Cultural Heritage Agency
Ministry of Education, Culture and Science

Nederlandse Archeologische Rapporten 055

Knowledge for Informed Choices

Tools for more effective and efficient selection of valuable archaeology in the Netherlands

Knowledge for Informed Choices

Tools for more effective and efficient selection of valuable archaeology in the Netherlands

R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, B.P. Speleers and J. van Doesburg (eds.)

Colofon
Nederlandse Archeologische Rapporten 55

Knowledge for Informed Choices.
Tools for more effective and efficient selection of valuable archaeology in the Netherlands.

Editors: R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, B.P. Speleers and J. van Doesburg

Authors: J.-E. Abrahamse, A.M. Blom, H.M.P. Bouwmeester, J.A.A. Bos, O. Brinkkemper, F.T.S. Brounen, K.M. Cohen, R. Dambrink, R. de Bruijn, T. de Groot, J.W. de Kort, F. de Vries, S. de Vries, M.C. Eerden, G. Erkens, H. Feiken, M.T.I.J. Gouw-Bouman, B.J. Groenewoudt, M.P. Hijma, D.J. Huisman, B.J.M. Jansen, M. Kosian, K. Koster, M.H. Kriek, M.A. Lascaris, R.C.G.M. Lauwerier, G.J. Maas, V.C. Marges, H.J. Pierik, E. Rensink, E. Romeijn, J. Schokker, B.I. Smit, M. Snoek, B.P. Speleers, J. Stafleu, E.M. Theunissen, R. van Beek, I.M.M. van der Jagt, J. van Doesburg, H. van Reuler, P.C. Vos and H.J.T. Weerts

Illustrations: M. Haars (BCL Archaeological Support), the authors, Cultural Heritage Agency of the Netherlands, unless otherwise stated
English translation or correction: Sue McDonnell Translation, Utrecht
Design and layout: Xerox/OBT, Den Haag

ISBN/EAN: 9789057992773

Rijksdienst voor het Cultureel Erfgoed / Cultural Heritage Agency of the Netherlands
P.O. Box 1600
3800 BP Amersfoort
The Netherlands
www.cultureelerfgoed.nl
www.archeologieinnederland.nl

Contents

Preface		**5**
Summary		**7**
Samenvatting		**9**
1	**Knowledge for informed choices. Tools for decision making in archaeological heritage management in the Netherlands**	**11**
1.1	Introduction	11
1.2	The European Convention and archaeology in the Netherlands	11
1.3	Evaluation of policy	13
1.4	Improvement actions and Knowledge Kit	13
1.5	Results	17
1.6	Conclusions and follow-up	19
2	**Periods, assemblage types and the Archaeological Landscapes Map**	**25**
2.1	Introduction	25
2.2	Four-period system of archaeology	25
2.3	Grouping archaeological assemblage types by main theme	32
2.4	The Archaeological Landscapes Map of the Netherlands. A new map for inventory and analysis at the archaeology-landscape interface	36
3	**Archaeological predictions in layers**	**49**
3.1	Introduction	49
3.2	Applied palaeolandscape research as a tool in archaeological heritage management. Modelling the Holocene coastal evolution of the Netherlands	50
3.3	A glimpse into the past. Mapping regional vegetation developments since the Late Glacial in Twente (the Netherlands)	64
3.4	Mapping buried Holocene landscapes. Past lowland environments, palaeoDEMs and preservation in GIS	73
3.5	Land Use in Layers. A digital insight into the complex occupation history of the Netherlands	94
3.6	Modelling the 16th-century urban countryside. A zone of influence and interaction	108
4	**Disturbance of the soil and of archaeological remains**	**121**
4.1	Introduction	121
4.2	Disturbance of soil and of archaeological remains resulting from soil tillage in the Dutch agricultural and horticultural sector	121
4.3	Mapping sources of soil disturbance information relevant to archaeology	128
4.4	Towards a predictive model for disturbances caused by agricultural land use	133
4.5	Mapping Disturbances. Potential disturbance of archaeological remains in built-up areas	143
5	**Mapping the Past for the Future. Local authority predictive maps and archaeological heritage management**	**155**
5.1	Introduction	155
5.2	The municipal level	157
5.3	Map images	158
5.4	Form	159
5.5	Content	159
5.6	Accessibility of maps	162
5.7	Conclusions and prospects for the future	162
6	**Prospection Made-to-Measure. A digital information system for archaeological prospection methods**	**165**
6.1	Introduction	165
6.2	Archaeological prospection in the Netherlands	166
6.3	The Prospection Best Practice project	167
6.4	Prospection methods	167
6.5	Prospection characteristics of find spots	169
6.6	From find spot properties to prospection best practice	172
6.7	Prospection Made-to-Measure digital information system	173
6.8	Considerations for the future	175
7	**Answers to questions. The new National Archaeological Research Agenda of the Netherlands**	**179**
7.1	Introduction	179
7.2	A brief history of the National Archaeological Research Agenda	179
7.3	Research agendas in archaeology at home and abroad	182
7.4	The need to make choices	183
7.5	Question-driven archaeology	184
7.6	National Archaeological Research Agenda 2.0, the general principles	185
7.7	National Archaeological Research Agenda 2.0: the process of drafting the agenda	186
7.8	National Archaeological Research Agenda 2.0: defining the research questions	187
7.9	How does the National Archaeological Research Agenda 2.0 work?	189
7.10	Concluding remarks	191

8	**Synthesising data from development-led archaeological research**	**195**
8.1	Introduction	195
8.2	Synthesising research before and after the Valletta Convention	196
8.3	Valletta Harvest synthesising research	197
8.4	Identification of knowledge opportunities and phase 1 selection	197
8.5	Identification of knowledge opportunities and phase 2 selection	200
8.6	Conclusions	206
List of products		**211**

Preface

Choices are inevitable in archaeological heritage management. There is nothing wrong with this, provided they are made in a well-informed, transparent and participative way. This idea is gaining more and more support internationally, and indeed it lies at the core of a recent European Archaeological Council (EAC) Action Plan prompted by the 15th annual EAC symposium held in Amersfoort, the Netherlands, in 2014.

In the Netherlands, care of the archaeological heritage is primarily the responsibility of local authorities. The signing of the Valletta Convention and the national legislation enacted as a result have had a major impact on the way we deal with archaeology. It is now an explicit element of the process of spatial planning, with the first option being to preserve remains *in situ*. If this is not realistically possible, the developer pays not only for an investigation but also for the publication of the information represented by the remains that are in danger of being lost. This approach has led to an increase in archaeological research, most of which is performed by commercial agencies. Local authorities play a key role in this. In spatial developments, they are the ones who largely decide the extent to which archaeology must be taken into account, how intensive any archaeological investigation should be, and what research questions should be taken into the field. The Cultural Heritage Agency supports local authorities in this task, providing specialist knowledge of archaeological heritage management and of the heritage itself.

Some years ago the Dutch State Secretary for Education, Culture and Science commissioned an evaluation of the effects of the archaeology legislation. It found that, though a great deal of good had been done, there were still areas requiring improvement. One of the conclusions was that the knowledge gained was not yet adequately reflected in local authority archaeology policy. It was clear that there was much to be gained by developing tools for local authorities and the agencies working on their behalf to ensure that: new insights obtained in archaeological investigations, and concerning the subsurface and past land use, lead to more accurate predictions of where traces of human habitation can be found;

- it becomes clear which supralocal questions about our past can be addressed by local research;
- insight is provided into what methods are most appropriate for tracing archaeological remains or verifying predictions, given the landscape and the remains thought likely to be found;
- an overview of the information and local authority archaeology maps is provided;
- overview studies are produced synthesising the many fieldwork reports into new knowledge of our past.

After a discussion in parliament the State Secretary commissioned the Agency to take action to strengthen the current archaeological system.

The present volume reports on the products developed to provide 'knowledge for informed choices' as part of the Archaeology Knowledge Kit programme. They include datasets, maps, methods, guidelines, best practice and web-based applications to facilitate the effective and efficient selection of valuable archaeological remains. These products have been developed by specialists and consultants at the Agency, in collaboration with local authorities, archaeological agencies, universities and other research institutions, a national farmers' organisation and other parties.

I hope that this volume includes matters of interest to you and, above all, that it will prompt you to join the discussion about the development of knowledge products that help us achieve the best possible standard of archaeological heritage management for the future.

