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Assessing the Planimetric Accuracy of Historical Maps (Sixteenth to Nineteenth Centuries): New Methods and Potential for Coastal Landscape Reconstruction

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Assessing the planimetric accuracy of historical maps (sixteenth - nineteenth centuries). New methods and potential for coastal landscape reconstruction.

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Abstract

Historical maps are a vital tool for landscape reconstruction from the late medieval period onwards. However, the planimetric accuracy of local and regional maps before the nineteenth century CE is often considered problematic. This paper proposes a method for evaluation of these maps, through integration in multiple computer programs like *ArcGIS*, *MapAnalyst* and statistical software (*SPSS*). This method was tested on a sample of historical maps depicting coastal landscape change in an area in present-day in the Dutch-Belgian border (ranging from the local to the supraregional level and from the sixteenth to the nineteenth centuries CE), and variations in planimetric accuracy over time were interpreted. Results point to an exceptionally high accuracy of earlier medium and large scale maps – scale being the first determinant of planimetric accuracy – since no significant rise in accuracy over time was found. Notwithstanding this overall accuracy many maps display pronounced local distortions. However, rather than disqualifying the map for landscape reconstruction, systematic analysis of these distortions can help to facilitate the interpretation of the historical map and its use for landscape reconstruction. Finally, a method for integrating map accuracies in landscape reconstructions based on multiple maps is proposed and illustrated.

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1. Introduction

For spatio-temporal modeling of landscape evolution, research usually relies on three types of data, depending on the time-frame chosen for the analysis. For more recent landscape evolutions (last decades to a century), accurate sources like satellite data, aerial photography, digital elevation data etc. are available, while long-term (for instance covering the Holocene) evolutions can be studied through the soil archive or using geophysical methods[3]. For mid-term analysis (from about 1400 CE till present) we dispose of a valuable alternative: historical maps. Although historical maps, especially those older than 1850 CE are often admired as pieces of art, they are scarcely used as sources to reconstruct landscape change in the past, mainly because of their heterogeneous quality and the uncertainty regarding scales, projections, mapping techniques, conditions of surveying etc. One vital component of the quality and usefulness of these historical maps is the planimetric accuracy, regarded as a key part of overall cartographical accuracy (Hu, 2010; Jenny and Hurni, 2011; Manzano-Agugliaro et al., 2013). Before using these maps, one should know how well distances and locations on these maps correspond to the actual distances and locations of corresponding (present day) features.

Knowing this accurateness, it is possible to evaluate the likelihood of a reconstruction to be accurately displaying the former area. Reliable reconstructions of historical landscapes are of prime importance to both archeologists, landscape planners and environmental scientists. Especially for those landscape features that are no longer visible in the landscape, but might be preserved in the underground, historical maps are often the most important sources. In this article we will present a time-efficient method of assessing the accuracy of historical maps. As we will argue, accuracy-assessment might significantly enhance the potential of historical maps for landscape reconstruction. Furthermore, our sample data also indicate that the (planimetric) accuracy of older local maps, produced before 1850 CE, often (but not always) equals the level of accuracy reached in the nineteenth century CE, which again pleads for the integration of such older and often overlooked maps in landscape analysis, archeology, history and planning, provided that their accuracy has been assessed.

The test-case developed in this article, focuses on coastal landscapes. Coastal areas are often prone to rapid change either induced by natural processes, like changes in sea-level or sediment distribution or due to often intense human pressure, which seems a permanent feature of many coastal areas over the last two millennia. The challenge of anthropogenic sea-level and climate change further pressures research to investigate coastal change in the past (Thoen et al., 2013; Woodroffe and Murray-Wallace, 2012). A systematic use of historical maps to reconstruct coastal or estuarine change has the potential to add an important level of analysis in our understanding of coastal evolution, but efforts to do are usually limited to the post-1850 period, precisely because of the uncertain regarding the accuracy of older maps (Thieler and Danforth, 1994).

1.1 Cartographical accuracy

In this article we will extensively use and analyse cartographical material, focusing on the planimetric accuracy of maps on various scales, and ranging over a time period from the sixteenth to the nineteenth century CE. When referring to accuracy, we will use definitions supplied by Blakemore and Harley who distinguish three main elements of the accuracy of historical maps: topographic, chronometric and geometric accuracy. The first aspect concerns the quantity and quality of the depiction of landscape features, the second aspect involves the correspondence of date of manufacturing/depiction of the map and *the termini post quem* and *termini ante quem*[4] of the features depicted in the map. The third aspect, subject of this study, comprehends both geodetic accuracy (referring to the positioning of a map in a global coordinate system) and planimetric accuracy (referring to distances and angles/directions as depicted by the map versus real distances) (Blakemore and Harley, 1982; Laxton, 1976). However, different terminologies for the geometric accuracy have been used in the past. In this paper we only refer to *planimetric accuracy* (as a part of the geometric accuracy) of a series of maps, since we do not assess the positioning within global coordinate systems.

In doing so, we try to offer an answer to questions which already arose in the 1960s: ‘Among the yawning gaps in work on cartographic history, is the lack of precise information about map accuracy’ (Imhof, 1964, pp. 141-44; 52, as cited by for instance Ravenhill and Gilg (1974, p. 48)) and ‘The process of evaluating the accuracy of maps is an ultimate goal of cartographical scholarschip’ (Harley, 1967, p. 9). Until very recently, Harvey’s call to investigate accuracy of older maps met with little response, a bit surprisingly especially seen the advances in computer aided analysis and more specifically the development of GIS (Geographic Information Systems) since the 1980s, which revolutionized spatial analysis in every discipline, including coastal research and history (Bodenhamer et al., 2010; Gregory and Ell, 2007; Knowles, 2008). And, moreover, most previous work on cartography and accuracy assessment concentrates on 'national' or regional maps overlooking the large scale local maps[5]. These are two issues on which this paper wants to elaborate.

1.2 Previous research on planimetric accuracy

As mentioned above, the debate on map accuracy was already opened in the 1960s. Early methods of estimating the planimetric accuracy are used by for instance Bönisch (1967, pp. 67-68) who proposed a very simple, but adequate, methodology for calculating mean positional errors by measuring a number of distances between points on the map, and comparing them by the real distances (based on a modern map). Other authors estimated latitude and longitude locations of points on a historical map which contained a regular geographical grid and compared those with the actual present-day latitude and longitude (Ravenhill and Gilg, 1974) or the length of line segments on historical and present-day maps (Yerci, 1989), alternatively done by line-point comparison (Locke and Wyckoff, 1993). A more elaborated analysis was conducted by Hooke and Perry (1976), who used both area, scale bars, straight line distances and the lengths of standard survey lines in order to investigate the accuracy of tithe maps used for taxations. Visual point-by point-comparisons were also made, using for instance churches as reference points by Laxton (1976). Other authors statistically analysed error vectors, generated through comparing transformed historical shoreline maps using Euclidian regression[6] (Lloyd and Gilmartin, 1987). Combinations of different formulas expressing the errors, together with regression analysis, were also made by Murphy (1978). The development of desktop GIS (Geographic Information Systems) from the 1980s onwards provided new possibilities for the evaluation of planimetric accuracy (Hu, 2010). Historical maps could now be directly overlaid with geo-located modern maps using geo-rectifying tools supplied by the GIS-system, possibly resulting in both analytical and graphical evaluations (Liveratos, 2006). Combining historical map-data and (more accurate) modern data of course requires more detailed insights in this accuracy (Skaloš et al., 2011; Timár et al., 2008). This led to several new studies on accuracy, for instance on regional maps using sinuosity measurements (Pearson, 2005) and sometimes even on a local scale by for instance Hu (2001), who assessed the *Map of the Prefectural Capital* of 1261 on its accuracy, still by using the method as described by Bönisch (1976), but now integrated in a GIS which facilitated the accurate measuring of distances and calculation of distortions in distance and rotation. Even some specialist software like *MapAnalyst* was developed (Jenny et al., 2007) and applied (Bower, 2009). All authors tend to use their specific methods, which makes results of the above mentioned studies interesting, but hard to compare to each other since the choice of methodology heavily influences − for instance − the calculated values.

Whoever tries to assess the planimetric accuracy of historical maps, automatically encounters certain difficulties. The largest issue[7] concerns the projection systems of historical maps (Laxton, 1976; Liveratos, 2006; Pearson, 2005, p. 20). Since this projection system is almost never mentioned on a historical map, mistakes are induced when we compare a historical map to a present day map[8]. Therefore, cartographers have tried to find (complex) solutions, often using a GIS as tool for analysis. Pearson (2005) described a possible solution by using sinuosity, unfortunately not applicable on for instance point features. Alternatively, Jenny and Hurni (2011) uses a trial-and-error method, based on probable projection systems and their specific parameters[9]. However, a satisfying solution remains elusive, let alone a solution that was applied to a series of maps over a large time period. This paper does not want to offer a method for reducing these projection-related problems, but relies on the fact that the induced errors are mostly small in case of medium and large scale maps (that form a large part of our database) and smaller areas: 'for the study of old maps, the influence of the geodetic coordinate system (i.e. the shape and position of the reference ellipsoid) can often be neglected, as the influence of mismatching geodetic coordinate systems is often small compared to the inherent planimetric distortions of the map' (Jenny and Hurni, 2011, p. 409). Furthermore, most land surveyors and map makers were not specifically interested in projection systems, but simply wanted to depict the real distances as accurate as possible (Laxton, 1976, p. 52).

1.3. Objectives

Summarizing: notwithstanding the rise of GIS[10] in historical research, the questions arising when integrating data with different accuracy levels and the opportunities of the computer aided methods surprisingly did not generate a real 'boom' of accuracy studies. Furthermore, systematic comparisons of the planimetric accuracy of a large series of historical maps depicting the same region over a longer period of time are absent. As a result, the uncertainty on the accuracy of historical maps remains high, and its inherent potential for landscape reconstruction on a time-scale of several centuries is not fully explored. This paper aims to evaluate the planimetric accuracy of a series of thirty maps for a coastal region in Northwestern Europe: the *Waasland* polder region, which is part of the Scheldt Estuary in Northern Belgium and the southwestern part of The Netherlands. The area offers an excellent test-case since historical map production took place with large intensity in this area from the sixteenth century CE onwards. Keeping in mind the above mentioned drawbacks of accuracy assessment, we aim to introduce new perspectives on map accuracy assessment by comparing a large number of maps, using a uniform methodology and using the opportunities given by GIS and specialist software *(MapAnalyst)*. In the last part of the article, we will develop a test-case showing how a more reliable assessment of the accuracy of the historical maps, allows to achieve better localisations of historical landscape features depicted on these maps.

2. Materials and methods

2.1. Study area

For this paper we will focus on local and regional maps of the *Waasland* polder region, accompanied by small scale maps depicting the (entire) Scheldt estuary (SW Netherlands and Belgium). The *Waasland* polder region is demarcated by the Dutch-Belgian border in the northwest and sandy soils in the south and forms a part of coastal Flanders (see figure 1). North of this border the former *Hulsterambacht* was found.

