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A new GIS approach for reconstructing and mapping dynamic late Holocene coastal plain palaeogeography

H.J. Pierik [a],*, K.M. Cohen [a,b,c], E. Stouthamer [a]

[a] Department of Physical Geography, Faculty of Geosciences, Utrecht University, PO box 80.115, Utrecht, 3508 TC, The Netherlands
[b] Deltares, Dept. Applied Geology and Geophysics, PO box 85.467, Utrecht, 3508 AL, The Netherlands
[c] TNO Geological Survey of the Netherlands, PO box 80.015, Utrecht, 3508 TA, The Netherlands

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ABSTRACT

The geomorphological development of Holocene coastal plains around the world has been studied since the beginning of the twentieth century from various disciplines, resulting in large amounts of data. However, the overwhelming quantities and heterogeneous nature of this data have caused the divided knowledge to remain inconsistent and fragmented. To keep improving the understanding of coastal plain geomorphology and geology, cataloguing of data and integration of knowledge are essential. In this paper we present a GIS that incorporates the accumulated data of the Netherlands' coastal plain and functions as a storage and integration tool for coastal plain mapped data. The GIS stores redigitised architectural elements (beach barriers, tidal channels, intertidal flats, supratidal flats, and coastal fresh water peat) from earlier mappings in separate map layers. A coupled catalogue-style database stores the dating information of these elements, besides references to source studies and annotations regarding changed insights. Using scripts, the system automatically establishes palaeogeographical maps for any chosen moment, combining the above mapping and dating information. In our approach, we strip the information to architectural element level, and we separate mapping from dating information, serving the automatic generation of time slice maps. It enables a workflow in which the maker can iteratively regenerate maps, which speeds up fine-tuning and thus the quality of palaeogeographical reconstruction. The GIS currently covers the late Holocene coastal plain development of the Netherlands. This period witnessed widespread renewed flooding along the southern North Sea coast, coinciding with large-scale reclamation and human occupation. Our GIS method is generic and can be expanded and adapted to allow faster integrated processing of growing amounts of data for many coastal areas and other large urbanising lowlands around the world. It allows maintaining actual data overview and facilitates new ways of analysis at national, regional, and local scales.

1. Introduction

The evolution of Holocene coastal plain landscapes has been studied extensively worldwide over several decades of research history and from several different scientific disciplines, resulting in a large variety of thematic studies and maps. Some of these studies contain palaeogeographical reconstructions (e.g., Baeteman, 1999; Metcalfe et al., 2000; Fitch et al., 2005; Tanabe et al., 2006; Alexakis et al., 2011; Hijma and Cohen, 2011; Tamura et al., 2012; Tanabe et al., 2015; Vis et al., 2015), in which geological and geomorphological data was incorporated. Although differences in approach behind the various palaeogeographical map products exist, they all have been compiled using conceptual insights, based on geological principles and region-specific knowledge, such as history of relative sea level change or shifts in availability of sediment. These (mainly static) maps were compiled to map and illustrate coastal plain development and usually lack a systematic (i.e., verifiable) mapping approach. This limits possibilities to query, verify, update, and expand the reconstructions. Further improvement of coastal plain mapping is generally reckoned to benefit from the integration of heterogeneous data in palaeogeographical maps or uniform databases.

For the Netherlands, many high-density data sets, dissertations, map series, and reports documenting the complex geological subsurface architecture are available. They have been produced over a period of decades and greatly differ in state of knowledge at the time of production, in spatial coverage, and in research focus. Integrated traditional palaeogeographical map products (Pons et al., 1963; Zagwijn, 1986; Vos and Knol, 2015; Vos et al., 2015a, 2015b) have found considerable application in geoarchaeological studies (e.g., Knol, 1993; Vos and van Heeringen, 1997; Gerrets, 2010) and in geological-geomorphological coastal plain studies (e.g., barrier formation: Beets and van der Spek, 2000; river avulsion: Kleinhans et al., 2010; transgression and peat growth: Hijma and Cohen, 2011; Bos et al., 2012). The

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* Corresponding author.
E-mail address: h.j.pierik@uu.nl (H.J. Pierik).

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attribution of age to the mapped elements especially is a major source of uncertainty resulting in differences between reconstructions. Even for the densely mapped and dated coastal plain of the Netherlands, the number of elements in reconstruction maps is so large that their majority remains relatively dated only. For all these elements, age-attribution decisions are then taken, often without explicit documentation of the underlying assumptions. This makes adapting these reconstruction maps to new insights and data difficult and hampers integration with maps of adjacent areas. To keep national late Holocene landscape reconstructions up-to-date, a dynamic approach to mapping and dating is required that facilitates producing palaeogeographical maps for any chosen time step and allows us to easily update the elements on the map. To take into account all accumulated knowledge, integration and documentation of maps based on heterogeneous, fragmentary data sets for various parts of the coastal plain are essential. Such a system provides new opportunities to study the geological architecture and evolution of the coastal plain over large regions based on more uniform source data than traditional maps provide.