Susan Lammers
Director, Cultural Heritage Agency of the Netherlands

Summary

Archaeological heritage management benefits from well-informed and transparent decision-making. With the aim of providing 'knowledge for informed choices', a series of tools have been developed for archaeological heritage management in the Netherlands. They include digital maps, datasets, methods, guidelines, best practice and web-based applications to facilitate the effective, efficient and transparent selection of valuable archaeological remains. The tools relate to archaeological predictions, disturbances by agriculture and other activities, archaeological heritage maps, prospection methods, research questions, and scientific syntheses to close the archaeological heritage management cycle. They are examined in the various chapters in this publication. The tools were developed as part of the Cultural Heritage Agency's 'Archaeology Knowledge Kit' programme, in response to an evaluation of archaeology legislation that entered into force in the Netherlands in 2007, implementing the Valletta Convention. The evaluation concluded that though many things are going well in archaeological heritage management, there are several points that are open to improvement. The State Secretary for Education, Culture and Science therefore commissioned a series of improvement activities.

Some of these activities have been performed as part of the 'Archaeology Knowledge Kit' programme. Chapter 1 outlines the goals of the programme, in the context of the legislation and the archaeological heritage management system in the Netherlands, as well as its constituent projects, the products it has yielded and the intended users. The organisational form chosen – a coherent programme with collaboration between projects that clearly overlap – has proved successful. It makes for better exchange and input of knowledge and information, allowing project teams to work more effectively, and undoubtedly raising quality. It is also a very pleasant way of working.

Chapter 2 presents 'tools' that were needed to develop the applications for archaeological heritage management discussed in later chapters: a chronology, a grouping of assemblage types and a map. Part 2.2 presents a new, simplified chronological classification of the archaeology of the Netherlands comprising four periods: hunter-gatherers and early farmers, early farming societies, late farming societies and state societies. This classification is based on similarities and differences in methods of subsistence and how the archaeological remains are manifested in the soil. In 2.3, the many assemblage types in the Basic Archaeological Register (ABR) are grouped into four main themes: settlement, burial, economy and infrastructure, and ritual practices. This was necessary for the 'Land Use in Layers' and 'Prospection Made-to-Measure' applications discussed in chapters 3 and 6. The new Archaeological Landscapes Map of the Netherlands is presented in 2.4. It distinguishes 26 landscapes with 39 different landscape zones. These zones are based both on landscape features and also various archaeological characteristics.

Predictions are the focus of chapter 3. The first contribution in this chapter (3.2) looks at the creation of the 12 palaeogeographical maps of the Netherlands for different points in time over the past 10,000 years. The reconstruction is based on the analysis and interpretation of tens of thousands of corings, research into the formation and age of geological deposits in the soil, and archaeological information. Part 3.3 explains how vegetation maps and reconstructions have been produced for various periods in the past on the basis of pedological, palynological and archaeological data. In parts 3.4 and 3.5 the focus is on how to make maps that show the probability of encountering archaeological remains from different periods, and at different depths. Part 3.4 discusses a way of reconstructing buried landscape zones used by humans in the past on the basis of a multitude of data on the coastal plain subsurface of the Netherlands (to twenty metres below the surface). Part 3.5 then considers the provision of information on how humans used these landscape zones – some of which are now buried – in the past. The final part of this chapter (3.6) looks at the development of predictive archaeological models for the urban countryside based on historical town maps produced by Jacob van Deventer in the second half of the 16th century.

Soils disturbed to such an extent by soil excavation or agricultural activities that they contain no useful information about the past need not be subjected to archaeological investigation. Part 4.4 discusses ways of

producing local maps that show the probability of disturbance. Prior to this, part 4.2 describes the impact of various agricultural and horticultural cultivation activities on the soil, and part 4.3 presents an overview of national and regional datasets containing information on locations that may be disturbed. Finally, part 4.5 presents a model showing how, in an urban context, the soil might be disturbed or preserved under various types of residential area constructed since the nineteenth century.

Local authority archaeological resource maps and predictive maps vary markedly, even in adjacent municipalities. This makes it difficult to compare them or use them in combination. Chapter 5 describes how the local authority maps – totalling more than 1500 – have been surveyed and analysed to gain an insight into the information they contain and how they were compiled. The results of the analysis provide a starting point for discussions with the makers and users of the maps, with the aim of establishing how they can be better coordinated so that more uniform maps are produced.

For years, archaeologists have been debating the correct way to locate find spots in the varied landscape of the Netherlands. Although a lot of experience has been gained with archaeological prospection in the past few decades, choosing the most appropriate method is neither simple nor clear-cut. Each method of prospection has its own applications, potential and limitations. Chapter 6 looks at the background and the creation of the Prospection Made-to-Measure online information system that provides advice on the most suitable methods.

Chapter 7 is devoted to the new National Archaeological Research Agenda 2.0, which sets out the most important archaeological research questions affecting multiple regions in the Netherlands. This chapter looks at the background to and creation of this user-friendly online agenda. It is centred around 117 specific research questions addressing the most pressing issues at this time. Practical guidance on each question suggests suitable approaches to fieldwork in order to answer the questions.

The goal of the Valletta Harvest project (chapter 8) was to synthesise the results of development-led archaeological research into new knowledge of the history of the Netherlands. The subjects of the syntheses were determined by the ‘knowledge opportunities’ identified by determining which areas, themes and archaeological periods had been reported on most, and then selecting questions from the national archaeological research agenda that could be answered using these reports. The results of the first syntheses were used to determine what we can learn about the scientific synthesis of development-led research reports and what recommendations might be made for further improvements to excavation and reporting.

The completion of the ‘Archaeology Knowledge Kit’ programme does not mean the end of all the activities. Over the coming period the products of the programme will be evaluated and improved where possible.
In addition add-ons and some entirely new products will be generated for the effective and efficient selection of valuable archaeological remains.

3.4 Mapping buried Holocene landscapes. Past lowland environments, palaeoDEMs and preservation in GIS

K.M. Cohen[50 a b c], R. Dambrink[c d], R. de Bruijn[b c], V.C. Marges[b], G. Erkens[a b], H.J. Pierik[a], K. Koster[a c], J. Stafleu[c], J. Schokker[c] and M.P. Hijma[b]

Abstract

In a geological GIS-data recombination project, a digital map was produced that contains information on the Netherlands' former coastal and delta plain landscapes over the last 14,000 years: the Holocene and the very end of the Pleistocene. The polygon map product is accompanied by a set of palaeoDEMs (Digital Elevation Models) indicating the attention depth for buried land surfaces and aquatic deposits for four time slices. This paper provides conceptual background information on the legend and construction principles behind the polygon maps and the palaeoDEMs, i.e. the decisions taken during the making of. It also provides a basic overview of the map product: landscape structure, burial depth and preservation, visualised for the four time slices in the RCE's Archaeology Knowledge Kit. The text links coastal plain buried landscape mapping for four time slices to the other Knowledge Kit activities described in this volume, notably that of the Archaeological Landscapes map (for the most recent time slice in the coastal plain area of the Netherlands, and for all time slices in the Pleistocene uplands).

Keywords: Buried landscapes, geology, geomorphology, digital mapping, palaeosurfaces

3.4.1 Introduction

This contribution describes the making of a series of digital map layers that contain information on the Netherlands' former coastal and delta plain landscapes. The map series was commissioned for the Predictions in Layers project, part of the Archaeology Knowledge Kit programme discussed elsewhere in this volume.[51] The map series aimed[52] to summarise information on buried former landscapes as known from geological mapping in such a way that it is compatible with the Archaeological Landscapes map,[53] the parallel product for the landscape structure of the modern surface. Given the time slice approach of the Predictions in Layers project, having just the latter map would have excluded earlier periods from the dissemination of meaningful, regionally diversified landscape-archaeological knowledge.

This chapter first outlines the goals and means of map production, and then highlights the different approaches needed when mapping buried landscapes as opposed to surficial geomorphological mapping. The remainder of the chapter focuses on describing the methodology used to construct the maps and palaeoDEMS.

Map production goals and means

The aim of the project was to produce a uniform series of maps (Fig. 1), distributed in the form of a GIS dataset, detailing the buried landscape structure and burial depth for four consecutive time slices. In line with the systems used in the other Archaeology Knowledge Kit products described in this volume, it makes use of an archaeological periodisation system that divides the time since 12,000 BC into four consecutive time slices (T1 to T4).[54] Combined with an initial 'Top Pleistocene' landscape state (at time slice T0), the full periodisation scheme is as shown in Table 1:

The GIS dataset was produced following a systematic - i.e. repeatable and automated - procedure that combined and converted existing digital map data available from past geological mapping (location, depth and age of deposits) and palaeogeographical research projects (past landscape functioning, landform inheritance, reconstruction of eroded landscape, links with past sea levels and groundwater tables). Importantly, the workflow was stored in a series of scripts, which serves to document the map production process, thus making it reproducible and maintainable.