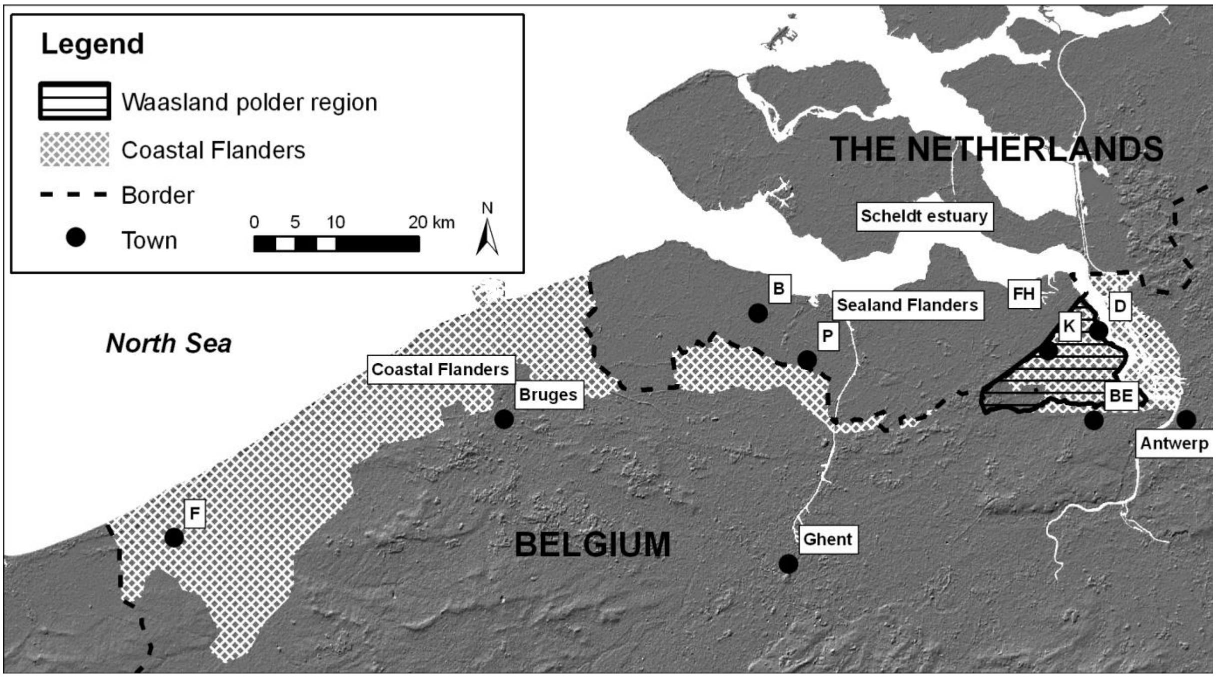


Figure 1. The Waasland polder region, Scheldt estuary, Sealand Flanders and Coastal Flanders (Place names mentioned in the text are indicated. F=Furnes; B=Biervliet; P=Philippinen; FH=former Hulsterambacht; K=Kieldrecht; BE=Beveren; D=Doel).

The *Waasland* polder region formed the northernmost part of the County of Flanders during the medieval and early modern period. Following the Eighty Years War and the Treaty of Munster (1648), the region was divided between the Dutch Republic in the North and the Habsburg Netherlands in the south. The environmental history of this region is dominated by the estuary of the river Scheldt. From the mid Holocene (c. 5500 BC) the area was gradually turned into a freshwater marsh and covered with a thick peat layer. In the Roman period, renewed tidal intrusion of seawater and human exploitation of the peat, resulted in a gradual drowning of this peat, and the conversion of the region into an estuarine landscape consisting of tidal channels, mudflats and salt marshes. In their turn the latter were gradually embanked from the high Middle Ages onwards (Vos and van Heeringen, 1997). During the late Middle Ages the Scheldt polder region, just like the rest of coastal Flanders, was heavily hit by the economic and demographic crisis, acerbated in this region by increased storm surge flooding and so-called military inundations of land in periods of civil war in the last quarter of both the fifteenth and the sixteenth centuries (Soens, 2011). Subsequently, the region was gradually re-embanked, mainly under the influence of absentee landowners (often residents from Antwerp) and, from the late seventeenth century CE onwards the Arenberg family who obtained most of the (former) seigniory of *Beveren* that covered almost the entire *Waasland* polder region (Soens et al., 2012).

2.2 Sources: maps and their production in coastal Flanders

The *Waasland* polder region forms an excellent test-case for a serial cartographic analysis, since this area was part of one of the 'core-regions' of early modern cartography where in the late fifteenth and sixteenth centuries major developments in cartography took place. Under the influence of the rediscovery of early writings on land surveying, the great explorations, the art of book printing and technical developments like trigonometry and measurement instruments, the quantity and quality of cartographical products rose significantly, mainly in Italy, Germany and the Low Countries (De Maeyer et al., 2004). In Flanders *Leuven* played a major role (Bossu, 1982) with scientists like Gemma Frisius (trigonometry), Jacob van Deventer and Gerard Mercator (projection system) (Koeman, 1983).

If we focus on coastal Flanders, land surveyors seem to have been active pretty early. We find references to land surveyors as early as 1190 in Furnes and from 1282 in Bruges (Janssens, 2006, p. 89). The oldest cartographical products from – Sealand − Flanders date from 1307 and 1358 (Augustyn, 1999, p. 44; Gottschalk, 1955-1958, pp. 153-55). Local and regional maps from the fourteenth and fifteenth centuries CE were still highly pictorial, with limited topographical information, but by the 1540s the 'land surveyor and mathematician' François Van de Velde was able to deliver high maps of different parts of the Scheldt Estuary, using a projection that at least visually corresponds with modern maps (figure 2):

Figure 2. detail of the map of the island of Biervliet and the surrounding part of the Western Scheldt Estuary by François van de Velde 1549 (RAG, Kaarten & Plans, 613).

From the sixteenth century CE onwards, the exponential increase in the production of local and regional maps, was mainly the work of land surveyors, who were increasingly asked to add a map to their measurements of individual plots of land, parishes or districts in the context of disputes, land tax assessments, and also land reclamations. In our test-area, the huge land reclamations in the Western Scheldt Estuary in the seventeenth and eighteenth centuries CE with many new 'polders' reclaimed on lands that had been flooded during the Eighty Years War (1568-1648) offered plenty of work to the land surveyors. Usually surveying the newly embanked polder was obliged in the so called *bedijkingsoctrooien* (embankment patents). Examples of this are found in 1650 ('perfect maps should be presented'[11]), 1667 (plots should be 'measured and priced'[12] by neutral persons) and 1688 ('land surveyors should do the delimitation of plots'[13]) (Wolters, 1869, pp. 103, 185, 231). So it should not come as a surprise that in 1696 the aldermen of the region formulated a desperate request to the central Habsburg Government to increase urgently the maximum number of land surveyors (Janssens, 2006, p. 165). Although the measurements by the land surveyors were often very accurate, they were performed with simple instruments: a teaching book of 1662 learns that the only instruments needed were a land surveying cross, a measurement chain (and someone to carry it), ten to eleven penetration pins, a 'wooden rod'[14], a notebook and a few pickets (Janssens, 2006, p. 306). To demonstrate their skill with these instruments and to guarantee a certain quality, the land surveyors had to take practical examinations (Janssens, 2006, p. 338).

The combination of the rapid development of techniques, the need for measurements for new embankments and the certified quality of land surveyors led to a large number of high quality maps for the coastal plain and the *Waasland* region. Luckily, numerous maps have been preserved and can be used for (e.g. coastal) research. An important note is that the most interesting maps are often not to be found in open access internet databases but in − State or local − archives. In the (State) archives of Ghent, Brussels, *Beveren* and *Middelburg* over 300 historical maps (sixteenth to nineteenth centuries CE), displaying the *Waasland* polders and surroundings, were found[15]. Many of these maps were ordered by or linked to the Arenberg family (who obtained most of the former seigniory of *Beveren*) who coordinated the embankment and drainage of four major 'polders' in the region: the *Oud-Arenbergpolder* (finished in 1688) the *Nieuw-Arenbergpolder* (finished in 1784, figure 3); the *Prosperpolder* (finished in 1846) and the *Hedwigepolder* (finished in 1907), the last three being integral Arenberg enterprises (De Kraker, 2007; Verelst, 2002).

Figure 3. Embankment plan of the Nieuw-Arenbergpolder, ordered by the Arenberg family in 1783 (ARA, Kaarten & Plans II, 8573).

Of course not all of these maps are suitable for the above mentioned analysis. Thirty maps, with dates ranging from 1570 to 1896, where selected based on scale, subject and date (see notes 21-23).

2.3 Methodology

The methodology described in this paper consists of a combination of different computer programs and methods to calculate, analyse and visualise the planimetric accuracy of the historical maps. In the data pre-processing phase the planimetric accuracy of each separate map was analysed, mainly using *MapAnalyst*. All results were exported and implemented in *SPSS* in order to conduct statistical analyses. Local accuracy was then analysed using *MapAnalyst* and *QuantumGIS* while a test-case (mostly using the same maps) was elaborated in *ArcGIS*. Figure 4 gives an overview of the most important steps (and computer programs) used in these three parts of the article.

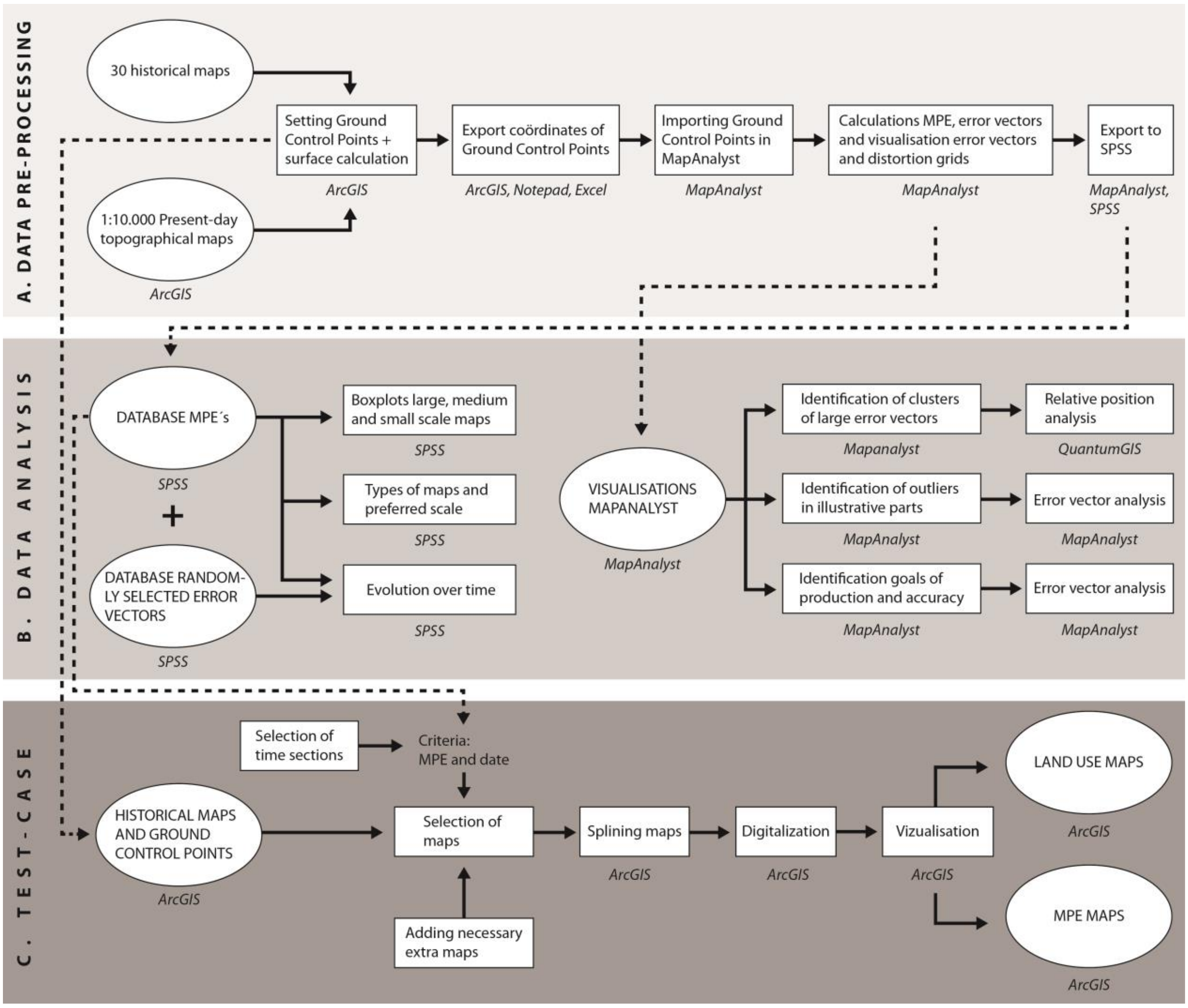


Figure 4. Methodology used in this paper.