Since the 1980s, the development of Geographical Information Systems (GIS) has allowed digital map recombination and computer-aided conversion and processing of data (e.g., Burrough, 1986), making it easier to produce coastal plain landform and substrate maps. The GIS methodologies provide the possibility to collect large amounts of data into a single information system in which querying and processing of data and statistical analyses can be done. In this paper we present an advanced GIS design for geological-geomorphological and palaeogeographical mapping of the late Holocene coastal plain of The Netherlands. Our method elaborates on an earlier developed GIS for reconstructing the river network evolution of the Rhine-Meuse delta (Berendsen and Stouthamer, 2000; Berendsen et al., 2001; Cohen et al., 2012). Our GIS stores the accumulated mapping and attribute data of geological architectural elements in a uniform way. It uses scripts to automatically generate time slice maps based on age information that is stored as element attributes. In this paper, we restricted the GIS to the late Holocene palaeogeographical development (roughly the last 3500 years) — the youngest period for which data is available at the highest resolution and is most diverse. We explain our workflow for converting architectural-elements and their attributed age into palaeogeographical maps. In the discussion we focus on some of its output products and the research applications of the GIS. The GIS design and workflow to combine geological mapping and production of palaeogeographical reconstructions is a generic one. It is applicable to other Holocene coastal plains and other types of Quaternary sedimentary environments for managing ever-growing heterogeneous data sets, especially when excessive data availability and diversity hamper systematic analysis.

2. General approach

The coastal plain of the Netherlands is considered an amalgamation of landforms with barrier systems, tidal inlet systems, and coastal peatland (Figs. 1 and 2). Each tidal system consists of a main inlet channel that connects the open sea to different environments in the back-barrier zone (Fig. 2). The architectural elements that make up these systems are genetically uniform geological features (e.g., Miall, 1985; element complexes cf. Vakarelov and Ainsworth, 2013) that can be distinguished based on their three-dimentional geometry, scale, and facies. We distinguished several types of architectural elements shown in coastal plain geological maps: beach ridges (topped by dunes), tidal channels (channel belts, subtidal deposits), fluvial channels (in the part of the coastal plain that is affected by the Rhine-Meuse system), intertidal flats (*wadden*), supratidal saltmarsh, and freshwater peatland that occupies the farther inland part of the coastal plain. These architectural elements represent different landforms and former landforms with associated depositional environments (e.g., indicating position relative to tidal range and degree of exposure to waves; Van Straaten and Kuenen, 1957; Reineck and Singh, 1980; Vos, 2015).

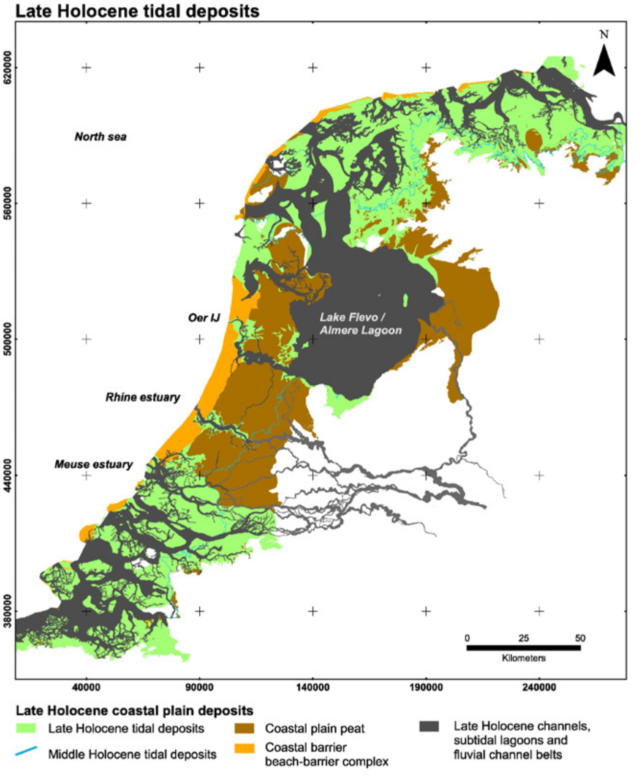

Fig. 1. Coastal plain of the Netherlands: coastal plain peat and middle Holocene tidal deposits after Cohen et al. (2015), tidal deposits (this publication).

In the last few 1000 years, the formation and abandonment of tidal inlet systems and connecting beach barrier and river systems have been controlled by natural and anthropogenic effects (e.g., Beets and van der Spek, 2000; Berendsen and Stouthamer, 2000; Vos, 2015). The multiple tidal systems that developed during the Holocene resulted in a complex stacked heterogeneous coastal plain subsurface. Bringing down coastal plain sequence mapping to generations of tidal systems not only serves the legend of geological mapping, but also is key to performing palaeogeographical reconstruction with that data.

In the redigitisation process of individual elements from earlier maps, four aspects were considered (Table 1): (i) their lithofacies, to decide the type of architectural element and palaeogeographical map legend; (ii) their planform geometry; (iii) a best estimate of their age; and (iv) their network position, i.e., the parent tidal system to which it connects. In some cases, these four aspects all followed straightforward from one single study. However, in many cases earlier mappings left aspects of dating and network position unspecified; here we assessed that information ourselves. For some elements, contradicting interpretations from different studies had to be assessed and judged. This was done element-by-element, taking into account the conceptual background of these studies, the year of map production and availability of new observations (Appendix). We started with unifying redigitised architectural elements from maps produced in national campaigns (geological, geomorphological, and soil surveys). In general, we retrieved the deeper preserved elements (>1–2 m below the surface) from geological maps, whereas soil and geomorphological maps were used for the shallowest elements (upper 1–2 m). We then supplemented the information further with more local studies, with higher dating resolution (e.g., Pons and van Oosten, 1974; Roeleveld, 1974; Vos, 2015). The extent of shallow elements with topographic expression (supratidal ridges; tidal channel micromorphology, etc.) was cross-verified with LiDAR elevation data, available since 2005. For a further overview of the incorporated materials we refer to the Appendix. At the most detailed level we stored absolute and relative dating information in a catalogue-style database that is part of the GIS. This includes a considerable amount of