The workflow used two spatial classification schemes in addition to time slicing. The coastal plain was divided into nine sectors (or regions) based on differences in the Pleistocene substrate and Holocene landscape evolutionary history (tidal, peaty and riverine parts of the plain; till affected vs. sandy substrates), while within each sector, the landscape structures within each region were mapped as 'landscape zones' (as on

50 Corresponding author: k.m.cohen@uu.nl; [a] Utrecht University, Department of Physical Geography, Utrecht, the Netherlands; [b] Deltares Research Institute, Utrecht, the Netherlands; [c] TNO - Geological Survey of the Netherlands, Utrecht, the Netherlands; [d] presently at: NWO domain TTW, Utrecht, the Netherlands.

51 Lauwerier 2017: this volume 1; Smit & Feiken 2017: this volume 3.5.

52 Cohen & Schokker 2014; Dambrink *et al.* 2015; Cohen *et al.* 2017a, b.

53 Rensink *et al.* 2017: this volume chapter 6; Smit & Feiken 2017: this volume 3.5; Cohen 2017.

54 Groenewoudt & Smit 2014 2017: this volume 2.2.

the Archaeological Landscapes map). The threefold division of time slice, sector/region and landscape zonation, served digital map visualisation by applying one legend to consecutive fields of the same polygons. It also serves polygon-level linking of bits of other tabulated contents to the map, so that relevant snippets of web-formatted information can be served to a user following a click on the map (envisaged portal functionality).

Buried landscape versus surficial geomorphological mapping

Although buried landscape mapping and surficial landscape mapping of past to present states of the Holocene coastal plain can use a shared end-result legend, the data sources and types of reasoning involved differ greatly from each other. One could say that the Holocene Buried Landscapes maps describe the natural landscape evolution of the Dutch lowlands up to c. AD 900,[55] whereas the Archaeological Landscapes map describes the human-induced transformations of that natural landscape since then. Differences in the making of these two maps extend beyond the triviality of dealing with differences in data availability and quality. They extend to the factors time (age and preservation) and humans (reclamations, man-made land).

Age is essentially a property of geomorphological mapping where it is witnessed by degrees of surficial soil formation and landform freshness. In geological mapping, however, it is treated more like a dimension than a property, and this dimension is considered partly interchangeable with depth. Further differences in dealing with the factor time exist between mapping present-day situations and past situations, and concern how preservation is taken into account. This is a given for maps documenting the present-day surface, but it is something to consider when mapping past surfaces, which buried surfaces are by their very nature.

Regarding human impact, the present coastal plain is dominated by human-modified landforms to such an extent that the standard geomorphological map legend for the Netherlands does not contain classes of the unaltered natural landforms. For example, the active riverine landforms recognised are the human-modified 'embanked flood plains' (Dutch: *uiterwaarden*) and 'water/river beds', complemented by fossil 'alluvial ridges' and 'residual channels'. Non-embanked flood basin and non-modified active meandering river beds do not exist as legend units. In the same way, deteriorated peat wetlands (Dutch: *veenvlakte, veenglooiing*) constitute a unit, while active peat-forming reed lands do not. What also happens is that cultivated, former salt-marsh polder land is mapped as the same geomorphological unit as remaining salt-marsh on the seaward sides of dike-protected areas. In other words, human presence has been regarded as a given in geomorphological mapping.

Data availability for buried landscapes reduces, the deeper the landscape is buried, and increases where the area is more densely built up. We know more about the subsurface of the city and port of Rotterdam than we do about more rural northern parts of Holland, despite their similar burial depth. For surficial natural landscape mapping, data availability is lower where the landscape has been historically built. Where the natural surface cannot be surveyed

Table 1 Overview of classification into archaeological periods.*

Periodisation	Archaeology	Geology / Palaeogeography	Map product
T4: AD 900 to present	State societies	Surficial reclamation landscape	RCE-T4
T3: 1500 BC to AD 900	Late farming societies	Late Holocene buried landscapes	T0123 – this paper
T2: 3400 to 1500 BC	Early farming societies	Late Holocene buried landscapes	T0123 – this paper
T1: 7000 to 3400 BC	Hunters, gatherers, earliest farmers	Middle Holocene buried landscapes	T0123 – this paper
T0: 12,000 to 7000 BC	Hunters, gatherers	'Top Pleistocene' buried landscape	T0123 – this paper

* In accordance with Groenewoudt & Smit 2014; this volume 2.2; their time slice T1 is equivalent to our time slices T0 + T1).

55 Cohen & Schokker 2014.

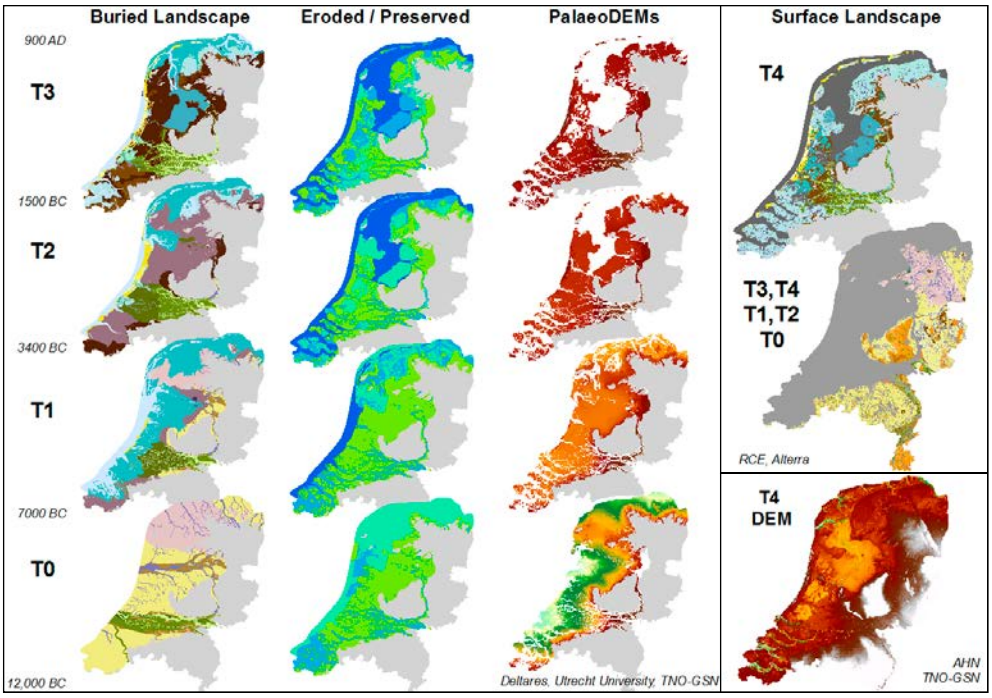


Figure 1 Full set of buried landscape zonation, erosion status and palaeoDEMs for time slices T0123 (this chapter) and RCE-T4 (Rensink *et al.*, this volume 2.4), from the 'buried landscapes' and 'archaeological landscapes' mapping projects.

from the air (traditional relief mapping, LiDAR mapping) and has been excluded from soil map surveying (not agricultural or forestry land), borehole data from geological mapping and archaeological digs have to be used to supplement geomorphological mapping.

The above has given rise to differences in the science practitioner paradigms underlying the Holocene geomorphological and geological mapping in the Netherlands, as approached by different institutions in the 1960-1980s.[56] As a result, the Wageningen school of classic pedological and geomorphological mapping[57] that echoes through in the patterns of the Archaeological Landscapes map (referred to as RCE-T4 in the remainder of this text), differs from that of the map datasets underlying the Holocene Buried Landscapes maps (referred to below as T0123), i.e. geological profile-type mapping as developed at the Geological Survey (RGD)[58] and profile-type mapping[59] and architectural mapping[60] as developed at Utrecht University (that echoes through in many municipal landscape archaeological maps in the Dutch coastal plain).