2.3.1 Data pre-processing

The ***data pre-processing phase*** comprised the integration of the scanned maps within the computer programs. In order to investigate the planimetric accuracy, different computer programs are available. Of course, mainstream GIS-software could be used (e.g. *ArcGIS* or *QuantumGIS*), making use of the calculated Root Mean Square Errors after georectifying an old map, but a more specialist program has been developed, mainly adding options for visualisation of the (local) errors: *MapAnalyst*[16]. The methodology in order to define the planimetric accuracy of historical maps, used in this program, is described by Jenny (2006, 2007, 2010) and Jenny and Hurni (2011):

Basically, after setting Ground Control Points (see below) on both an old and a new map, an Euclidian (four parameter, also called Helmert-transformation) or affine (five or six parameter-transformation) is used to transform points on the old map to the new map and vica versa[17]. Parameters for the transformation are calculated with the 'least-squares-method', resulting in minimum errors between point sets (Jenny, 2006, pp. 240-41; Jenny and Hurni, 2011, pp. 403-04)[18]. For this paper we used the Helmert-transformation which only uses scaling, rotation and translation in x and y and therefore leaves the historical map as original as possible during overlay with a modern map. According to Jenny the standard new map in *MapAnalyst − open street map −* which uses the Mercator projection, 'can be considered an unfortunate choice for the distortion analysis of old maps, because the Mercator projection adds considerable areal distortion at medium and higher latitude' (Jenny, 2010, p. 179). This distortion is removed in further calculations, but for this reason and for the reason that *open street map* is not the most accurate map for local use, we chose to base our analysis on the recent 1:10.000 digital topographical maps for Belgium and the Netherlands, both (re-) projected in the Lambert 1972 coordinate system (i.e., the system used for the Belgian topographical maps). Since these base maps were too large to import directly in *MapAnalyst*, Ground Control Points (see below) were set using *ArcGIS 9.3*. The coordinates of these points were then imported in *MapAnalyst* and visualised on a low-resolution version of the combined 1:10.000 maps which was spatially located through a *.jgw-file*. Through this method GCP´s were set with maximum precision and further calculation could be done correctly.

As mentioned before, in order to transform the new map, identical points on both old and new map (Ground Control Points, GCP´s) have to be identified, a somewhat delicate task

(Laxton, 1976, p. 20). Therefore attempts were made to: (1) distribute the GCP´s as uniform as possible over the entire map; (2) use various features as GCP´s; (3) use unambiguous GCP´s as road crossings, fortresses, dike corners; (4) use no features that change over time (e.g. tidal channels); (5) set a large number of GCP´s. However, in some small scale maps towns were only depicted by church or point symbols. In that case, the 'centers' of present day towns were defined by the main churches, which were used as GCP´s. Note that for some large scale maps, especially the ones depicting the (temporally changing) tidal marsh, only a limited number of GCP´s could be set.

Overall quantification of the planimetric accuracy can be done by calculation of the Mean Positional Error (with accompanying standard deviations). The Mean Positional Error (MPE) is in this case defined as $\sqrt{((\sum v^2)/n-2)}$ for the old map. The factor v is defined as $\sqrt{(vx^2+vy^2)}$ with vx and vy the vector distances in x and y − in meters − between the actual points in the old map and the place they would be if the old map was perfect. Alternatively the same calculations could be made in real meters, using the new map and corresponding vector distances[19]. The result should be interpreted as the average distance a randomly chosen point on the map has to its position in case the old map was as accurate as the modern map (in scaled 'mapped' meters or 'real' meters). The displacement vectors (v) were exported to the statistical program *SPSS* in order to do further statistical tests. In addition, *MapAnalyst* offers a few very helpful tools for visualisation of local distortions in the historical maps using error vectors and diction grids. For each map an image of these local distortions was generated.

2.3.2 Data Analysis

The pre-processing phase resulted in a database with the MPE´s and individual error vectors, integrated in SPSS, and a series of visualisations of local errors and distortions grids for each map. In total we analysed thirty maps, with a period range from 1570 to 1896. In order to make 'fair' comparisons, the maps were divided according to scale. Classical scale assessment (dividing distance on map through real distance and classifying them into large, medium and small scale maps) is not always the best choice to use on historical maps. The size of old maps could vary widely, of course having its influence on the calculated scale. If old maps were excessively large, they would in many cases be defined as 'large scale' while visual interpretation would classify them as 'medium scale' and *vica versa* in case the maps were excessively small. Applying the classical scale values (<5.000 as large scale, 5.000 to

50.000 as medium scale and > 50.000 as small scale) on our database would result in very comparable maps being classified differently since their original size varied widely. Furthermore, this classical choice of scale values would be very arbitrary, and influencing all further outcome.

Therefore the choice was made to classify the maps through mapped surface. In order to calculate this surface, boundaries of the map area were digitalised (using *ArcGIS 9.3*), using the georectified maps[20]. The database could be easily divided by using surface break values of around 100 km² and 1000 km². Maps with a mapped surface below 100 km² displayed a single or a few embankments, maps with a mapped surface between 100 and 1000 km² displayed the *Waasland* polder region (sometimes completed with the area north of the boundary)[21] and maps with a mapped surface of over 1000 km² displayed the entire Western Scheldt estuary (sometimes completed with a large inland surface). Therefore we classified the first catergory as what we will call 'large scale maps' (class 1, <100km², twelve maps[22]), the second category as 'medium scale maps' (class 2, 100 to 1000 km², twelve maps[23]) and the third category as 'small' scale maps (class 3, >1000 km², six maps[24]).

The MPE´s for the different maps are compared by scale using SPSS for creating boxplots. Significance was tested using a non-parametric Kruskall-Wallis test, while evolutions over time were visualised through scatterplots and quantified using linear regression. R^2-values were calculated in order to quantify the explanation in variation of MPE by the factor 'date of production'. As mentioned before, each MPE was calculated from numerous GCP´s (see formulas in section 2.3.1) all having a 'v-value', which is the real distance between a point in the actual landscape and the corresponding point on the historical map after translation, rotation and scaling. This means we have a large number of v-values for each map, amounting to 1482 samples in total. Therefore, further investigations on the MPE and its evolution were made by splitting each MPE in these partial components. Additional benefit of analyzing individual v-values lies in the fact that no more calculations (and therefore data-alterations and simplifications) for an overall MPE had to be used. Results could be biased by the fact that maps with a larger number of GCP´s have a larger influence on the outcome. In order to avoid this potential bias for each map a random sample of v-values was taken, according to the smallest number of GCP´s for a map in its class. This resulted in six samples for each large scale map, nineteen samples for each medium scale map and fifty-seven samples for each small scale map, amounting to 642 samples in total.

The visualisations in *MapAnalyst* were used in order to investigate the local distortions within each map. The displacement − or error − vectors (visualised in the old map) start at the location of a GCP in the old map and end were it would be if the old map was as accurate as the new map. The longer the vector, the bigger the displacement (Jenny et al., 2007, p. 90). Outliers (vectors with a length of over three times the standard deviation) can be marked. Based on the displacement vectors and using a method based on multi-quadratic interpolation (which minimises the influence of outliers), a distortion grid is visualised. The meshes (cells) of the distortion grid are rotated and compressed or enlarged (Jenny et al., 2007, pp. 90-91). Compressed cells mean that the distances on the old map appear smaller than they would be in case the old map was as accurate as the new map, for enlarged cells the opposite holds. A scaled and rotated (but undistorted) reference grid can be shown for comparison. Note that on parts of the map were no GCP´s were set, the mesh cells will appear rectangular since no local distortion could be calculated. Alternatively, the mesh could only be visualised for areas containing GCP´s. These visualisations were assessed by visual comparison, complemented with quantified analysis in *MapAnalyst* and *QuantumGIS* in order to investigate clusters of error vectors or individual outliers and the relation between goal of production and local distortions.

2.3.3 Test-case

In order to explore the potential of the accuracy-testing of historical maps for the study of (coastal) landscape changes, we used part of the dataset of thirtty maps, with their respective accuracy measurements, to reconstruct the coastal landscape of the *Waasland* polder region between 1570 and 1850 CE, including historic landscape features like dikes, roads and buildings which are no longer visible in the present-day landscape. Integrating historical maps in a GIS to enable retrogressive landscape analysis, is of course not new (Cousins, 2001; Heere, 2008; Oetter et al., 2004). Integrating planimetric accuracy assessments however remains scarce (Lloyd and Gilmartin, 1987; Vuorela et al., 2002) and studies combining different maps per time section, including estimated accuracies, are especially hard to find.

To explore this issue, a retrogressive landscape analysis was conducted in the area surrounding the (former) embankments of the *Doelpolder* (embanked around 1567, inundated around 1583-1585, re-embanked in 1613-1614), *Luyspolder* (embanked around 1567, inundated in 1583-1585, re-embanked in 1650, inundated around 1715) and *Peerdenschor* (embanked around 1650, inundated in 1715) (Van Gerven, 1977, see figures 13a-13e). Borders of the study area are formed by the maximum extension (and a small buffer surrounding this) of the above mentioned embankments. Based on these dates of (re-) embankments and inundations, and on the availability of historical maps (often produced just prior or after important embankments in the region) in the database, five time sections were chosen: 1570, 1620, 1690, 1790 and 1850. A few 'extra' maps had to be added to the selection of maps that were suitable for the planimetric accuracy assessment in order to cover the complete study area for each time period. This was the case for maps of the *Luyspolder* around 1686 (ARA, Kaarten & Plans I, 2655) and *Peerdenschor* (ARA, Kaarten & Plans I, 411) around 1715 which could not be checked on planimetric accuracy since almost no present-day Ground Control Points could be found. In addition parts of four series of maps were integrated: the famous Ferraris maps, the Primitive Cadastral maps of around 1830, the commercial versions of these maps (made by P.C Popp) of around 1850 and the *Bonnebladen* of Sealand, dating around 1850. Since a quantitative analysis of these large series of maps surpasses the goals of this paper, only an estimate for the accuracy based on a small part of these series of the first three maps was made[25]. For these reasons the maps of large series and the before mentioned maps which could not be checked on planimetric accuracy (indicated with 'unkown' or bracked MPE´s) have not been included in further statistical tests.

Table 1. List of maps used for the test-case, maps with bracked or 'unknown' MPE were only included in the test-case, not in further analysis. Codes will be referred to in figure 13a-13e (time sections).

