From historical map to online 3D recreation: the 1861 cadastral map of Horta (Barcelona)

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The recent study and classification of over 200 cadastral maps created in the nineteenth century in Catalonia have provided a valuable source of information about the agricultural landscape country’s past, but by linking them with data recorded in tax books known as amillaramientos, it is possible to gain a better knowledge of the past. By applying this method to the 1861 cadastral map of Horta and its corresponding amillaramiento, a planimetric map showing the land use distribution in the town was created. The resulting land use map was subsequently overlaid on top of a digital elevation model to create 3D visualizations which show the altitudinal distribution of crops and other features. Finally, the article explores a way of distributing the results online, making them accessible to the public and increasing the research impact of future findings.

Therefore, the method described in this article allows the systematic recreation and distribution of past landscapes by using Catalan cadastral maps of the nineteenth century, something which can help enrich the scientific knowledge of many disciplines.

Keywords: historical cartography; cadastral maps; distributed GIS; visualization; Horta

Introduction

The progressive digitalization of historical cartography by archives, libraries, and map collections has made working with antique maps a real possibility to researchers of many fields, including geographical information science (GIS). A common way of combining historical cartography and GIS is to use current spatial data to georeference digitized paper maps to perform spatial analysis or other cartographic operations, but this is not always a straightforward process. Due to their size, conservation status, or cost, some historic maps are difficult to digitize, leading to geometric errors which can deform the digital product (Daniil et al. 2003). Furthermore, many historic maps lack accuracy and/or precision necessary to be combined with modern referenced data sets as doing so creates important geometrical distortions (Balletti 2006, 32–42). One way of increasing the chances of bypassing these problems is by using cadastral cartography, which due to its nature is usually quite detailed, accurate, and precise albeit usually covering small areas. One of the main advantages of using cadastral information is that it often includes land use information, which can be used in land use change studies, as it provides a picture of what grew where in the past. There have already been several experiences which have successfully managed to integrate past cadastral cartography with current cartographic databases to study land use change in several areas of the world such as Norway (Hamre et al. 2007, 1563–1574) or Germany (Bender et al. 2005, 111–125). These and other examples have shown that combining historic cadastral information and GIS can help improving the understanding of the present by using the past.

Most studies, however, are limited to using georeferenced historic cadastral maps, extracting the information they contain and transforming it into a current data model such as vector or raster. In this article the initial process is applied to a Catalan cadastral map from the nineteenth century to test if similar maps could be systematically processed to achieve a digitized historic data bank, but it does not stop at this point. On the contrary, the article continues by exploring how by combining the map with current elevation data more information about the geometric correctness of the map and altitudinal land use can be obtained. Finally, in order to make the research results available and spur interest by other academics and the general public, a means of distributing the outcome using a web interface is described. Consequently, the article explains the complete process by which a historic paper map is transformed into an interactive online application, giving it second youth and developing new uses to all the data that were once stored in an archive.

Nineteenth-century cadastral cartography in the Barcelona Province

One of the peculiarities of the Spanish tax system introduced in 1845 by the ruling Liberals was the lack of rural cadaster plots. This deficiency affected the Spanish tax system until...
the twentieth century. Thus, in 1846, the Spanish Government began to apply the contribution of properties, cultivation, and livestock tax, which charged agricultural and livestock wealth of municipalities. The tax worked via a vertical spread quota system, with a certain element of arbitrariness, and was collected by the Spanish Treasury (Pro Ruiz 1992).

The quota system meant that the Treasury assigned to each of the different Spanish provinces – with some exceptions – a certain share of money to collect, the amount of which was defined by using vague and sometimes outdated information. Then the heads of the various provincial treasuries distributed the quota allocated to the province between the towns that were part of it. Finally, local authorities were responsible for distributing among local taxpayers a share of the land tax that had been assigned to their town (Vallejo Pousada, 2010, 81–115). Towns had, moreover, the obligation to deliver to the provincial fiscal authorities a document: the town’s amillaramiento or tax assessment. The amillaramiento was a written document created by local authorities who numerically described the list of land and livestock taxpayers who lived in the town, both urban and rural (Llorente Roselló, 2008, 295–346). The information contained in these books allowed public servants to register the fiscal duties of each owner and town (Nadal et al., 2006). The management of this tax soon generated many fiscal conflicts. First, they were created by councils that disagreed with the amount of land tax that had been assigned to them by the provincial Administration of Finance. Second, there were those promoted by provincial Administrations of Finance in order to prevent tax evasion. And third, those sponsored by private citizens who were unhappy with the amount of this tax assigned to them by the councils.