The map series described here is not the first national-scale palaeogeographical map series[61] showing the evolution of the Netherlands' coastal plain, but it is the first such map series that has been systematically produced and that is explicit in considering erosion/preservation issues. The map combination and mapping integration potential of the current digital era (2015) and broad professional demand for geological-geomorphological maps that communicate integrated knowledge regarding landscape *and* subsurface, called for a syncing of the map products from all these schools.

Thus, the 'Prediction in Layers' called for a map product covering the coastal plain buried landscapes was an opportunity for Utrecht University (UU), TNO - Geological Survey of the Netherlands (TNO-GSN) and Deltares to work on map production solutions that would achieve such syncing. Overcoming critical issues regarding legend setup and naming units became an exercise in recognising and overcoming the differences resulting from the paradigms of the surficial and the buried Holocene landscape mapping schools in the Netherlands, especially when it came to the design of the production workflow.

56 E.g. Berendsen 2007; Van der Meulen *et al.* 2013.
57 Maarleveld, Ten Cate & De Lange (eds.) 1977; Koomen & Maas 2004; Alterra 2006.
58 Geological map sheets, e.g. Westerhoff; De Mulder & De Gans 1987; Verbraeck 1984.
59 Berendsen 1982; Berendsen, Törnqvist & Weerts 1986; 'geomorphogenetic mapping'.
60 Berendsen & Stouthamer 2001; Gouw & Erkens 2007; Cohen *et al.* 2012.
61 Vos 2015 mentions Pons & Wiggers 1959-1960 and Zagwijn 1986 as precursors to the Vos *et al.* 2011 (v1) and Vos & De Vries 2013 (v2) map series. See also Vos & De Vries 2017: this volume 3.2.

3.4.2 Materials and Methods

The buried landscape maps and palaeoDEMs[62] were produced in a digital workflow carried out in GIS (developed in ESRI ArcGIS 10). This workflow was fed with existing digital map data, notably those of the 3D geological mapping programme at TNO-GSN (GeoTOP national scale 3D modelling[63]), datasets from UU palaeogeographical research (Delta Evolution[64]) and the Netherlands in the Holocene map series[65] (produced by Deltares, TNO and RCE).

After prototyping the methodology, the eventual series of technical steps was stored in a series of scripts. These scripts can be re-executed and thus not only document the production steps in coded statements, but also make the production process reproducible. The full digital product consists of the newly created maps (T0123 shapefile and a set of palaeoDEM grids) with standard layout files, and of the sets of scripts (ESRI ArcMap Toolsets) and input maps (i.e. copies of their live versions at UU and TNO-GSN). In other words, both the maps and the production methodology were solicited output in this project.

The input maps are referred to below as base maps, and the output product T0123 as a derived map. The approach using base maps and derived maps was previously deployed for reconstructive mapping of the Rhine-Meuse delta. The approach was pioneered between 1998 and 2012, when a single base map of channel belts was developed to generate a derived-map time series of river network development.[66] In 2013-2014, the approach was used to generate predictive archaeological maps for embanked flood plains in ten time slices as derived maps, from a base map of floodplain age between river and dikes.[67] Over the period 2011-2016, the suite of base maps was expanded to cover the Netherlands' coastal plain outside the riverine area too, introducing base maps holding information on pre-deltaic valley landforms, tidal channel belts, intertidal areas (wadden), areas of supratidal cover (salt marsh), and fluvial natural levee complexes. The main purpose for the expansion, had been to generate palaeogeographical time series as interactively interrogatable and reproducible derived maps.[68] The current project is however the first to create derived map products combining several base maps obtained from multiple institutes.

The design of the map-production workflow involved conceptual decisions besides technological steps. These decisions were responses to issues such as how to code things and what landscape zones to map explicitly, and what to merge and map only implicitly. The technological steps were practical execution rules, such as what polygon(s) to select, copy, intersect, merge and relabel. Some of the conceptual and technological solutions were predetermined, i.e. intrinsic to the process of incorporating information from the base maps and the systematics in them as decided upon in past studies. Examples are the lithostratigraphical system in TNO-GSN's geomodelling and the age encoding system in the UU palaeogeographical GIS approaches. The conceptual and technical decisions thus also addressed the question of the extent to which existing UU or TNO-GSN coding and workflow should be used, and from which point to tap in and append new scripts.

This section describes the workflows for 1) derivative mapping of the geomorphological zonation of buried landscapes (past geomorphology) and their erosion status, and 2) the palaeoDEM construction from combining 3D geological mapping information with accommodation space 3D interpolations (past elevation).

3.4.3 Buried Landscape map production and legend setup

The workflow to calculate the T0123 map and associated palaeoDEMs (Fig. 2) comprises a long series of logical steps, completed in parallel paths. The first path covers the mapping of landscape zonations, the second the mapping of erosion status, and the third the production of the palaeoDEMs (section 2.3). Throughout the workflow, the paths use the same input map data. Both mapping paths comprise long series of actions that involve selecting features from multiple input maps, extracting them from the input files, storing intermediate recombined results per time slice and converting their encoding.[69]

For the landscape maps, the final step of the workflow is to merge the partial results on

62 DEMs are Digital Elevation Models, also known as digital terrain models, often for modern surfaces but equally for buried surfaces. PalaeoDEMs are DEMs for past situations. The term is used in various earth surface modeling and palaeo-environmental reconstruction user communities.
63 Stafleu *et al.* 2012; Van der Meulen *et al.* 2013.
64 Cohen *et al.* 2012; Pierik, Cohen & Stouthamer 2016.
65 Vos *et al.* 2011, Vos & De Vries 2013; Vos 2015.
66 Berendsen & Stouthamer 2001; Berendsen 2007; Erkens 2009; Cohen *et al.* 2012.
67 Cohen *et al.* 2014.
68 Pierik, Cohen & Stouthamer 2016, in prep.
69 Cohen *et al.* 2017a,b.

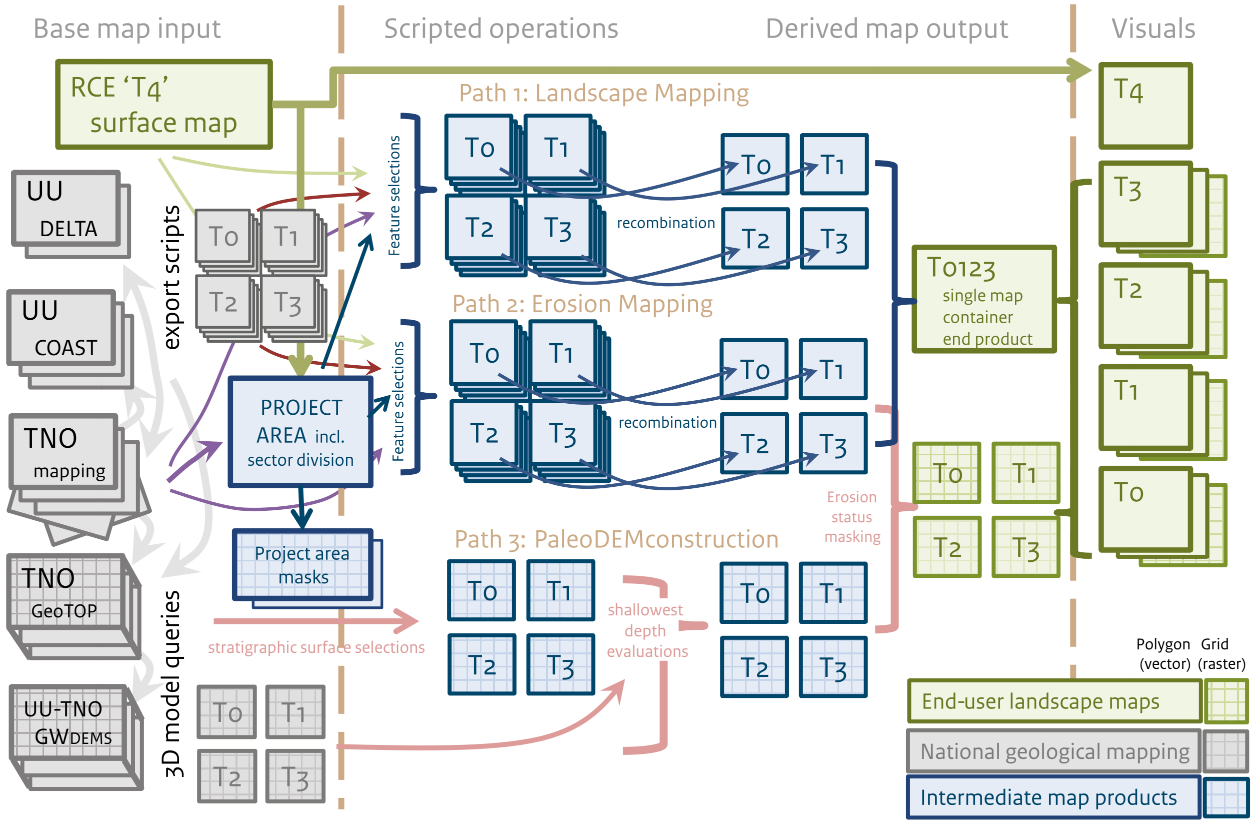


Figure 2 Flow diagram of the production of the buried landscape maps and palaeoDEMs: base map input, processing paths, output data files and visuals.