Date (original)	**Used for time period**	**Reference**	**Scale**	**Map contents**	**MPE NEW (m)**	**Code**
16th Century	1570	ARA, Kaarten & Plans II, 8562	Large	Comparison former embankments surrounding the Oud Arenbergpolder	Unknown	A
1567-1614-1650[26]	1570-1620-1690	ARA, Kaarten & Plans II, 8623	Large	Comparison old and new embankment of Doel and Luys	18.83	B
+- 1570	1570	RAG, Kaarten & Plans, 451	Large	Pictural map of old Doelpolder	23.74	C
+- 1575	1570	RAG, Kaarten & Plans II, 2454	Medium	Waasland polders and Saeftinghe	722.40	D
+- 1600	1620	Map of Coeck (Scheepvaartmuseum Amsterdam)	Medium	Inundations	1383.90	E
1676	1690	ZA, De Waard, 1303	Small	Doel and Luys (and wide surroundings)	1507.06	F
1685	1690	ARA, Kaarten & Plans I, 2655	Large	Luys, including plots	Unknown	G
1688	1690	ZA, Hattinga, 505	Large	Luyspolder	Unknown	H
1708	1690	RAG, Kaarten & Plans, 35	Medium	Waasland polders and surroundings Hulst	Unknown	I
+- 1715	1690	ARA, Kaarten &	Large	Paardenschor, just before	Unknown	J

		Plans I, 411		inundation		
+-1767	1790	ARA, Kaarten & Plans I, 410	Medium	Doel and surroundings	511.94	K
+- 1780	1790	*Carte de Cabinet des Pays-Bas autrichiens leve´e a` l'initiative du comte de Ferraris,* Santvliet 71	(Large)	Doel and surroundings	(167.05)	L
1791	1790	ZA, Aanwinsten 1948, 41	Medium	Waasland polders and surroundings Hulst	161.21	M
1806	1790	ARA, Kaarten & Plans II, 8599	Large	Nieuw-Arenbergpolder	12.23	N
1813	1790	ARA, Arenberg,842	Large	Tidal marsh measurements surrounding Doel	103.68	O
1816	1790	ARA, Kaarten & Plans II, 8554	Large	Tidal marsh measurements surrounding Doel	32.54	P
+- 1830	1850	Primitief Kadaster, Beveren (Doel, Kieldrecht)	(Large)	Doel and surroundings	(5.36)	Q
+- 1850	1850	Maps of PC.Popp – Beveren (Doel, Kieldrecht)	(Large)	Doel and surroundings	(8.97)	R
+- 1850	1850	*Bonnebladen* (Zeeland)	(Medium)	Doel and surroundings	Unknown	S
1892	1850	ZA, Polder van Walcheren, 683	Small	Western Scheldt and surroundings	78.40	T

As the table above explains, for each time section in the reconstruction, several maps were used. In order to choose the most appropriate map for each part of the reconstruction, we aimed to use the map with the smallest positional error since this would, at least in theory, provide the most accurate depiction of that area. Note that topographical detail (in most cases increasing with a higher positional accuracy) and date (as close as possible to the date of the time section) also play a role, so qualitative interpretation still plays a crucial role. As an example, figure 5 shows two maps of around the same date, depicting the same part of the tidal marsh. The left map was made in 1813 and was ordered by the embankment government of *Doel*. The tidal marsh (divided in higher and lower parts) was measured and depicted by Coppens, a quite active cartographer in this region. The map at the right – dating 1816 − was ordered by the Mayor of *Doel* and contains a detailed division between higher and lower tidal marsh. Based on the lower MPE of the map at the right, this map was chosen for this particular part of the analysis.

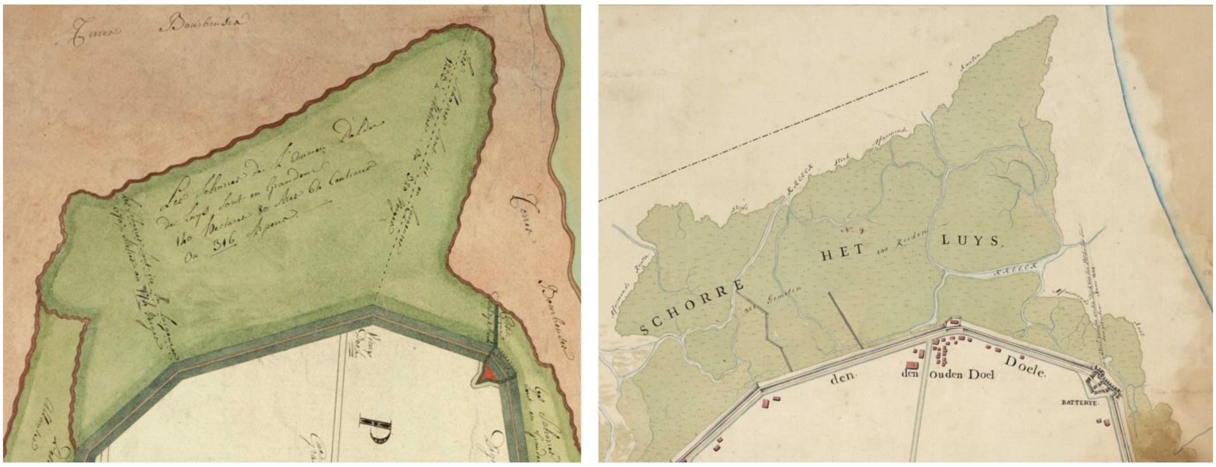


Figure 5. Two maps depicting the same part of the tidal marsh. Left a map from 1813 (ARA, Arenberg, 842) with an MPE of 103.68 meters, right a map from 1816 (ARA, Kaarten & Plans II, 8554) with an MPE of 32.54 meters. The map at the right with the lowest MPE was chosen for this part of the reconstruction of 1790.

All this resulted in 'parallel' maps, obtained by digitizing the georectified maps in *ArcGIS 9.3*, for each time section: one depicting the land use within the study area and one depicting the MPE´s (divided in classes) of the maps that were used for the particular parts of the land use map.

3. Results and discussion

3.1 Data-analysis: evolution and differences in MPE

The first tests that were conducted concerned the MPE of the series of maps. The boxplots in figure 6 show a large difference in MPE between the maps of different scales. This is illustrated by the Kruskall-Wallis test on the mean ranks (p-value = 0.000). Mean values differ significantly but some medium scale maps have exceptionally larger MPE´s than expected while some small scale maps tend to be more accurate than averaged. These anomalies explain why further tests (Mann-Whitney, note 27) show no significant difference between medium and small scale maps. However, looking at the boxplots it can be concluded that scale is a major variable influencing the planimetric accuracy of a map.[27]

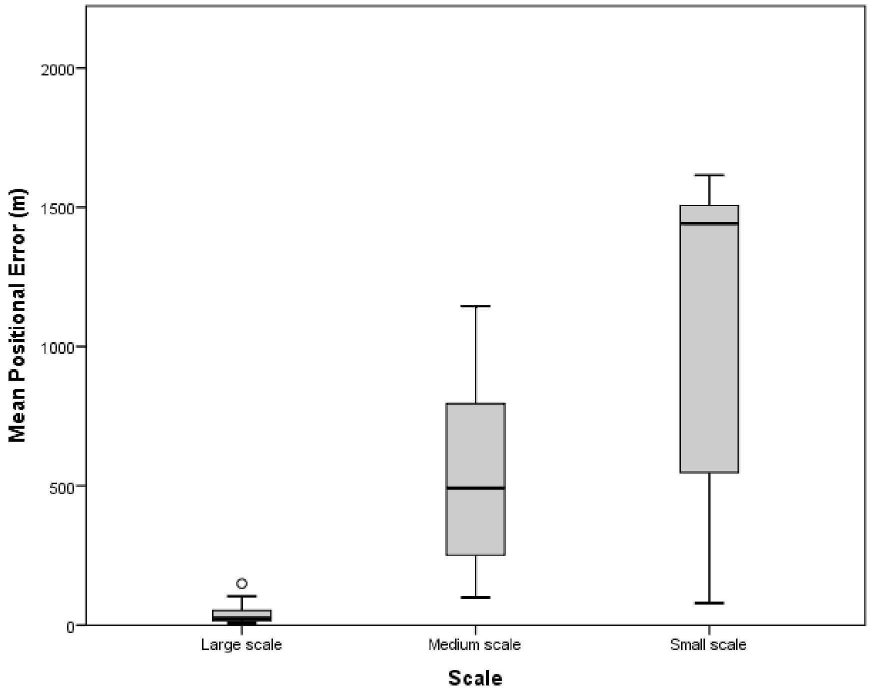


Figure 6. Boxplots of the MPE (meters) of large (N=12), medium (N=12) and small scale (N=6) maps[28].

Next, the evolution of the MPE over time was analysed. Overall − for the three classes together − map accuracy increased over time (decreasing MPE), although the low R^2-value (0.266) indicates a low amount of the variation explained by the independent variable 'time' (figure 7). However, it is best to look at the different map scales separately. Results point to increasing map accuracy over time for medium and small scale maps, but only for small scale maps the R^2-value (0.880) points to a real interrelation of time and accuracy. For medium scale maps only 17.2 percent of the variation could be explained by the independent variable time. For large scale maps the accuracy even decreased according to the trend line, but the R^2-value is exceptionally small (0.046) so this decrease is not significant. In conclusion, time as an – independent − variable offers only a limited explanation for map accuracy: sixteenth, seventeenth or eighteenth century maps can be just as accurate as more recent (nineteenth century), at least when mapping relative concise territories − smaller than 1000 km² in our sample – since for the medium and large scale maps no significant changes over time in map accuracy were found . However, sample size when analyzing the different map scales (twelve samples for the large and small scale maps and only six for the small scale maps) limits the reliability of the above mentioned results.

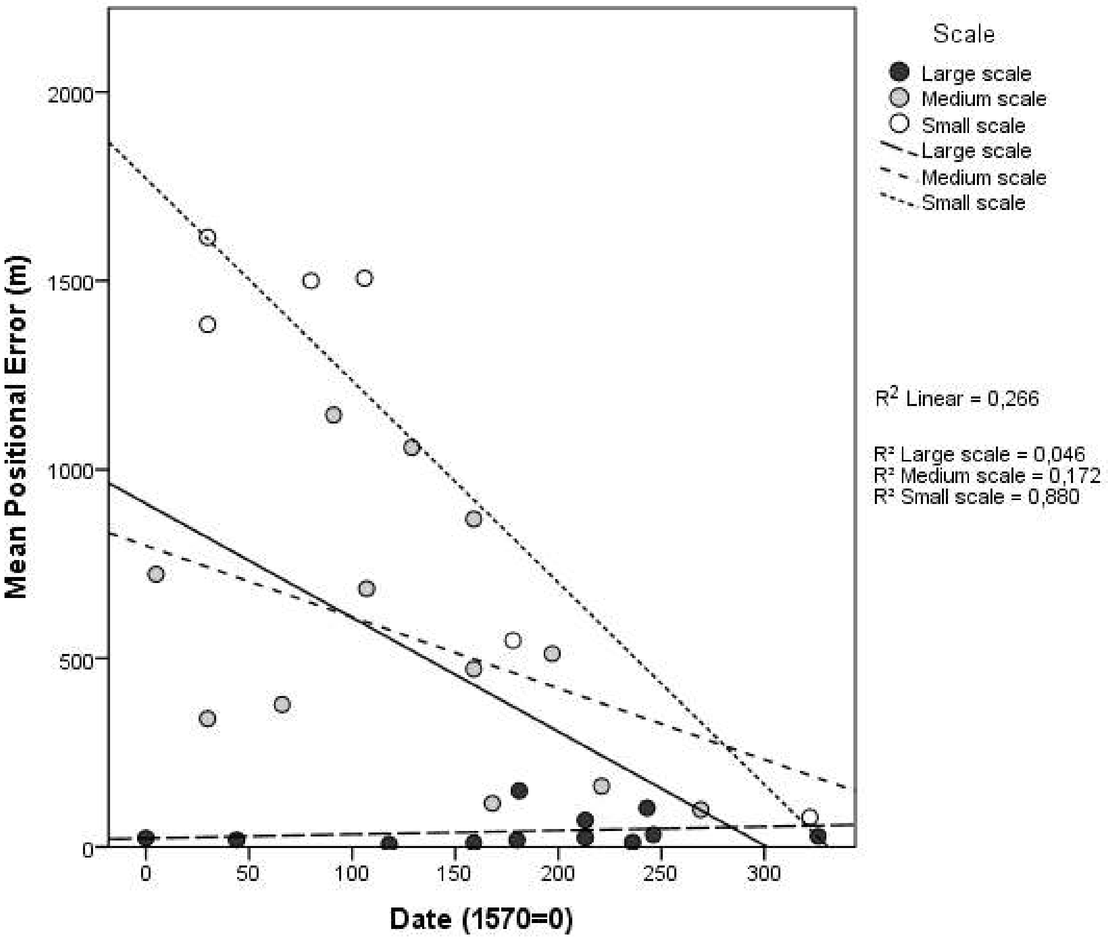


Figure 7. MPE over time for large (N=12), medium (N=12) and small scale (N=6) maps [29].