Due to all these conflicts, the government passed a law in 1847 whereby local councils that thought they had been unfairly overtaxed by at least 12% could file a claim before the authorities of the Treasury to adjust the amount allocated to the real amount of farming wealth and cattle the town had (Nadal, Urteaga, and Muro, 2006, 83–109). A year later, the Ministry of Finance created provincial statistical committees nationwide, which were directed by public servants and composed of surveyors and agricultural experts. The function of these committees was to prevent tax fraud in the amillaramientos and to try to resolve tax disputes raised by the new fiscal law (Nadal et al., 2006).

To resolve the generated conflicts, or just to avoid them, many municipalities decided when drawing up their amillaramientos to hire qualified surveyors – known as agrimensores – to measure the different plots in the existing rural municipality. As a result of their work, surveyors generated two different types of tax documents: the “Books of Measurements of Land” and a diverse and rich cartography of the rural composition of municipalities. The first type of documents informed about the number of the plot, the name of the taxpayer, the surface of the plot, and the type of existing crop. In the province of Barcelona a total of 17 Books of Measurements of Land relevant to many municipalities were drawn between 1847 and 1852 (Nadal et al., 2006). The second type of documents contained the same type of information, but in this case expressed as a map. The preparation of land plot maps and atlases was mainly an initiative of municipal nature, but also provincial authorities of the Treasury became involved. All this mapping activity generated three different types of cartographic documents: (1) parcel maps consist of a single sheet, usually of considerable size – like the Horta example – (2) atlas plots consisting of multiple pages, most of them presented bound, and (3) perimeter plans, in which only the limits of the municipality were represented. The latter was prepared by surveyors hired by provincial Administrations of Finance, as they were interested in knowing as fast as possible the exact surface of those municipalities which were thought to defraud the Treasury.

The elaboration of all of this mapping activity was very expensive, which is why many councils only decided to carry it out in case of major conflicts with the provincial authorities or in situations of intense conflict between some of the prominent local taxpayers. In fact, the areas most intensely mapped were Catalonia and the Balearic Islands (Burgueño and Nadal, 2011, 127–141; Rosselló and Rotger, 2011). Between 1849 and 1883 163 rural plot maps of 105 different municipalities were drawn in the province of Barcelona. One area of the province that was the subject of many surveys during this period was the Barcelona plain, which in mid-nineteenth century was populated by a series of small towns like Horta, but nowadays is fully integrated within the current Barcelona city limits. Thus, between 1851 and 1872 seven plot maps of this area were drawn: Barcelona, 1851; Gràcia, 1851, 1872; Horta, 1861; Sant Martí de Provençals, 1853, 1871, and Vallvidrera, 1859 (Nadal et al., 2006).

Since this cartographic project did not respond to any official mapping instruction, the scale and format of the produced maps varies from one province to another. For example, the scale adopted in the majority of cadastral maps of the province of Barcelona was 1:5000, while in the province of Girona it was 1:2500. Moreover, in Barcelona 19 atlases were created, while only two of them have been found in Girona. All the maps that have been found are manuscripts and polychrome. In general, only a manuscript copy of each map has been preserved, but there are some exceptions such as the cadastral map of Barcelona drawn by the architect Juan Soler i Mestres in the year 1851, of which three copies have survived. Most plans contain graphic scales that follow the metric system; although in the early years many of these scales were
expressed in measures such as traditional Catalan cana or the Barcelonese span. With the exception of city perimeters maps, most of these charts have all plots numbered. They also contain abundant and valuable local geographic information, which means that, among other features, the hydrographical network, roads, settlements, the limits of the municipality, or cultural elements such as spas and shrines can be identified. In addition, most of these maps are accompanied by a book or books that record information for each plot such as surface, agricultural use, the taxpayer’s name, soil quality, or the tax levy.