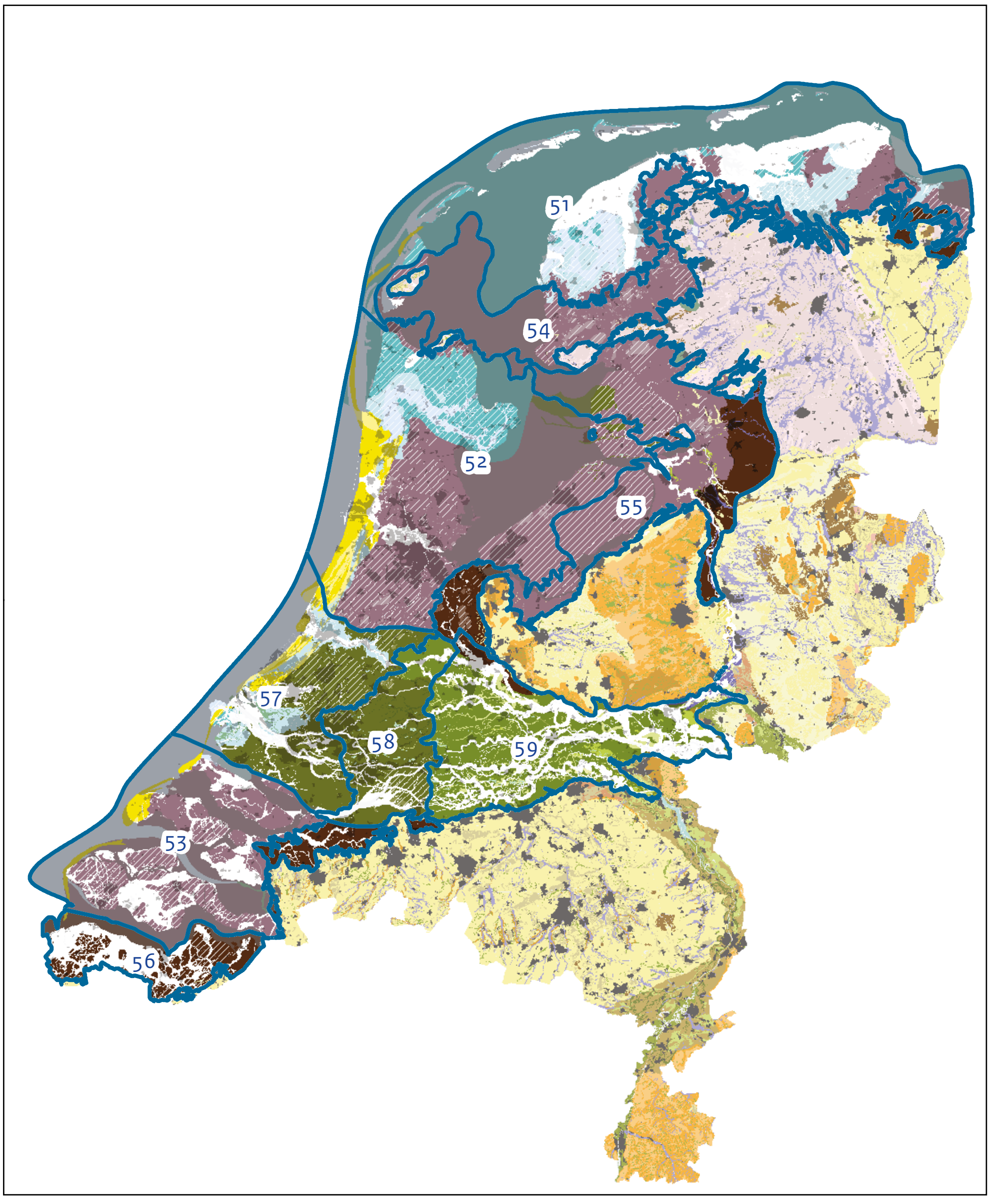
landscape mapping and erosion zonation and store it in a single polygon mosaic in digital map format, which is the end product. Each polygon in this digital map holds encoded information stored in a series of attribute columns (nine in total, see below). To visualise the series of maps, the legend is recycled through these attribute columns, i.e. for each successive time slice, the legend is applied to the following attribute. All map visualisations for each time slice are thus based on one and the same parent file.

A first single attribute *H_B_HFD* is used to distinguish the regions[70] that share similar buried landscape development over the period under consideration. Next, the attributes *LZ_0, ..1, ..2* and *..3* hold the information on landscape zonation maps for the T0, T1, T2 and T3 cycle. Similarly, the attributes *T0.., T1.., T2..* and *T3_EROD* hold the information on erosion status. For this purpose, the LZ.. fields have numeric values between 1 and 45, whereas the attributes in the ..EROD attributes have numeric values between 1 and 4. The *H_B_HFD*, LZ.. and ..EROD attributes together are the 1 + 2 x 4 = 9 attribute columns referred to in the previous paragraph.

The legend for landscape zone display uses a uniform polygon fill colour scheme and encoding in the LZ.. field. The colour scheme and numeric encoding are shared[71] with those used on the RCE-T4 map (its LSCPZONE field; see Table in Smit and Feiken).[72] The landscape zone encoding covers, for example, alluvial ridges (#24), salt marshes (#29), beaches (#32), types of peat land (#26, 43, 44, 45), types of inland dune (#13, 14, 23, 40).

The legend for erosion status uses half-transparent overlay signatures in black-and-white (Fig. 1, Fig. 3). Anything preserved retains the landscape zone legend colour, anything partially reworked a hatch overlay signature, and anything fully eroded is masked out - based on the values of the ..EROD attribute. This field has no equivalent in the RCE-T4 map and the numeric scheme has been introduced for the

70 Cohen 2017. Regions labeled #51-60, adding to regions 1-26 in RCE-T4.
71 LZ#1-38: Rensink *et al.* 2016; LZ#40-45: Cohen 2017.
72 Smit & Feiken 2017: this volume 3.5: their Table 3.



Regional subdivision   51 Number of region

Figure 3 Buried landscape mapping for time slice T2: regional subdivision in nine sectors (blue outlines, #51-59), landscape zonation and erosion status. Full series in Figure 1. Landscape zonation legend same as archaeological landscape map (see Rensink *et al*. 2017, this volume 2.4). White masking and hatching: eroded, resp. partially eroded land surface area.

buried landscape part of the Prediction in Layers project specifically. The four classes in this legend indicate whether in more recent times the landscape has 1) been preserved, was 2) partially eroded / shallowly reworked, 3) fully eroded / intensively reworked, or 4) was never a terrestrial surface.

Workflow steps and overcoming conceptual problems

Designing the technical workflow for the buried landscape maps, involved the following actions:

1. Collecting and selecting the input data (TNO, UU, Deltares) for the project.

2. Defining the T0123 project area, as a selection of regions (*LSCPHFDEEN*) from the RCE-T4 map: part of the Netherlands buried in the Holocene.
3. Manually inspecting and partially updating the input data and RCE-T4, checking for inconsistencies and where feasible fixing them (synchronising).
4. Defining and manually encoding (polygon labelling) a regional subdivision of the project area, resulting in nine sectors/regions, differing in the nature and timing of gross Holocene development (Fig. 3).
5. Defining and manually encoding (polygon labelling) an *a-priori* blanket landscape zone and erosion status value, for each region and time slice.
6. Determining the order in which to process and combine input data in the automatic procedures (honouring stratigraphic order, honouring time slicing)
7. Sequentially executing 'feature selection' and 'attribute calculation' steps, per input data set, per time slice, for landscape zonation, for erosion status.
8. Combining the above prepared partial data, in the correct order, using 'Union', 'Combine' and 'Dissolve' operations – resulting in the T0123 shapefile.
9. Preparing layout and legend files to correctly display maps per time slice. The layout and legend design in GIS discloses the integrated map content, and allows for interactive inspection and export of graphics. As such, this is a prototype data viewer, of direct use to GIS-trained professionals and our way of transferring the product to developers of the Archaeology Knowledge Kit portal (see Discussion).