As mentioned before, further investigations on the MPE and its evolution were made by splitting each MPE in its partial v-values, resulting in six samples for each large scale map, nineteen samples for each medium scale map and fifty-seven samples for each small scale map. Individual v-values were plotted according to date of the original map (figure 8). Results are similar to the results for the overall difference in MPE and point again to increasing map accuracy over time for medium and small scale maps, but only for small scale maps the R^2-value (0.290) points to a limited interrelation of time and accuracy. This value is far smaller than the value found for the MPE, due to the influence of outliers (not erased by MPE calculations, see further) and a far larger variation in the individual v-values within each map. For medium scale maps only 6.3 percent of the variation could be explained by the independent variable time. For large scale maps the accuracy decreased according to the trend line, but the R^2-value is exceptionally small (0.033). We come to the same, but in case of the medium- and small scale maps statistically significant (see note 29 on ANOVA-testing), conclusion as for the evolution of the MPE: time as an independent variable offers only a limited explanation for map accuracy, sixteenth, seventeenth or eighteenth century maps can be just as accurate as more recent (nineteenth century) ones, in contradiction with for instance some findings on maps of the British Isles (Carr, 1962, p. 142).

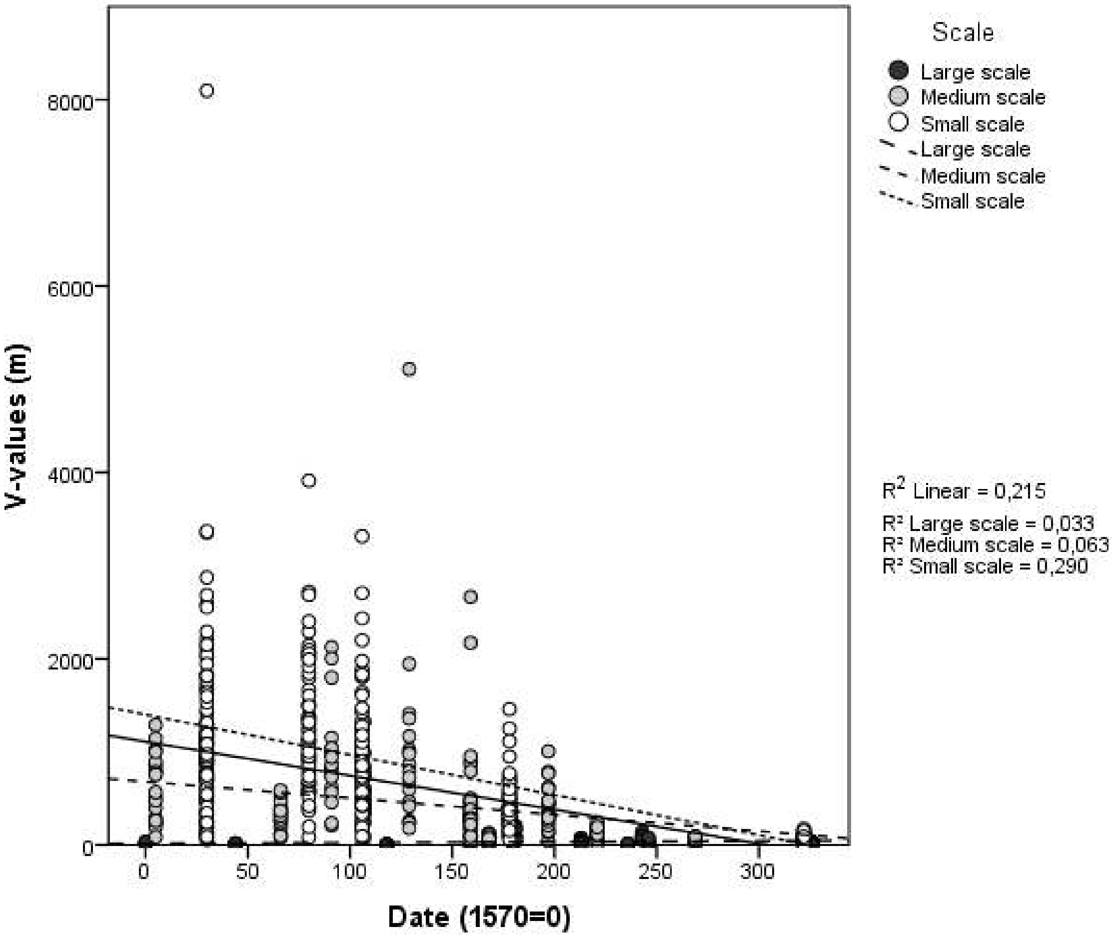
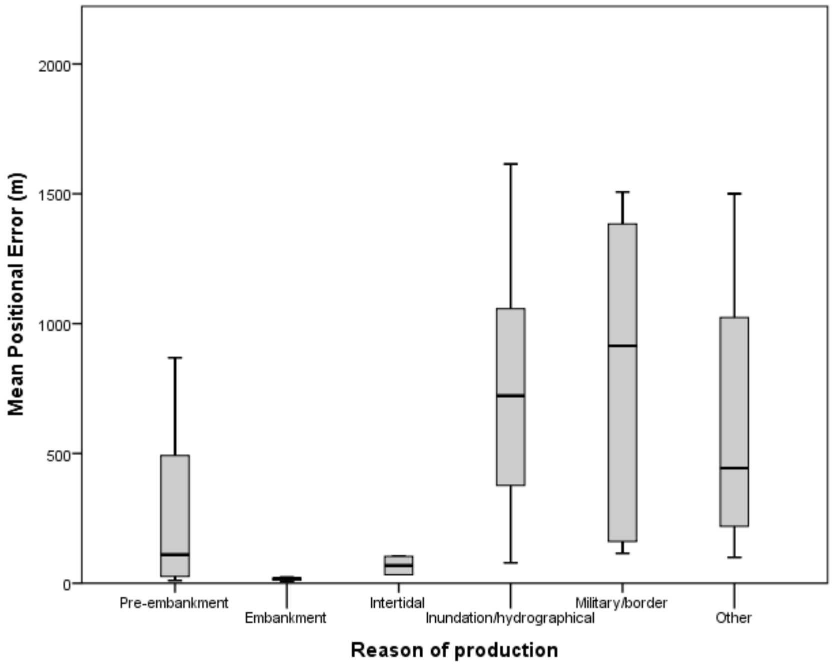


Figure 8. V-values (displacement vectors), random samples for large (N=6), medium (N=19) and small scale (N=57) maps[30].

The above mentioned analyses show that date of the map is not an all-explaining variable for map accuracy. Therefore we analysed the reasons for production of the maps, and their MPE´s. The reasons were categorised in six classes: (1) pre-embankments maps (depicting the projected new embankments), (2) embankment maps (aiming to depict an embankment accurately), (3) intertidal maps (depicting the intertidal area outside embankments), (4) inundation/hydrographical maps (made to show the extent of historical inundations/inundation risks or hydrographical details), (5) military or administrative maps (including maps resulting from the delimitation of state boundaries), and (6) other maps (maps not belonging to any of the above mentioned categories). Boxplots (figure 9, top) show high accuracy (low MPE) for pre-embankment, embankment and intertidal maps while inundation/hydrographical and military maps are clearly less accurate, although exceptions (lower bottom tail) are to be found. These divergences between different categories of maps are largely explained by the preferred scale of the map: intertidal and embankment maps were unexceptionally made at a large scale (see figure 9, bottom). For pre-embankment plans medium scale maps were also used mainly in the thirst phase of embankment planning, while the other categories only comprised both medium and small scale maps. Administrative maps focusing on state boundaries, might be very accurate with regard to the position of the boundary they aim to depict, but the overall accuracy of the map can be very poor (as other landscape features are only depicted for the visual orientation of the user). In any given period, different levels of accuracy could be obtained by the mapmakers. Retracing the original aim of the map is highly instrumental in explaining both the level of accuracy and the scale of a map, as well as the difference between landscape elements which are located in an accurate way and others which are not.



		Reason of production						Total
		Pre-embankment	Embankment	Intertidal	Inundation/hydrographical	Military/border	Other	
Scale	Large scale	5	5	2	0	0	0	12
	Medium scale	3	0	0	3	4	2	12
	Small scale	0	0	0	2	2	2	6
Total		8	5	2	5	6	4	30

Figure 9. MPE according to reason for map production, random samples (top)[31] and crosstab of classes and reasons for map production (bottom).

3.2 Data-analysis: local distortions

In most cases map ‘cartouches’ or legends contain few information on the original mapping process, making it difficult to predict which features are mapped in an accurate way, and which are not. Software like *MapAnalyst* not only helps to reveal the overall accuracy of a map, but it can also inform us on local variations in accuracy within one map image, and therefore relative displacements of points (Bower, 2009, p. 124). Only extreme outliers[32] are clearly marked, but visual interpretation of the length of error vectors makes it easy to reveal smaller anomalies. This allows to distinguish between geographic zones and landscape features which are located in an accurate way, and others where distortions are more important. In the end, such analysis allows to retrieve information on the mapping process, which was not provided by the map legend or additional data. After visual interpretation, two elements were strikingly present on a large number of maps: grouped clusters of error vectors (occurring in ten out of the thirty maps) and clearly misplaced features in illustrative parts of the maps (occurring in six out of the thirty maps).

The first observation concerning the distortion vectors is that GCP´s with large displacement vectors tend to be grouped in clusters, especially on small scale maps. An excellent example illustrated in figure 10 (left) is found on the military map of 1676 (ZA, Zelandia Illustrata, 1303, showing – former − fortifications and possible areas for military inundations although it seems the map was never entirely finished), where about ten GCP´s in one area should be located far more eastward, resulting in enlarged distortion grid cells. This clustered group has an average error vector of 2025.91 meters, extremely large since the entire group is dislocated. However, when removing this structural distortion, the error vectors of the seven GCP´s only average 496.84 meters, showing that their relative positions are far more accurate[33]. Similar distortions are found on the medium scale map of around 1650 (ARA, Kaarten & Plans I, 269, showing the administrative boundaries within Sealand Flanders) in figure 10 (right). The clustered group (N=7) has an average error vector of 1900.12 meters, while their relative average error is only 215.24 meters. Not surprisingly, these large error vectors are found in the part south of the boundary between Flanders and Sealand Flanders, while the northern part was the point of interest of the map.