All this mapping was done by a small army of 46 private cartographers, some of whom, like the mathematician Llorenç Preses i Puig or the surveyor Pedro Moreno Ramírez, managed to create and manage enterprises that specialized in carrying out territorial municipal surveys. All these cartographers were not a homogeneous professional group, as they came from different backgrounds, with surveyors being the largest group with 29 members, followed by master builders and architects with 10 and 4 members, respectively. Finally, there were three cartographers who belonged to other professional bodies.

Since all these series of maps were not systematically produced, the current location of the finished product can be found scattered in multiple archives and map collections of both public and private ownership. Even if many maps are preserved in local public archives – such as Horta’s map – there are several map collections that are located in regional or national map libraries. Moreover, there are many that have never been located even after finding evidence of their existence. The reader can get an idea of the situation and geographical spread of this Catalan cartographic documentation by accessing the up-to-date online catalogue of all cadastral maps that have been discovered (Montaner and Nobajas 2011, 281–286).

Integration of a cadastral map with GIS: Horta’s map from 1861

The map of Horta from the year 1861 is one of these cadastral maps and was selected as a pilot to test whether the cadastral maps of this period were suitable to be integrated with current cartography using GIS due to its characteristics, availability, and the fact that it was already professionally digitized. Nowadays Horta is an integral part of the city of Barcelona as it has become one of its neighborhoods, but until 1904 it was an independent rural settlement (Diez i Quijano, Arxiu Municipal de Barcelona, and Barcelona 2005). The town’s city council commissioned the surveyor Joan Serra and Bonet, a recent graduate from the School of Fine Arts in Barcelona, to make the necessary measurements and drawings in order to elaborate a cadastral map of the fields within the town limits (Montaner and Nobajas 2011, 281–286). In 1861 he delivered a map entitled “Plano geométrico del pueblo y término de San Juan de Horta” (Nadal et al. 2006), which is the only cadastral plan known of Horta in the nineteenth century. It is a manuscript map, polychromic, drawn on a scale of 1:5000 and has a size of 105 × 136 cm, of which several copies exist (Diez i Quijano 1982). The surface within the town limits is divided into five sections, which are subsequently divided using the cadastral boundaries, which means that each agricultural plot is assigned to its legal owner. If more than a crop was grown in a single parcel of land, agricultural plots are further divided. Apart from the agricultural plots, the map also has the name of the owner of each parcel, and it represents the municipal road network, the streams and rivers, human settlements, and several place names as well (Montaner and Nobajas 2011, 281–286). Surface measurements in the map are not represented using the International System of Units but in “mujades” and “mundinas,” local units of measurement nowadays deprecated. A last singular characteristic of the map is that it is not oriented to the north, but to the northwest, following the traditional system used in the Barcelona shire by which the Mediterranean Sea is represented at the bottom of the map (Figure 1).

Since the map is an 150–year-old manuscript, obtaining a digital copy of it is a delicate matter as the original map could be damaged in the process. This is the reason why it was considered to be more suitable to take a high-resolution picture of it than the traditional scanning approach. The problem when using a picture is that there is a risk of distortion in the scale of the points furthest from the center of the map. In some cases, as it is the case with aerial photographs, this phenomenon requires performing a photogrammetric restitution to minimize this effect (Imhof 2007). For the map at hand, however, it was not considered necessary to rectify the image since the map itself occupied the central portion of the picture and it was far away from the margins, greatly reducing the levels of distortion within the area of interest.