The above steps encompass the selection, merging and conversion scheme for polygons that originally outlined subsurface geological features (i.e. bodies of deposits), and relabelled them to geomorphological features (i.e. landscape zones). This process of translation involved making conceptual design decisions as well as technical IT decisions, and when deciding on solutions the map maker weighs up various bits of knowledge. This includes knowledge of the original descriptions of sediments and the associated dating information (quality of the underlying data, understanding of past mapping practices), as well as knowledge of the successive depositional environments during the Late Glacial and Holocene epochs, essentially Quaternary geological textbook knowledge.[73]

The workflow design dilemmas that we encountered were not entirely new. They have been experienced by earlier authors in verbal, written and graphic translations, when they introduced landscape settings in words or print in reports, scientific papers, map sheet memoirs, popular books, animations and hand-drawn maps. The difference in this project is the extra step needed to capture the response to the dilemmas in strict decision rules and conversion schemes. In the earlier contexts, decisions and conversions were usually ad-hoc, while the issues surfaced when part of the map was processed (either on paper or digitally), and not necessarily followed up in a systematic way over the entire map area. Nor were they fully documented everywhere.

In this project, the rules and schemes were to function as instructions to a computer to execute the process as an automated workflow – ensuring that, once formulated, they would be executed consistently over the entire map area and would be written up. Solutions to dilemmas were not always implemented as procedures in the same step where the issues first surfaced. Possible ways of dealing with the dilemmas were explored during the prototype workflow design, and the most pragmatic was selected. This could be either a manual edit to a base map, or a code fix in scripts for the derived map calculations. Some of the dilemmas we came across are presented below by way of illustration. They are presented as questions and the answers are linked to the technical workflow steps.

Should we attempt automatic map production at all?
This was assessed at the very beginning of the project (Steps 1 and 2). Feasibility was judged to be good because the breaks between the four time slices for which buried landscapes maps were needed from an archaeological perspective matched moments in time known to have been distinct breaks in the coastal plain build-up from a geological perspective. This was especially important for the breaks between T0-T1 and T1-T2, time periods for which palaeogeo-graphical base maps that allow age-based selections are not as well developed as for the

[73] E.g. De Mulder *et al.* 2003; Wong, Batjes & De Jager 2007; Stouthamer, Cohen & Hoek 2015.

more recent time periods. The fortunate semi-synchronous matching of the archaeological and North Sea coastal sedimentary changeovers meant that TNO-GSN lithostratigraphical distribution maps could be used to supplement UU palaeogeographical mapping systems, so that the full project area for each of the time slices had suitable base map cover. It would not have been possible to split time slice T1 or T2 into shorter divisions and produce buried landscape maps consistently across the entire Netherlands, because no age-encoded base map for tidal systems is yet available for that time.[74]

How to deal with inconsistencies in input data from different sources?

Input data inspection and problem area identification was the first phase in the execution of the project (Step 3). Mismatches resulting from mapping inaccuracies could be fixed by correcting one of the base maps (and informing the owning institute about it). Mismatches that resulted from applying principally different mapping criteria were simply listed as to be dealt with at a later stage. Such issues were resolved in steps 6 to 8, either by selecting the feature from one input map only (other mapping ignored) or by selecting from all input maps (maximising the local feature areas).

How to partition the study area for buried landscape mapping?

In discriminating sectors/regions with similar buried landscape sequences (Step 4), we complied with established lithostratigraphical division schemes for the Netherlands and distribution maps based on them from shallow geological mapping. Applying three simple gross-scale architectural criteria (which can overlap) to the coastal plain area allowed nine adjacent sectors to be distinguished: 1) Seaward coastal plain sectors with T1 and/or T2 tidal sediments (four out of nine sectors are tidal, one of them fluvio-tidal). These are the regions with relatively thick, complex architecture with erosive and depositional landforms, where relatively large burial depths were distinguished from inland regions dominated by peat formation, where thinner, mostly depositional landforms and shallower burial depths are common (four other sectors, one of them fluvio-organic). 2) The Rhine-Meuse delta plain (three out of nine sectors are fluvial, one of them fluvio-tidal, one fluvio-organic, one exclusively fluvial) as characterised by freshwater clay deposition was distinguished from non-fluvial coastal plain sectors. 3) Coastal plain regions overlying Pleistocene areas with glacial till near the surface located in the Northern Netherlands (two sectors, one tidal, one organic) were distinguished from the rest of the coastal plain, which has a predominantly sandy Pleistocene substrate (the other seven sectors, whether tidal, organic, fluvial or combined). This ensured that coversand ridges and brook valleys on till plateaus, for example, with their particular hydrology and soil conditions, archaeological site taphonomy, types of gravel resources, etc., could be treated separately from those in sandy areas. Figure 3 illustrates the resulting partitioning for time slice T2, Figure 1 the consistency between time slices.

The nine-fold partitioning of the study area was helpful for the mapping of erosion status, not least because of the notion that the time slice T1 and T2 tidally-influenced part of the coastal plain is also the area where the Pleistocene substrate (T0 buried landscape) is found at the greatest depth, out of reach of erosion for all but the bottoms of the largest-deepest channels as we know them today. This means that the T0 surface could be regarded as beyond the reach of reworking from the channel systems (estuaries, alluvial ridges, rivers) appearing on the maps of T2, T3 and T4 in these seaward sectors, and thus relatively well preserved (Fig. 4), whereas in inland sectors these same rivers are known to have eroded the Pleistocene subsurface.

Specifically mapped features or envelope map units?

When legends of geomorphological maps are analysed, some units tend to be area-extensive landforms (e.g. flood plains, coversand plain), whereas others are smaller landforms recognised within them (e.g. alluvial ridges, coversand ridges). This is also the case in the RCE-T4 legend (and its parent the Geomorphological Map of the Netherlands). What often happens is that the smaller landform map units are explicitly mapped ('outlined'), whereas the area-extensive map unit is the remaining surrounding area ('enveloping'). The latter are the more suitable for a-priori coding (needed in Step 5) because in the later steps of the workflow (Steps 6-8) they will be replaced by feature selections drawn from

[74] Cohen & Schokker 2014.