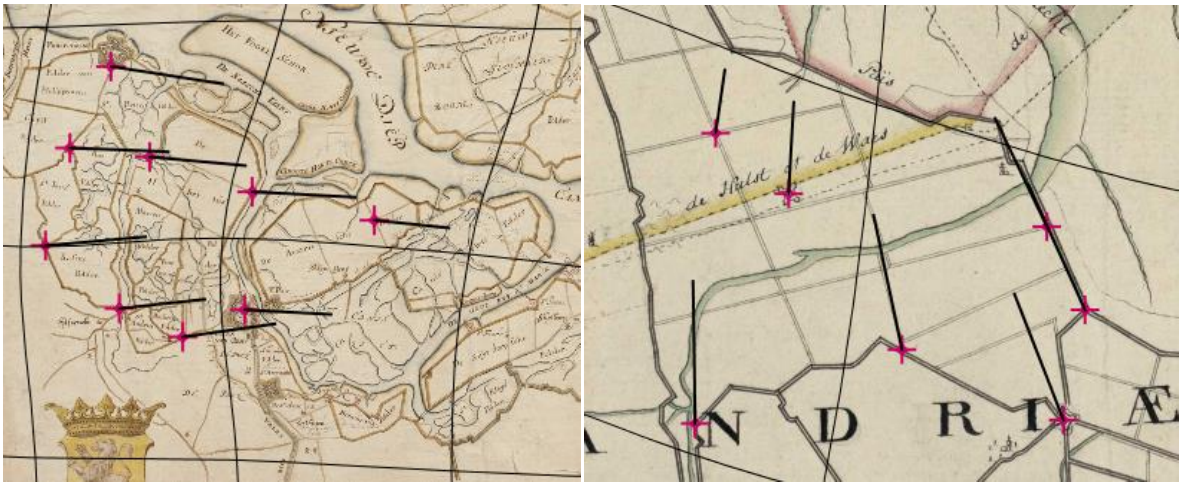


Figure 10. Local clusters of distortions. Left: ZA, De Waard, 1303 (small scale military map of 1676) with uniform distortions in the area surrounding Sas van Gent and Philippynen. Right: ARA, Kaarten & Plans II, 269 (medium scale map of 1650), showing uniform distortions in the area of the Konings-Kieldrechtpolder.

Some maps (like the inundation map of 1745, ZA, Hattinga, 270) even show groups of large displacement vectors with contradictory directions, resulting in both relatively larger and smaller displacement grid cells. Even more recent maps, like the hydrographical map of 1892 (ZA, Polder van Walcheren, 683), suffer from these misplacements, in this case the dikes between *Philippine* and *Biervliet* which are less accurately displayed then the rest of the elements on the map. Probably this part of the map was of less interest to the map makers, who intended to show water depths in the Western and Eastern Scheldt. However, the error vectors are much smaller since the overall accuracy of the map is outstanding.

Larger distortions also occur on the more illustrative parts of certain maps. An excellent example is to be found for the map of the inundation risk in the coastal area of around 1600 (ARA, Kaarten en Plans II, 176, figure 11, left) where the villages in the left bottom corner are clearly 'misplaced' and four very large (two even more than three times the SD) displacement vectors (including two outliers) can be found. These four places should be located far more west and therefore the distortion grid shrinks in this area. Perhaps this obvious error might be explained by negligence on behalf of the cartographer, as the map primarily discussed flood risk in an area far more north than the four villages. But perhaps, positioning these villages closer to the area threatened by flooding could also have been a deliberate strategy by those who commissioned this map, as the map was used in a law suit deciding on which villages had to pay for flood protection…

A frequent error also concerns the inclusion of large cities on a map. On several maps in our sample, the city of Antwerp is located in a corner of the map, with its geographical location significantly less accurate than other parts of the map. Often the mapmaker had probably insisted on including the city for the purpose of the overall geographical orientation of the map-user. In order to do so, he sacrificed part of the overall topographical accuracy of his map (ZA, De Waard, 1303 and ZA, Hattina, 270). Map ZA, Hattinga, 270 (figure 11, right, showing the results of the tactical inundations during the Eighty Years war, copied by the famous cartographer Hattinga), for instance, has an extremely large error of 5108.87 meter for the city of Antwerp compared to an overall mean positional error of 1057.82 meters. Of course, these local outliers (point pairs with extremely large errors) have an impact on the overall map accuracy. Removing the Antwerp point pair lowers the overall MPE from 1057.82 meters to 858.30 meters. Logically, the effect of these outliers on overall MPE depends on the number of outliers, the v-values of these outliers (in this case an extremely large value) and the total number of GCP´s. This also implies an effect of subjective choices made during the setting of GCP´s, best countered by distributing the GCP´s as evenly as possible and by choosing different elements as GCP.

Figure 11. Left: illustrative towns with large error vectors in map ARA, Kaarten & Plans II, 176 (inundational map dating around 1600). Right: local distortions surrounding 'illustrative' part of a map, located at the city of Antwerp (ZA, Hattinga, 270).

Sometimes entire parts of a map are displayed with a lower accuracy. This is most clearly illustrated by the northern coast of the Western Scheldt, for instance in the above mentioned map of 1676 (ZA, De Waard, 1303), the map of Coeck dating 1664 (Scheepvaartmuseum) and the map of 1748 (ZA, Zelandia Illustrata I, 1560), where almost all topographical detail is left out for the northern coast. On the same maps the more inland parts are also less accurate, indicating that the map maker was primarily focusing on the coastal (shoreline) area, south of the Western Scheldt.

This observation raises the issue of the relationship of the goal of a map and its local accuracy. Logically elements of specific interest to the map maker should be localised more accurately, but was this true for the maps in our selection? As indicated in the map cartouche the small scale military map 1676 (ZA, De Waard, 1303) aimed to display fortifications (*forten, redouten* and *retrensimenten*) in the border region of the Dutch Republic and the Habsburg Netherlands, with special reference to the inundated ones. And, as might have been expected, most of the fortifications are located more precise than parts of the map with little fortifications.

The study of partial distortions can also help to reveal the actual origins of a map when information on its production and original goal is missing, for instance because the 'cartouche' is empty or incomplete. The map of 1664 (Coeck, scheepvaartmuseum, displaying the situation around 1600, figure 12) does not come with a cartouche describing the reason for making this map. However, looking at the displacement factors in the map, it turns out that most points with smaller error factors are fortifications in the frontier zone while other locations tend to be less accurately localised. The GCP´s in figure 12 have an average error of 625.35 meters for the fortifications (N=6) and 1809.57 meters for the other elements (N=4, road crossings and churches). A military reason for manufacturing of this map seems to be most plausible.

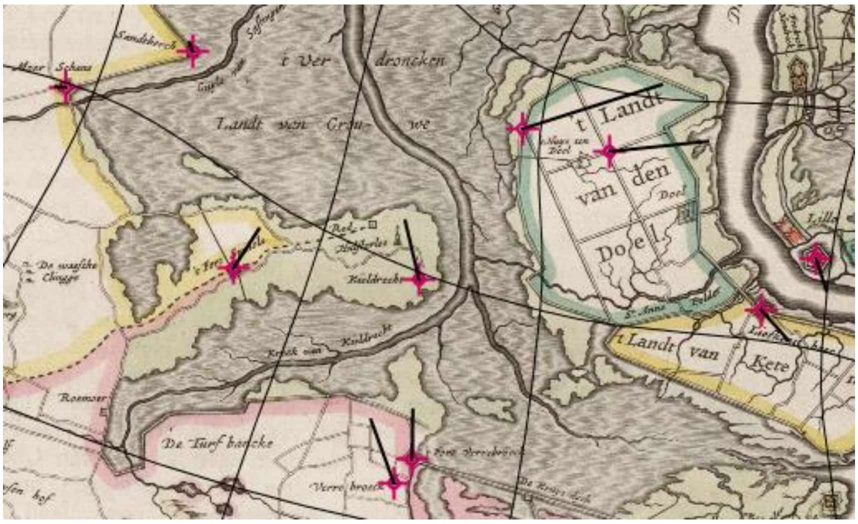


Figure 12. Map of 1664 (map of Coeck, Scheepvaartmuseum) showing large differences in MPE between the accurate display of fortifications (upper left, extreme right) and the inaccurate display of the Doelpolder (upper middle).

Of course, the methodology used, which is based on the visualisation of positional errors, also presents some potential threats. First of all, the way GCP´s are selected during digitalisation influences the planimetric errors in the map. If a large city is depicted in a simplified (pictural) way, setting many GCP´s within or near the city influences both the local distortions and overall map accuracy. Not setting GCP´s in certain areas leads to an undistorted grid, while this area still might be inaccurate. Therefore it is always recommended to distribute the GCP´s as uniform as possible. However, sometimes certain areas simply are not suitable for setting GCP´s. Rapidly changing features, like a tidal marsh in a coastal or estuarine area, are not suitable since the location of for instance tidal channels in the seventeenth century does not correspond with their location today. Therefore, on maps with an extensive tidal marsh (quite common in this test-region) our analysis seems to indicate that the tidal marsh has been depicted accurately, but in reality there simply were no data available to assess accuracy.[34] Drawing error grids only surrounding the GCP´s offers a solution for this problem. Secondly, some GCP´s are inherently less subject to causing large error vectors. Corners of embankments, fortresses, road crossings etcetera are more easily and correctly identifiable in the present day landscape then ‘symbolised’ elements like church towers, for which it is inevitably to only assume which present day part of these elements the map symbols point to.

3.3. Test-case in ArcGIS: the further use of historical maps.

As mentioned in section 2.3.3 five chronological cross-sections were chosen in order to conduct a landscape analysis of the *Doelpolder* and its surroundings. For each time section, several maps were selected, georectified and digitalised. This resulted in two 'parallel' maps for each time-slot (figures 13a to 13e), one depicting the land use within the study area and one depicting the MPE´s (divided in classes) of the maps that were used for the particular parts of the landuse map. For the MPE-maps the grayscale symbolizes the planimetric accuracy of the maps used for (parts of) the reconstruction. The darker the element, the higher the accuracy. Since GCP´s could only be set on constant elements (and therefore not on for instance tidal channels), the MPE was extrapolated to the intertidal area. The maps used for this landscape analysis were 'splined' based on their Ground Control Points, making these points on the historical maps completely falling in place with the actual points on the geolocated 1:10.000 present-day maps. In a few cases (for instance for small scale maps having the GCP´s uniformly spread around the entire map) extra GCP´s were added. In case of maps depicting an area that is presently completely drowned, GCP´s were set based on the historical map and the landscape reconstruction. For these maps, no positional error could be calculated. Note that by using the 'spline' function, the calculated MPE´s do not reveal how far a certain element of the reconstruction is exactly misplaced. Nevertheless, the MPE's are mostly useful as a relative measurement of the accuracy of parts of the reconstruction. On the MPE-maps, grayscale indicates the accuracy of parts of the map. Inner dike polygons were not assessed (and therefore marked in white) since the outline of these polygons is defined by multiple line or polygon elements (like former tidal channels), all having different MPE´s, making it impossible to define one mean positional error[35]. Black parts of the MPE-maps indicate elements that are still present in the actual landscape and therefore a MPE of 0 was assigned. If an element was continuous to a more recent situation, the MPE of the maps depicting this more recent situation were used. For instance: if for a certain time section the outer dike area was derived from maps with a high MPE but the dikes depicted on these maps were still present on a more recent map with a low MPE, the outer dike area for this time section was reconstructed with a lower accuracy than these dikes.

The first reconstruction (dating 1570) concerns the situation, just prior to the military inundations at the end of the sixteenth century. Based on map RAG, Kaarten & Plans, 451, the villages that were later drowned and covered with sediments (located as buildings left of the most westward dikes) are located with a surprisingly high accuracy.