Integration between historical cartography and modern digital cartographical tools like GIS software – such as ArcMap or QGIS – is not as straight forward as it is with modern maps or data. The process of georeferencing the digitized historical map is critical when displaying historical information within a GIS. There are a series of challenges that can render a historical map as unsuitable for georeferencing like the lack of common reference points between old and new maps, lack of geometrical consistency, or lack of geographical accuracy. If the georeferenced historical map does not comply with those minimum qualities the image may be dramatically warped (Orciani et al. 2007, 92–104), making it unsuitable for a GIS unless major adaptations are undertaken.
The old town of Horta is nowadays an integral part of the city of Barcelona, but 150 years ago it was a rural town which relied heavily in farming to sustain its inhabitants (Nobajas and Nadal 2012, 244–248). Since then, changes in land use have been radical, making it a difficult place to georeference since there are not many common points with other maps whose coordinates are known accurately. In this case, the document used as a cartographic base to georeference the historical map was the 2008 edition of the 1:10,000 topographic map of the Cartographic Institute of Catalonia (Institut Cartogràfic de Catalunya 2008a, 2008b, 2008c, 2008d). Fortunately, some common points were identified; the country house of Cal Mariné, the chapel of St. Cyprian, and the corner between the current Tajo Street and Torrent de Can Mariné Street represented as rivers on the map. Those points, in addition to other topographical control points as the top of the Tibidabo Mountain or the Collserola ridge, helped to georeference the map. The overlap between the old map of Horta and a slope map generated from a digital elevation model (DEM) of the area (Institut Cartogràfic de Catalunya 2011) shown in Figure 2 proves that the final result has been quite positive, as the municipal boundary north of the old town of Horta matches the crest of the Collserola Mountains, which was what defined the administrative divide. Also, rivers digitized from the original map follow almost in a seamless way the lower part of valleys, where streams flow nowadays.

Furthermore, the deformation of the map after its georeferencing is minimal, with a root mean square (RMS) error very close to zero. Therefore the geometric quality of the map drawn by the surveyor Joan Serra in 1861, even if it lacks a projection system, is remarkable. The overlap of the old map of Horta with modern base maps, like Google Maps or the Catalan Cartographical Institute topographic maps has attested that the outcome of the georeferencing is almost entirely coincidental, mainly thanks to the drawing and technical abilities of Joan Serra.

The next step in the GIS integration process was to manually digitize the map into different layers to allow performing spatial analysis as Figure 3 shows. Once created, the layer containing the plots was linked with information obtained from the correspondent amillaramiento. Inconsistencies between the original map and the amillaramiento were found, some of them understandable because the amillaramiento is a year older than the map, some due to typing errors, and some arbitrary (Nobajas 2011a, 237–248). Once the map had been
linked with the information of the amillaramiento, it was ready to be integrated with an elevation model and to perform analyses. It should be noted that while the map was created in 1861, the information gathered in the associated amillaramiento was written in the following year (Ministerio de Hacienda. Delegación Provincial de Barcelona 1862), so even if the map dates from 1861, the information relating to owners or land use corresponds to 1862, a fact that has led to some minor discrepancies between both works (Nobajas 2011a, 237–248).

Combining nineteenth century Catalan historical cadastral data and DEMs

The integration of Catalan cadastral maps with geographical information systems is quite novel as the discovery and classification of the series of maps has mostly occurred in recent years (Nadal et al. 2006). Some of the first experiences in integrating Catalan historical cadastral maps and GIS were carried out to explain landscape evolution by comparing them with more current cadastral maps (Parcerisas 2008, 67–79; Badia-Miró and Rodríguez 2007, 177–186). The first studied area was the Maresme shire, a region that has experienced dramatic changes in the last 150 years as it has evolved from being a mainly rural area to becoming densely populated and one of the Catalan tourist hot spots (Parcerisas i Benedé and Vilassar de Mar 2010). The area that nowadays falls within the Barcelona city limits has also been studied in search of landscape changes (Font Casaseca 2008, 383–392). The methods followed by all these existing studies are similar to the one previously described in this article, which consisted in digitizing the land parcels and then linking them to the information located in the amillaramientos to obtain spatial land use and property data. What previous work had not done was linking the newly created data with DEM, and in many cases, they did not georeference the maps, greatly limiting their analysis, visualization, and distribution potential.
The original map from 1861, as all Catalan historical cadastral maps, is planimetric so it does not provide information about the terrain’s altimetry. However, when linked with the appropriate data, the newly created layer can be visualized in 3D representing the relief of the mapped area (Orciani et al. 2007, 92–104). To graphically represent the altitudinal distribution of Horta’s land use a DEM was utilized. Since the scale of Horta’s map is quite large, a highly detailed DEM was used with a resolution of $15 \times 15$ m and an altitudinal average quadratic error of 0.9 m (Institut Cartogràfic de Catalunya 2011), provided by the Cartographic Institute of Catalonia (Institut Cartogràfic de Catalunya 2010).