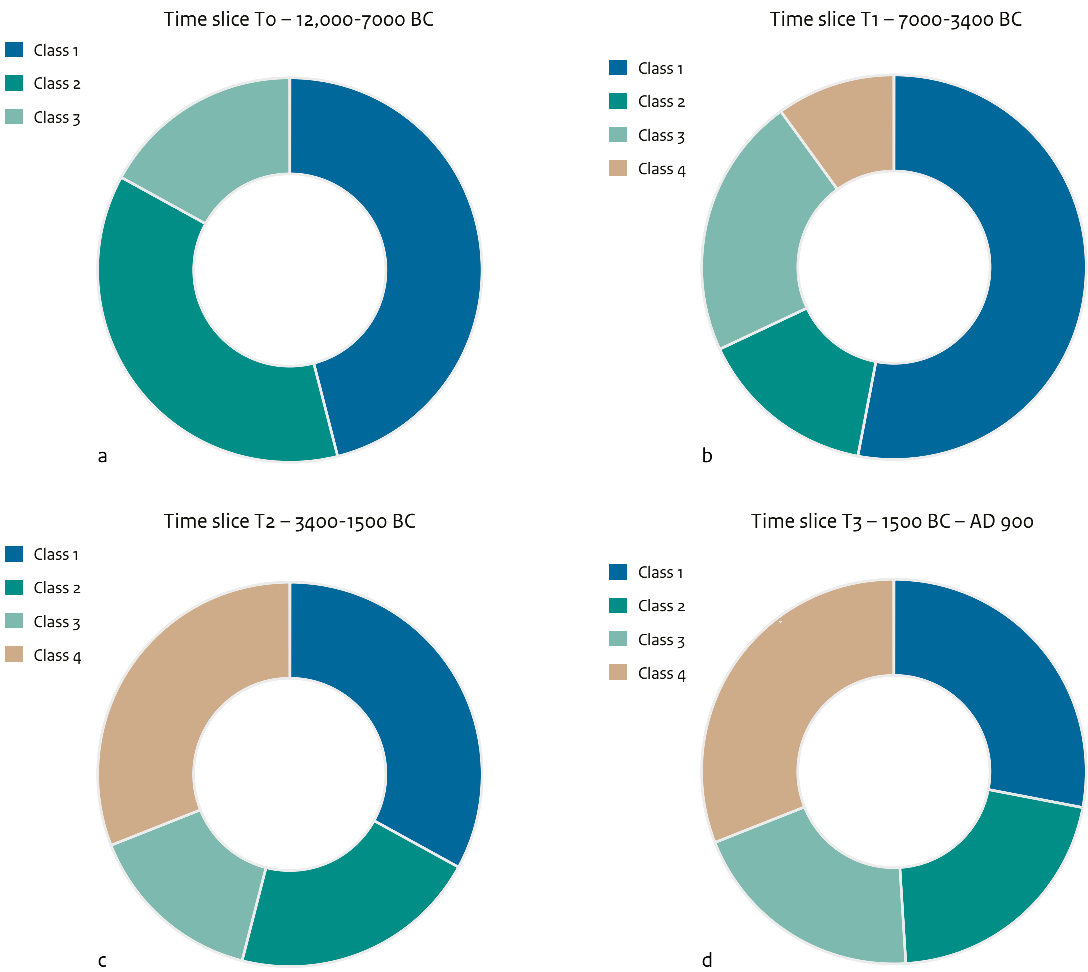


Figure 4 Pie charts showing coastal-plain total areal preservation statistics for buried surfaces from four time slices. Class 1: preserved land surface; 2: partially eroded / shallowly or surficially reworked land surface; 3: fully eroded / intensively reworked land surface; 4: originally subaquatic surface area. Depending on the application, class 4 is included or excluded in reporting statistics.

other input maps that contain explicitly mapped features. For example: the Rhine-Meuse valley and flood plain in each time slice is first considered a large 'flood plain' (Step 5; a-priori value for attributes in the *LZ..* field), and in Steps 6 to 8 ribbon-shaped smaller polygons of mapped channel belts are queried (from a base map storing their age, as time-slice dependent selections), and pasted into the map, replacing 'flood plain' with 'alluvial ridge' where appropriate. The filling of the erosion status attributes (*..EROD*) was based on the same principle.

In what order should the various features from multiple sources be assembled?

Here the decision was taken in two parts. First, the landscape-zone mapping and erosion status mapping were parallel workflows. This made it possible to work from the 'bottom up' in the buried landscape workflow (Steps 5, 6 and 7), honouring the aggradation process so typical of the Holocene coastal plains. Assigning landscape zones on the map to each successive, more recent, time slice starts with the assigned result for the previous time slice. Where appropriate, the workflow replaces landscape zones with those from the newly established environment, and where change has not yet happened, the previous assignment is retained. The parallel workflow for erosion status mirrors this. Here, it is the mapping of more recent features that should be considered when assigning preservation status to older surfaces, especially where channel and barrier system landforms are concerned ('top down'). However, dissection of a buried landscape surface is not the only form of erosion in the workflow: the loss of old coastal plain landscapes due to human reclamation is also included. Areas labelled with a certain reclamation history on the RCE-T4 map are copied over to the maps for T3 and T2 as areas with 'non-preserved' or 'disturbed' erosion status.[75]

How to individually classify landscape zones for time slices lasting millennia, in which multiple palaeo-environments are known to have succeeded each other?

This question is most relevant for time slices T1 and T2 (several millennia long, with several metres of relative sea-level rise occurring *during* the time slice),[76] but it applies in principle to all time slices. Note, however, that the question applies to landscapes in dynamic natural conditions (actively forming) that are not the landscape zones featured on the RCE-T4 map (whose legend covers the many forms of reclaimed and man-managed land as it has existed since time slice T4, but not the pre-drainage/pre-reclamation natural counterparts). Such active natural landscapes, by their very nature, represent diachronic states in a succession of landscape zones. Part of the solution was to introduce additional landscape zones, for use on the T0123 map, completing the RCE-T4 legend.[77] These landscape zones relate to actively forming coastal plain tidal and peat landscapes, which include stages of succession (as the individual descriptions make clear). Such active coastal landscape zones first developed in T1 and T2 (owing to relative sea-level rise) and in the area under consideration ceased to exist around the T3/T4 time slice break (owing to the scale of human impact), as explained in section 3.

How to individually classify landscape zones over consecutive time slices, while diachronic landscape change occurred across time slice breaks?

While the small number of time-slices (decided on at the outset) and the introduction of six active landform units (as a solution to the previous problem) reduced this problem, additional rules-based decisions were needed where the succession in the landscape zonation occurred across the time slice breaks. These were executed as late as possible in the procedure, in Step 7. When designing these rules (evaluations at polygon level), we considered and weighed up three issues: (i) 'What was the landscape zone at the end of the time slice?' (T1: SW Netherlands and Rhine delta: fairly silted-up tidal area, freshening and forming terrestrial surfaces early; NW and N Netherlands: slower to silt up, brackish open water rather than land at the end of T1); (ii) 'Which of the successive landscape zones existed the longest?' (during T1: intertidal environments seaward and reed peatland in inland sector; during T2: salt marsh and reed peatlands in seaward sectors, freshwater peats and emerging bogs in inland sectors); (iii) 'What was the landscape zone in the previous time slice?' and 'What will the landscape zone be in the next time slice?' (do not favour the same option in each of the time slices; tweak the age-based selection criteria so that river avulsion and marine ingressions that occur very late in T2 or T3 are transferred to the start of T3 and T4). In most cases the choice was relatively straightforward (go for supratidal or reed peat in T2 if the area was intertidal in T1), but in a few cases it was a decision that one may choose to alter in the future, for example after confronting the derived maps with archaeological distributions for the area and time period (by modifying the scripted rules and generating a new version of the map product).

What legend to use for erosion status when mapping the full coastal plain?

When working at the scale of an archaeological dig or a detailed cross-section reconstruction, one would typically observe and map erosion status as a Boolean phenomenon: the feature is either preserved or not. In national mapping campaigns, however, erosion status must be addressed over larger areas between patchy observation locations, on the basis of features that are mapped on a coarser scale. This means that the assignment is no longer based on direct observation, but on conceptual knowledge and appreciation of the spatial scale and depth ranges of erosion. Like the legend choices when mapping landforms and subsurface features (what phenomena to map individually, which to combine into bulk units), the legend choice for

[75] Conversely, in the deep polder areas (Dutch: Droogmakerijen), tidal landscape features from time slice T1 were copied over to the surficial map (i.e., landscape zone #41 appears in the T4 map).

[76] Van de Plassche 1982; Van Dijk *et al.* 1991; Van de Plassche *et al.* 2010

[77] Overview in Table 3 in Smit & Feiken 2017: this volume 3.5.

mapping erosion status thus boils down to the mappability of features at current data availability.

Geological mapping and dating of the Netherlands delta and coastal plain explicitly resolves the larger landforms with erosive bases such as recent ingressive tidal channel sand bodies, fluvial channel belts, and beach barrier sand bodies. The depth to which these elements eroded at the time of their formation, generally exceeds 5 metres below the present surface / water level. Where these are mapped, one can thus presume full erosion of surfaces from the previous time slice. The known age-depth relations for relative sea-level rise and associated water table rise (see also section 2.3) place the surfaces produced in late T1, T2 and T3 within approx. 5 metres of the eventual coastal plain water table (modern base level; mean water level in rivers and estuaries). The surface from time slice T0 in the seaward sectors of the study area lies deeper than and can be considered unaffected by recent channel erosion. Thus far, the Boolean (Yes/No) approach to erosion status works.

Erosion due to human reclamation of wetland areas (oxidation of peaty topsoils in areas drained by ditches) is omnipresent in the Netherlands. It is known to have fully erased peat surfaces from time slice T3 in the parts of the coastal plain mapped as 'peat area' polders on the RCE-T4 map, and also to have deteriorated Iron Age and Roman Age drained surfaces that were flooded and buried beneath sediment in Medieval periods (owing to marine ingression and river avulsion). In the Northwestern and central Netherlands considerable expansion of lake, lagoon and wadden tidal areas occurred during time slices T3 and T4, not just centred around deep cutting channels as mentioned above, but also due to calving and diffuse erosion along shallow lake and lagoon edges. This fully erased terrestrial surfaces from time slice T3 (and also T2in the western Wadden Sea), but affected T2 and T1 surfaces more diffusely. Here the Boolean (Yes/No) approach no longer works. Given the fact that, at the scale of mapping, preservation was partial, a third, intermediate, 'fuzzy' class of erosion status was introduced.

