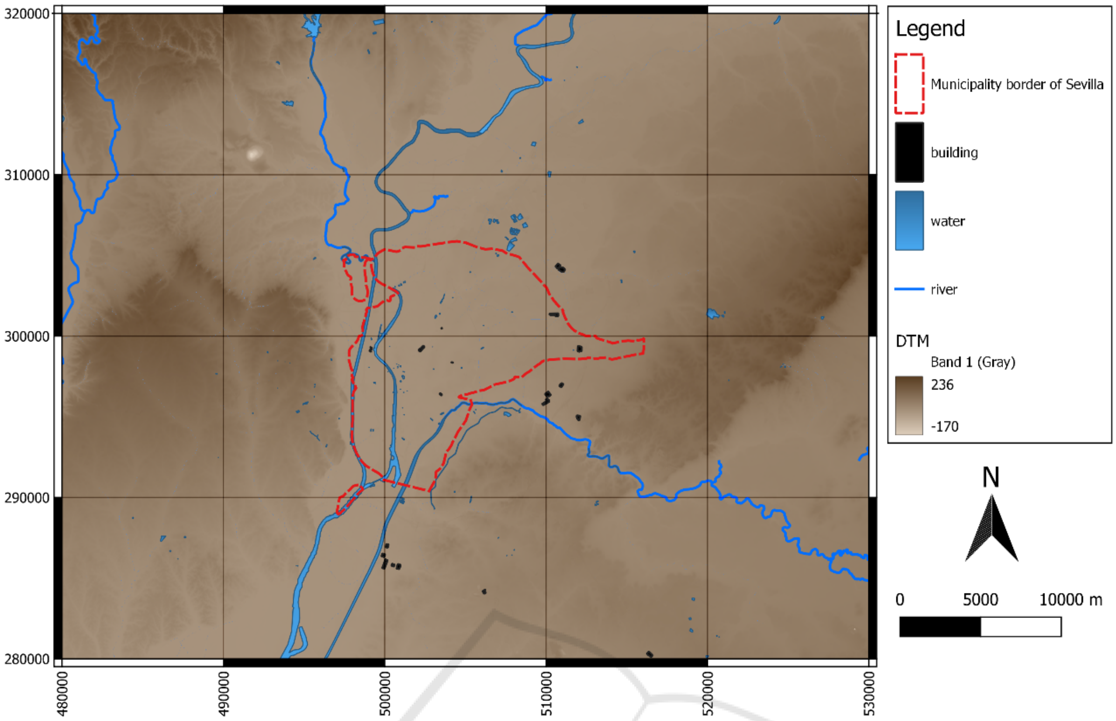

Figure 8: DTM of Sevilla. Water surfaces, rivers, and some buildings are marked as 'no data'.

various height measurements with a different spatial distribution and accuracy. The cone model of DTM correction presented in this paper is a simplified version of a local terrain correction. The method analyses diverging height values from different measurement points for each grid cell in the DTM. However, further investigations are required in order to combine the only punctual available height measurements of high accuracy with the less accurate but area-wide LiDAR data while preserving the terrain profile. The correction of elevation data may require a local trend surface to derive at a smooth distribution of height corrections. Consequently, the improvement of the methodology of incorporating elevation data from various sources and accuracies requires further research.

Finally, it is necessary to mention that the DTM presented in this paper is based on the most recent data valid until now (2023), but the test drillings described in many reports were performed since 1970 until present (2023). Determining the exact elevation of the surface above sea level for each location at the time of the drilling is beyond the scope of the paper. Not only has the terrain been modified over the years, but also has undergone changes due to the construction of basements, underground car parks and metro lines. Therefore, the improvement of the methodology of incorporating elevation data from various sources and accuracies demands extensive investigations.

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SOFTWARE

The calculations and the cartographic outputs were made with the help of QGIS (version 3.28.10) and a PostgreSQL/PostGIS database.

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