It is when combining the DEM, which in this case was provided by an ancillary institution, with the primary data created from the historic map that its georeferencing quality is put to the test. If either the geometrical or geographical quality of the original map is low, or the precision of the georeferencing is not good enough, the overlay of both layers will show it. However, in this case, both the original map and the georeferencing process were of an adequate quality, as the correct overlay between the physical characteristics present in the DEM and the digitized features from the map shows (Figure 2). Another issue when overlaying historic cartography with a current DEM is that the relief of the area may have changed. While it is unlikely that large structural geomorphologic changes have taken place in the 150 years which have passed since these maps were drawn, there is a chance that smaller modifications of the landscape have occurred. However, the most noticeable changes can be produced by human activity, especially in an area as densely populated as the Barcelona plain. For example, the DEM clearly shows a trench that corresponds to the B-20 urban motorway (Figure 4), which was completed by the 1992 Olympics (Waldheim 2006). Nevertheless, apart from the motorway, the area covered by Joan Serra’s map has not suffered big changes which could change the 3D recreation of Horta’s past.

Once the geometric and geographic appropriateness of the historical map and the suitability of the DEM have been assessed, both layers can be put together to convert a planimetric map into one with relief, so historical 3D reconstructions can be created. These representations can be made directly with the DEM raster layer or by converting it into a Triangulated Irregular Network (TIN). In this study case, both ways of representing relief have been used to compare the visual results, and while there are advantages and inconveniences when working with one type of data or the other, the final visual result does not change greatly.

The influence of elevation in past environments

While digitizing agricultural plots and linking them to their corresponding land uses from the information contained in the amillaramientos on a 2D environment is...
already an achievement, which can be used to improve the knowledge of the past, adding a third dimension greatly increases the level of understanding of how past environments were. Scholars from many different fields can use the information contained in these 3D recreations as they can be a window to the past, allowing studying how landscapes have evolved in the last 150 years and giving a deeper knowledge of how these areas were like in the past. For example, having information about the elevation at which different crops were planted can give an indication of the prevalent climatic characteristics of the area in the past. Even if a similar information could be used without the use of 3D visualizations by using a 2D DEM, the final result provides a much easier way of interpreting results as there is less need of abstraction. In fact, the use of 3D technology can be the base in which future interactive recreations are designed.

In Horta’s case, the influence elevation had in the land use distribution can be quickly observed by presenting a series of short examples. First, it shows that the former municipality of Horta had two differentiated parts; one corresponded to the basin of the Horta brook, and it was where the town of Horta sensu stricto was located. The second area corresponded to the left side of the Vallcarca brook basin, and the main settlement there was the Vallcarca hamlet. The area covered by the Horta brook basin was the largest, and it held the main settlement within the city limits, together with many isolated country houses. On the other hand, the Vallcarca zone was on the other side of a small mountain ridge and had a quite smaller area, so it only held one hamlet and a few isolated houses. As Figure 5 shows, the division between both basins and population areas was so significant that when the town of Horta became a part the city of Barcelona it was included in the Horta-Guinardó district, while the Vallcarca zone was annexed to the district of Gràcia which historically had been a completely different town. A second piece

Figure 5. Old town limits of Horta, current Barcelona districts, and built areas. The Vallcarca basin has been annexed to a different district, in part due to its orographic characteristics. River layer created from the current DEM.
of information that can be extracted from Figure 5 is that the distribution of the population follows a clear altitudinal pattern, in both the Horta and Vallcarca sectors. Largest settlements were located on the lowest parts of the town, where streams crossed the old town limits, while isolated country houses could be found in higher areas usually near waterways. However, the highest parts within the city limits did not have any buildings whatsoever.