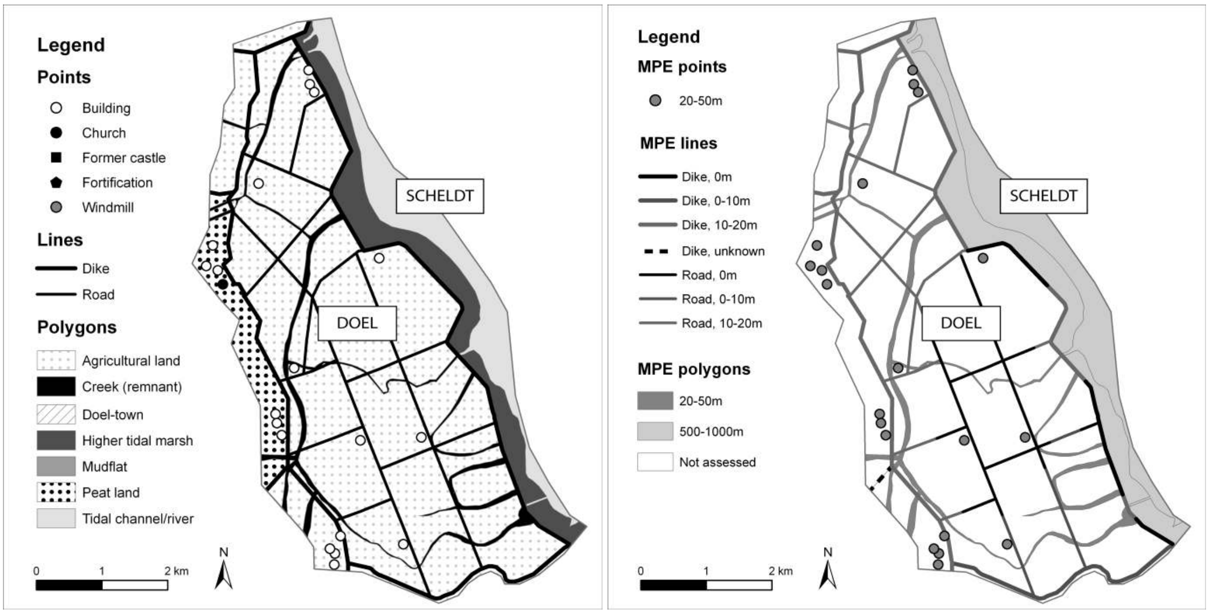


Figure 13a. Landscape reconstruction and MPE-map around 1570, just before large-scale flooding of the 1580's. Based on maps A, B, C, D and Q (see table 1).

In 1620, the entire *Luyspolder* had already been flooded by the large scale military inundations. The *Doelpolder* (located south of the former *Luyspolder*) was re-embanked. The most interesting element is a former fortification located north of the *Doelpolder*, unfortunately the location is highly questionable since the MPE of the map (Map of Coeck, Scheepvaartmuseum) used for this reconstruction only has a moderate score.

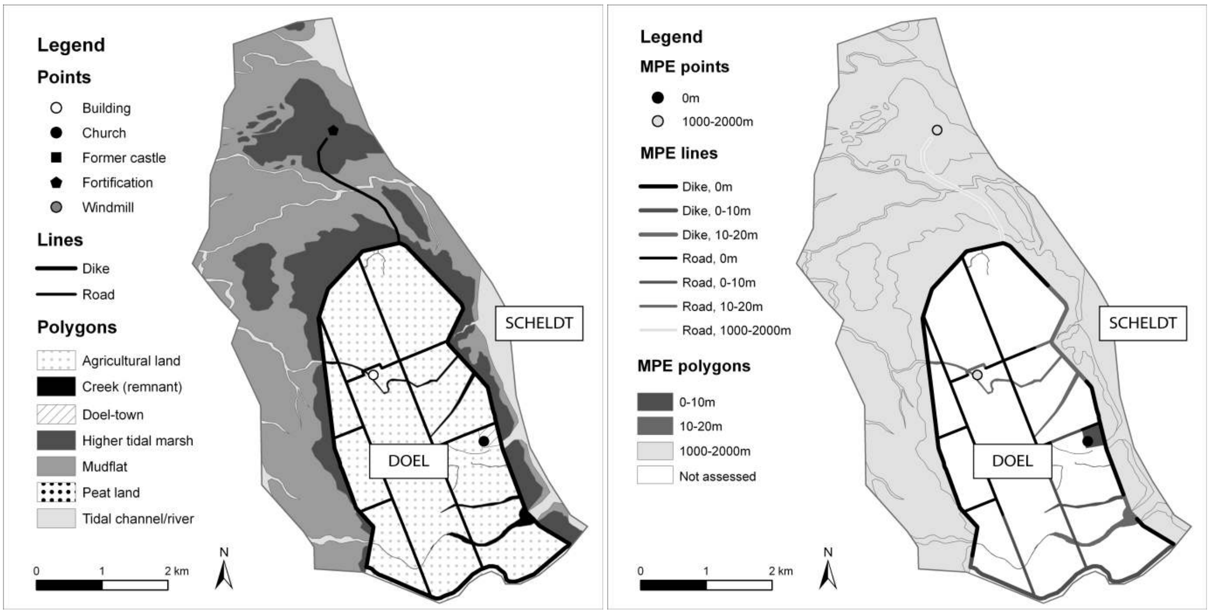


Figure 13b. Landscape reconstruction and MPE-map around 1620, just after inundations. Based on maps B, E and Q (see table 1).

In 1690, the *Luyspolder* was already re-embanked, just as the *Peerdenschor*. Note that MPE-values are impossible to give for certain parts (like for instance the buildings in the *Luyspolder*, including a former castle or the *Peerdenschor* itself) since for these maps, only very little identifiable points in the present-day landscape could be found.

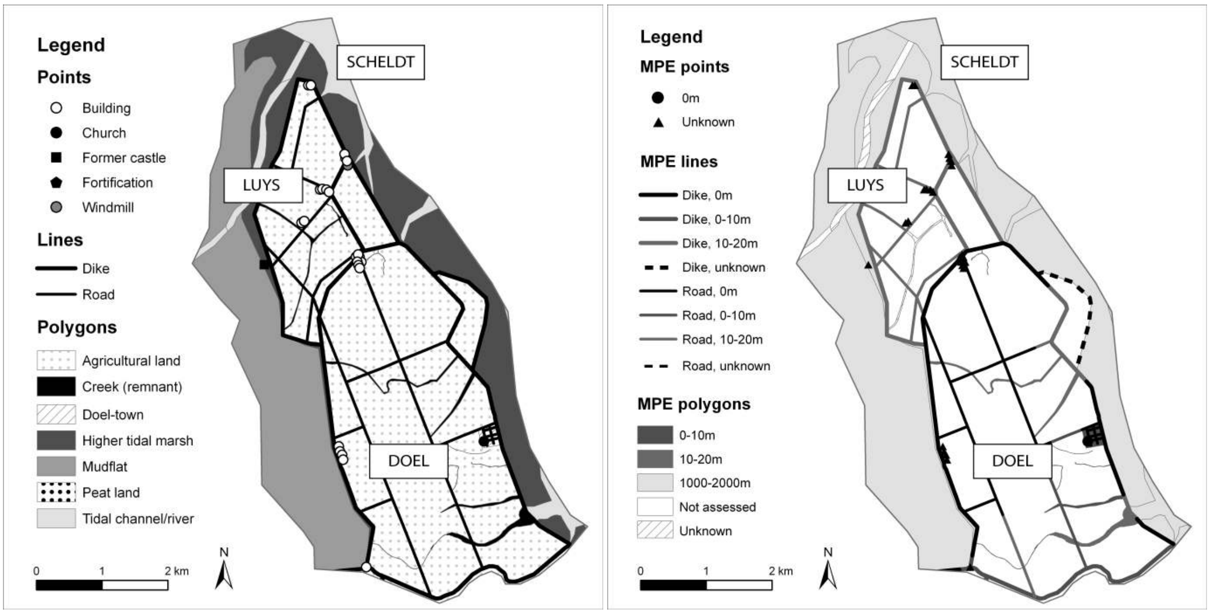


Figure 13c. Landscape reconstruction and MPE-map around 1690, showing the first re-embankments. Based on maps F, G, H, I, J and Q (see table 1).

For 1790, many interesting maps were found. Therefore the reconstruction consists of various maps (with various MPE´s) and effort was made to use the most accurate map for each part of the reconstruction. This led, for instance, to a highly accurate reconstruction of the tidal marsh northwest of the *Doelpolder*. Note that buildings in the polder west of the *Doelpolder* (*Nieuw-Arenbergpolder*) were located more accurately than buildings in the *Doelpolder* itself.

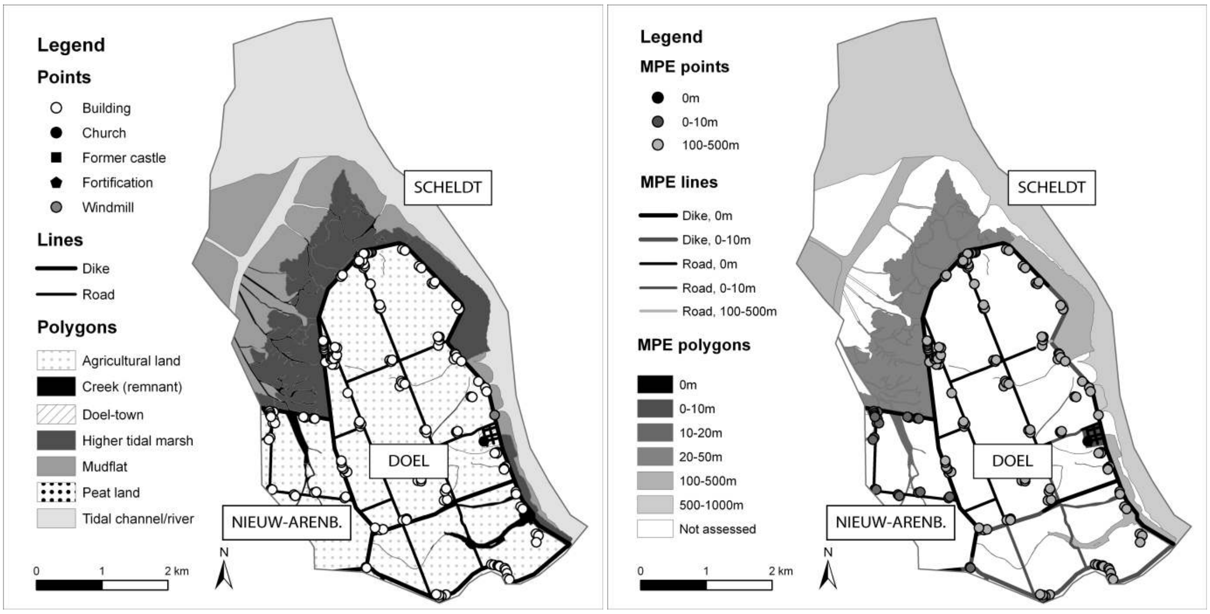


Figure 13d. Landscape reconstruction and MPE-map around 1790: the northern area is inundated, in the west a new polder was embanked. Based on maps K, L, M, N, O, P and Q (see table 1).

The maps used for the reconstruction of 1850 proved to be accurate as well. Only the tidal channel in the North was superimposed from a different map (Bonnebladen, 1850) with unknown accuracy. Buildings in the *Doelpolder* are now positioned with almost perfect accuracy.