If land use is analyzed together with a 3D model, it can be easily observed that there was a clear altitudinal distribution of crops. As Figure 6 shows, in 1861 Horta’s land use followed a traditional three-ring pattern, as it was common in the ancient regime’s European rural areas. Orchards were located near the village, cereals and vineyards were a bit furthest away, and forest and land were in the areas further away from the town or where access was difficult (Ruiz Montejo 1998, 107–124). As the visualization of the cadastral map shows, the areas within immediate reach from the town mainly had orchards, and fruit trees, while cereals were predominantly located on the flat areas of the town. Vineyards, on the other hand, were located on steeper slopes but at an intermediate distance from the village. The highest and steeper areas within the city limits were predominantly forests and uncultivated land. This land use distribution, which still followed the preindustrial scheme, was therefore greatly influenced by altimetry, so a relief representation greatly helps to identify this trend. It should be mentioned that those lower areas that are represented as uncultivated land were presumably former vineyards that had perished due to the powdery mildew (Uncinula necator) outbreak that ravaged Catalonia during the years previous to the drawing of the map (Nadal and Urteaga González 2008, 39–60).

The last chosen example to illustrate the importance and usefulness of combining historical cadastral cartography with elevation models is that allows observing trends in the evolution of land use and the influence elevation and slope has had on them. Between 1862 and 2003 the area that was included within Horta’s town limits has experienced dramatic changes. As Figure 7 shows, in 1862 the populated area represented a very small portion of the available land and was circumscribed to small areas at the bottom of valleys, while at the beginning of the twenty-first century all low and flat areas have been colonized by the urban fabric. This change of land use has meant that all agricultural land has disappeared under a layer of tarmac and buildings. On the other hand, higher and steeper areas have remained almost untouched by the urban sprawl. Those parts are still forested, while some of the land classified as barren has become either forested or shrubland.

Even if just descriptive examples, the cases shown here prove that elevation and topography are factors that must be taken into account when studying past landscapes. It is therefore clear that giving a third dimension to the digitalized cadastral map can help identifying previously unknown trends and patterns, providing a deeper knowledge of the area covered by the cadastral map. However, all the methods described up to this point have been designed to run on local GIS systems, which greatly limit the access to the results to people who have experience with digital cartography. If results could be distributed on-line, members of the public would have access to the information and even perform their own analyses.
Distribution of historical geographical information online

With the advent and popularization of distributed cartography (Ormeling 2010, 1–16), Internet-based maps have become ubiquitous, and the user base is virtually anyone with an Internet connection (Peterson 2013). The increasing ease in the use of digital cartography allows distributing research results online so society can benefit from academic studies. When distributing planar cadastral cartography using an online mapping service, the amount of options available is very broad. There are several proprietary providers of distributed cartographic services like Google Maps, Bing Maps, Yahoo Maps, or Apple Maps, which volunteered open source projects such as OpenStreetMaps or OpenLayers and WMS, all of which can be used as a way to display the cadastral data. However, when dealing with distributed 3D visualizations the available options shrink. While there are products such as NASA’s World Wind or Marble which could also be used, it was decided that the best option was to use Google Earth for two reasons, its high popularity (Yu and Gong 2012, 3966–3986) and its web browser plug-in (Google 2013). The plug-in allows accessing the information in a customized and easy way, as it is not necessary to install the software, while keeping all the rendering and interaction capabilities Google Earth has. Also, it allows working with Keyhole

Figure 7. Land use change in Horta (1861–2003). Pink – urban, yellow – agriculture, grey – barren, light green – shrubland, dark green – forest, red – roads.
Markup Language (KML) files, which are an Open Geospatial Consortium (OGC 2008) standard.

Distributed GIS allows sharing historical findings with users worldwide and overlaying them with current aerial imagery. To achieve this purpose, an interactive web application that allows the virtual reconstruction of Horta in 1862 was created and made public on the Internet (Nobajas 2011b). The application uses the Google Earth web browser plug-in to disseminate the results of the work described throughout the article. It allows not only navigating the 3D recreation, but it also permits adding or removing layers to see, for example, past streams or paths overlaid with current imagery of the area (Figure 8). Since the potential audience to these types of recreations is virtually anyone, a clearer visual representation is needed. This is why on top of the choropleth map representing variables; 3D models were added, allowing an easier interpretation of the results (Figure 9). These 3D models were created within a desktop GIS and exported as a KML file which could be opened within Google Earth, but they were also added to the web browser service. By using the tools provided by the distributed version of the research, and since they are quite straightforward to interact with, people from outside the academic community can visualize how the area was decades ago. Potential educational uses include studying the former path of rivers which nowadays run below the street level, exploring urban growth or the local history of the area, just to mention some.

Figure 8. Old Horta perimeter and streams on top of a current aerial photography within Google Earth’s plug-in.

Figure 9. Online recreation of the old town of Horta in 1862.
Limitations and future research

The methodology and results described are quite successful in extracting and distributing historical cadastral information, but they have a series of limitations that should be noted and improved in future research. The main limitation the method has is that it is extremely time consuming, as all the digitalization of the old map has been done manually. This has meant digitizing over agricultural 300 plots and all the features present in the map like roads, streams, or settlements, a process that due to the manuscript nature of the map requires a lot of attention to detail and limits the possibilities of automation. If the process was replicated with other Catalan cadastral maps the amount of time required to achieve it would be vast. The fact that the creation of those maps was not centrally planned meant that as many as 46 different cartographers authored cadastral maps in Catalonia (Montaner and Nobajas 2011, 281–286), each one using a different technique and symbology to create their maps. This heterodoxy in the map characteristics means that designing and creating an automated algorithm which extracts the cadastral map features is very difficult to attain, a challenge that would be increased due to the bad condition some of the maps have and which would require them being restored. However, even if a method to automate the digitizing process was found and all maps were successfully restored, in order to provide information about the land use, it is necessary to link them to the information contained in the amillaramientos, which are also manuscript. It would be therefore necessary to digitize all amillaramientos as well, a task which should be endeavored by public institutions, since they are kept in public archives and they contain public fiscal information. Digitizing all the information contained in the amillaramientos would be useful not only to people working in mapping and GIS but also to many researchers from a wide array of disciplines who would benefit if they were made easily accessible.

The second limitation that could be improved in future models is increasing the visual appeal of the 3D recreations. In order to reduce the visual angularity and crudeness of the final results, more detailed elevation models should be used. In this article a 15 m resolution DEM was used (Institut Cartogràfic de Catalunya 2011), but more detailed elevation models for Catalonia exist and could be used to smooth the generated 3D surface (Instituto Geográfico Nacional 2013). Together with the increase of the coverage quality, more detailed and historically accurate 3D models could be used to improve the recreation of the past. Even if the buildings rendered in 3D which have been used to improve the quality of the visualization are very similar to stereotypical nineteenth century Catalan edifications (Figure 10), no research has been carried out to precisely recreate the urban fabric of Horta. In order to have a full recreation of that area, it would be necessary to create 3D models of all existing buildings which in 1861 already existed and fill the empty spaces with data from archaeological and archival research. This way the urban fabric of Horta would be correctly represented and the visualization quality would greatly improve.

Conclusions

There are many well preserved maps from before the Digital Revolution, but many of them have yet to be digitized and georeferenced. Once the information they contain has been extracted in a format compatible with GIS, spatial analysis, past representations, or land use evolution analysis can be carried out. However, the process is full of challenges; historical maps have to have a minim degree of geometrical correction to avoid...
unbearable map deformation. There must also be common recognizable points with modern cartography to achieve a proper integration within GIS. In addition, unless an automation system can be used – for example, if maps from the same series are digitized – it is a time-consuming process since each layer has to be digitized by hand.

Nevertheless, once a historic map has been successfully integrated within a GIS, it can be used to perform spatial analysis of past periods, to visualize historical data in a non-planar way or to distribute it online. The potential for geographers, historians, economists, or anthropologists when using GIS together with historical data is almost unlimited (Knowles 2002). The Horta case presented in this article shows that integrating Catalan cadastral maps from the nineteenth century with a GIS is possible due to the high geometrical quality of the maps created by the agrimensores. If a systematic digitalization, georeferencing, and vectorization of all the nineteenth-century cadastral maps found in Catalonia were carried out, a magnificent source of information would be made available to researchers of many fields.

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