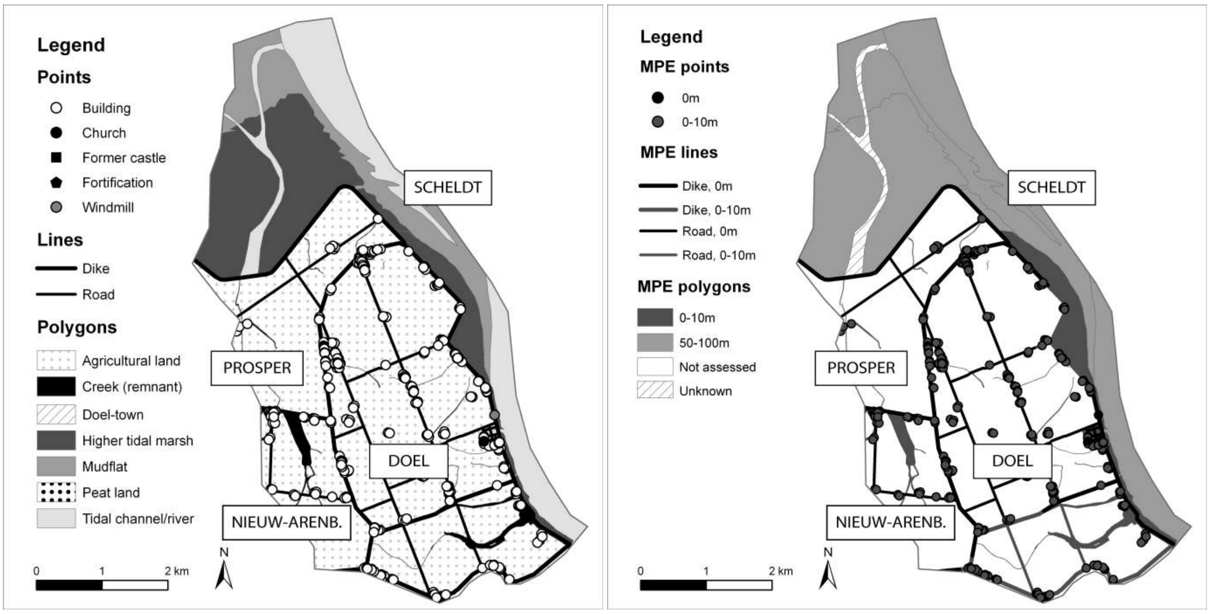


Figure 13e. Landscape reconstruction and MPE-map around 1850: further embankments in the northwest. Based on maps Q, R, S and T (see table 1).

As the analysis shows, some reconstructions could be made with a large level of accuracy. while other reconstructions should be interpreted more carefully. The combination of both land use maps and MPE maps makes it possible to assess these anomalies.

4. Conclusions

Because of doubts with regard to their planimetric accuracy, historical maps produced before 1850 CE have only reluctantly been integrated in GIS-based analyses of landscape change. In this article we have argued that a systematic assessment of the accuracy of these maps, using specialized software like *MapAnalyst* allows to clear out at least parts of the uncertainties, and enables researchers to explore the potential of historical maps, without being misguided by the positional errors they display. Using a sample data-set of thirty historical maps from the sixteenth to the nineteenth centuries CE, we first assessed their accuracy and then used them for the reconstruction of a partly (submerged) coastal landscape in the Western Scheldt Estuary (Belgium / The Netherlands).

During the assessment of the planimetric accuracy of these maps, some striking findings emerged. As one might expect, the scale of the historical map (for a large part determined by the original goal of the production of the map) had a large influence on the planimetric accuracy of the map. Large scale maps (for instance to be found as embankment plans) have a significantly larger planimetric accuracy then medium or small scale plans (for instance made for military reason). More surprisingly however, the quality of older maps (dating from the sixteenth or seventeenth century) could be as high or even higher than more recent maps. This is certainly the case for large scale maps, but even medium and small scale maps showed rather weak correlations between date and positional accuracy.

The Mean Positional Errors are not the only variable describing the planimetric accuracy of the historical maps. Local distortions may play a large role. Maps proved to be containing clusters of large displacement vectors, exceptional outliers (for instance more illustrative depictions of large cities) or higher accuracy for typical elements like fortresses. Following the automated detection of these clusters, a qualitative non-automated expert-judgment might explain these clusters, and even can shed a light on the original goal and production process of the map

Knowing the quantitative properties of these maps, more reliable landscape reconstructions can be made, including the geographic location of lost landscape features. As such historical maps can once (again) become a major source of information on landscape evolution in the past, which can be confronted with other data like aerial photography, digital elevation models, geophysical surveys, soil samples and archaeological excavations.

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6. Notes

[1] University of Antwerp, department History, S.R-A.112, Rodestraat 14, 2000 Antwerp (Belgium)

[2] Kruskall-Wallis tests reveal a significant difference between the averages (p-value=0.005).

[3] For a recent study on combining these techniques, see: De Smedt et al. (2013).
[4] The first date of appearance of a feature and, if applicable, the date of disappearance of the same feature.
[5] Some works do pay explicit attention to these large scale maps (e.g. Bower, 2009; Harvey, 1993), or specifically for the *Waasland* polder region: Guns (1973) and Van Gerven (1977), but apart from an exemplary paper (e.g. Hooke and Perry, 1976) the maps were not analysed in a serial and quantitative way.
[6] Refitting the historical maps using scaling, rotation and translation in x and y.
[7] Next to for instance differential paper shrinking (Ravenhill and Gilg, 1974, p. 48), map defects as tears, folds and creases (Crowell et al., 1991, p. 843) or non-material related issues like distortions in the depicted length of elements due to generalisation (Baugh and Boreham, 1976, p. 168; Maling, 1968) .
[8] Even for present-day map comparisons differing projection systems can induce mismatches (Sen and Bhattacharrya, 2000).
[9] See also: Tobler (1966)
[10] See for instance: Bodenhamer et al. (2010) and Knowles (2008)
[11] *'dat de geoctroyeerders sullen hebben over te leveren aen den Raedt van State perfecte caerten van de lande ende jurisdictiën, met het district ende van thienden ende thiende-heffers alles tot koste van de bedijkers'*
[12] *'gemeten ende gepresen'*
[13] *'geswoore lantmeters [...] de separatie ende afdeelinge, beneffens de groote cavelsloten daer van te doene'*
[14] *'roede van goed stijf hout dat wel recht is'*
[15] In the following, references to the State archives of Ghent are abbreviated as RAG, the State archives of Brussels as ARA, and, the *Zeeuws Archief Middelburg* as ZA.
[16] We used the latest fully functioning version (1.3.22, 8 january 2012), free download at: http://www.mapanalyst.org/
[17] For recent work on georectifying methods and comparisons between transformations, see: Brovelli and Minghini (2012), Manzano-Agugliaro et al. (2013) and Yilmaz and Gullu (2012)
[18] The Helmert transformation is defined as:
$X = x0 + ax - by$; $Y = y0 + bx + ay$
With: $a = m * \cos(alpha)$ and $b = m * \sin(alpha)$
x0: Horizontal Translation; y0: Vertical Translation; m: Scale Factor; alpha: Rotation in Counter-Clockwise Direction
[19] Note that for scans of maps that are not 1:1, the meters measured in the old map do not correspond with distances on the real (paper) map, but the calculations for the MPE in the new map are correct since the scale factor has the same deviation. The formulas are derived from (Beineke, 2001). Errors can be calculated in the old map or in the new map. Calculations in new map proved (after comparison with calculations in *QuantumGIS*) to be more reliable than calculations in the old map, since the last calculations use map meters for which the (sometimes occurring) extremely small values result in error prolongation when rounding off during between calculations. Therefore all statistical tests and other calculated values are based on calculations in 'new map'. Additionally standard standard deviations are calculated through $\sqrt{((\sum(v^2)/(2n-4))}$ (after Beineke (2001)).
[20] Note that only parts of the maps which actually contained an image were digitalised, so for instance cartouches or blank areas were left out.
[21] One exeption was found: Map ARA, Kaarten & Plans I, 2634 displayed the frontier zone between the Northern and the Southern North Countries but only a small inland part was

mapped, resulting in a relatively small mapped surface while the Waasland Polder region was exceeded.

[22] Large scale maps used for the planimetric accuracy assessment:

Archive	Division	Number	Date original		Date copy	
RAG	Kaarten & Plans	451	+-	1570	+-	1570
ARA	Kaarten & Plans II	8623	+-	1614	+-	1655
ARA	Kaarten & Plans II	8617		1688		1688
ARA	Kaarten & Plans II	8577		1729		1729
ARA	Kaarten & Plans II	669		1750		1750
ARA	Kaarten & Plans II	8616		1751		1751
ARA	Kaarten & Plans II	8573		1783		1783
ARA	Kaarten & Plans II	8557		1783		1783
ARA	Kaarten & Plans II	8599		1806		1806
ARA	Arenberg	842		1813		1813
ARA	Kaarten & Plans II	8554		1816		1816
ZA	Zelandia Illustrata	783		1896		1896

[23] Medium scale maps used for the planimetric accuracy assessment:

Archive	Division	Number	Date original		Date copy	
RAG	Kaarten & Plans	2454		1575		1695
ARA	Kaarten & Plans II	7210	+-	1600	+-	1600
ARA	Kaarten & Plans II	1185	+-	1636		1752
ARA	Kaarten & Plans I	2634		1661		1716
ARA	Kaarten & Plans I	19	+-	1677		1677
ZA	Zelandia Illustrata	270	+-	1699	+-	1745
ARA	Kaarten & Plans I	414	+-	1729	+-	1729
ARA	Kaarten & Plans II	8549	+-	1729	+-	1729
ARA	Kaarten & Plans I	441		1738		1738
ARA	Kaarten & Plans I	410	+-	1767	+-	1767
ZA	Aanwinsten	41		1791		1791
ARA	Arenberg	839		1839		1839

[24] Small scale maps used for the planimetric accuracy assessment:

Archive	Division	Number	Date original		Date copy	
Scheepvaart-museum	Atlas van Loon	Kaerte Vier Ambachten	+-	1600		1664
ARA	Kaarten & Plans II	176	+-	1600	+-	1600
ARA	Kaarten & Plans II	269	+-	1650	+-	1650
ZA	De Waard	1303		1676		1676
ZA	Zelandia Illustrata	1560		1748		1748
ZA	Polder van Walcheren	683		1892		1892

[25] The *Bonnebladen* were obtained in an already georectified form so no accuracy tests could be conducted.

[26] Note that this map depicts the several embankment phases of the *Doel*- and *Luyspolder*. The accuracy was determined for the situation of 1614 and extrapolated for other time periods.

[27] Note that the size (and therefore original scale of the map) could influence these MPE-measurements. A drawing error of 2 centimeters on a 1:10.000 map results in smaller MPE in real meters than the same drawing error on a 1:50.000 map. However, tests in old map distances reveal that the median of the MPE in map meters is almost six times smaller for

large scale maps than for medium scale maps. The differences in between medium and small scale maps are less pronounced.

[28] Kruskall-Wallis tests reveal a significant difference in means (p-value=0.000) However, Mann-Withney test calculations are: U=3, W=81, p-value=0.000 (large-medium); U=2, W=80, p-value=0.001 (large-small); U=17, W=95, p-value=0.075 (medium-small). Large scale compared to medium scale and small scale gives significantly differencing means, medium scale compared to small scale not significantly differencing means.

[29] ANOVA-testing gives p-values of 0.004 (3 classes); 0.504 (large scale); 0.180 (medium scale) and 0.006 (small scale).

[30] ANOVA-testing gives p-values of 0.000 (3 classes); 0.128 (large scale); 0.000 (medium scale) and 0.000 (small scale). Large scale sample size proves to be insufficient. Unfortunately, due to the small amount of identifiable (present-day) points on some old maps sample size could not be increased.

[31] Kruskall-Wallis tests reveal a significant difference between the averages (p-value=0.005).

[32] Defined as three times bigger than the standard deviation: $\sqrt{((\sum(v^2)/(2n-4))}$.

[33] These values were calculated using *QuantumGIS.* The structural distortion was removed through using the 'spline function' which makes all GCP´s correctly located, and thereafter unchecking each GCP of the cluster, giving its relative positional error compared to all the other GCP´s. Residuals in pixels were multiplied with the Helmert-scale factor.

[34] These kind of uncertainties can for instance also be found for mountainous areas (Jenny, 2006, p. 242).

[35] Note that for the reconstructions of 1690 and 1850 the northernmost tidal channel was superimposed on the tidal marsh based on two different map. For the tidal marsh, the MPE was still deducted from the map it was based on.

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