The final system for encoding the erosion status of patches of coastal-plain buried former land surface thus considers these four classes: (1) has been preserved, (2) partially eroded/shallowly reworked, (3) fully eroded/intensively reworked, (4) never a terrestrial surface. The fourth and final class was introduced to deal with areas in the seaward fringes of the study area that, with transgression, became near-shore underwater landscapes and in some time slices thus neither represent a Pleistocene remnant landform nor fresh coastal plain land.

3.4.4 PalaeoDEM map series production

The palaeoDEMs are a calculated set of raster maps. They were created using a scripted workflow that combines features from multiple input raster maps.[78] The workflow used to create each of the DEMs comprises a path of logical steps (Fig. 2) that combines three types of source data (all in grid format):

1. Buried geological surfaces (GeoTOP-DEMs), such as 'Top Pleistocene', 'Top coastal barrier sand', 'Top Wormer Member tidal deposits / base of Holland Peat' – used in 3D national geological mapping programmes[79] at TNO-GSN. The elevations are expressed in metres +/- NAP.[80]
2. Interpolated palaeogroundwater levels (GW-DEMs), based on ^{14}C dates of peat where sampled at compaction-free positions from studies of relative sea-level rise and provision of accommodation space,[81] and calculated in the same environment and grid as the geological mapping [in m +/- NAP]. Near the coastline, the groundwater level correlates with former sea-level positions. In-land a gentle water table slope exists. The GW-DEM for the end of T3 (1000 AD) was manually reconstructed (correcting for T4 polder drainage effects that dominate groundwater levels today[82]). It intersects the Pleistocene surface along the inland boundary of the project area at an elevation of approx. 1 m NAP (outside the Rhine-Meuse delta). The GW-DEMs for T2, T1 and T0 were interpolated (3D trend fitting + kriging of residuals[83]). These intersect the Pleistocene surface at increasing depth and seaward position, inside the study area.
3. Masking grids, allowing the output palaeoDEMs to be restricted to those parts of the study area where a terrestrial

78 Dambrink *et al.* 2015.
79 www.dinoloket.nl/en; Stafleu *et al.* 2012; Van der Meulen *et al.* 2013.
80 Netherlands' O.D.; 0 m NAP ≈ present MSL.
81 Cohen 2005; Koster, Stafleu & Cohen 2016.
82 Erkens, Van der Meulen & Middelkoop 2016; Rensink *et al.* 2016, 2017: this volume 2.4.
83 Cohen 2005; Koster, Stafleu & Cohen 2016.

palaeosurface is reckoned to have survived – produced from the T0123 mapping described in section 2.1 above.

The scripts producing the palaeoDEMs first collect partial surfaces from the GeoTOP 3D model and aggregate them to a single composite palaeosurface. For example, the Top-Pleistocene geological surface, which is the composite GeoTOP-DEM for time slice T0, is derived for part of the area by mapping the presence of periglacial aeolian coversand (Boxtel Formation, particularly the Wierden Member), while for adjacent areas it is derived by mapping Rhine-Meuse valley deposits (Kreftenheye Formation, incl. Wijchen Member). For time slice T1 different selections of formations are processed by the scripts, and for time slices T2 and T3 yet further selections, including subdivision of channel systems into generations.[84] As in steps 1 and 2 of the vector mapping, this is also the step where the time-slice breaks are tied to mapped geological surfaces, a measure whose feasibility was assessed at the very start of the project. It was adjudged to be feasible because the archaeological scheme breaks happened to match distinctive coastal-plain geological breaks (between T0 and T1 and between T1 and T2).

The second step of the palaeoDEM production was to evaluate whether the geological mapped surface (GeoTOP-DEM) or the palaeogroundwater table (GW-DEM) was at the shallowest buried position (in m +/- NAP). Because the GeoTOP-DEMs were based on tracing lithological boundaries (e.g. the top of sand), in some areas covered they represent positive topographic terrestrial relief (coversand inland dune field undulations, flood plain terraces), whereas over other areas they represent bathymetric underwater relief (the bed of brooks and river channels, thaw lake bottoms). The former are land surfaces on which we locally find terrestrial archaeological sites (settlements, camps, burial sites, farmsteads, houses, hearths etc.) in styles, densities and distribution patterns that differ from one time slice to another. The latter are areas of water and wetlands during these same time slices, where channel fill and lake fill deposits collected (subaqueous muds and organics, peats).

The purpose of the PalaeoDEMs was to indicate from what depth onwards one should expect to encounter land surfaces (existing in the time slice in question), including wetland and local lake/channel fill deposits (accumulated during the time slice in question). Accordingly, the indicative metric stored in the PalaeoDEM is called Attention Depth[85] and calculated as: PalaeoDEM = MAX (GeoTOP-DEM, GW-DEM).

In the final step, the PalaeoDEMs for the four time slices were clipped using the masking grids, constraining the output to 1) the project area inland border, 2) the GeoTOP coastline model limit, 3) the areas mapped as 'preserved' or 'partially reworked' for the given time slice in the T0123 polygon map. The latter means that no PalaeoDEM value is provided for areas that have been subject to large-scale erosion – such as marine ingressions, recent fluvial channel belts, human extraction of peat, clay and sand (Fig. 1). The GW-DEMs do cover these areas.

3.4.5 Map series description

For each time slice, the maps present information on 1) the structure of the buried landscape (i.e. landscape zones) prior to burial and as burial was happening; 2) the depth of the buried landscape, as defined by the surface elevation at the beginning and end, and the water table at the beginning and end of the time slice; and 3) whether the buried landscape has been preserved.

Buried landscapes from time slice T0

In this first time slice (Fig. 1), coastal landscape zones (beaches, tidal flats etc.) are still absent from the study area, and terrestrial landscapes dominate. Sea-level rise from the Last Glacial Maximum low stand was ongoing at this time, but nowadays one needs to go to offshore areas to find coastal environments from the Late Glacial and the earliest part of the Holocene (west and east of Dogger Bank or between the cliffs of Dover and Calais).[86]

The landscape during T0 (12,000-7000 BC) consisted in part of landforms inherited from earlier ice-age stages. These include vast sandy terrace plains and boulder-clay till plateaus, and both are topped with sheets of local wind-blown coversand. Confluent networks of active streams dissected the older Pleistocene landscape. These networks follow directions inherited from earlier

84 Dambrink *et al.* 2015: their Fig. 3.

85 After Berendsen *et al.* 1994, who introduced this term in the context of mapping 'depth-to-sand' of alluvial ridges in the Rhine-Meuse delta plain. See also: Cohen *et al.* 2009.

86 It becomes feasible to map this area for this time slice using the same methods and legend as the maps described – Gaffney, Thomson & Fitch 2007; Peeters, Murphy & Flemming (eds.) 2009; Hijma *et al.* 2012; Peeters & Cohen 2014; Cohen *et al.* 2014; 2017; Moree & Sier 2015. This was not within the scope of this project, however.

Pleistocene stages, notably the deglaciation episode at the end of the Saalian ice age, approx. 150,000 years ago. These networks comprise larger rivers (Rhine, Meuse), smaller rivers (Scheldt, Vecht, Ems) and local rivers or brooks. As a result of snow-affected hydrology (spring melt peak discharge), the gradual thawing of permafrost (affecting infiltration of precipitation), and lag effects between climate change and vegetation development (gradual establishment of forest cover and soil A-horizons), the brook and river valleys in time slice T0 are relatively large in terms of their active width.[87] As time passed, this active width shrank. In the latter part of time slice T0 all rivers and streams had adopted a meandering style and concentrated their routing of discharge through single main channels.[88]

The land surface of time slice T0 is encountered at 10 to 20 metres below NAP in the most seaward sectors. Considerable regional relief (4-7 metres' depth difference measured cross-valley) separates the Early Holocene valley floor of the Rhine-Meuse and Noord-Holland main palaeovalleys from the interfluve coversands on terraces (SW Netherlands; central western Netherlands) and the till plateau (northern Netherlands). Considerable local relief is present owing to inland dune forms, which are especially well developed along river channels dated to this time slice (the sand in these aeolian dunes is sourced from bars in the then active rivers).

The buried surface of time slice T0 is fairly well preserved in the northern, northwestern, central and downstream parts of the Rhine-Meuse delta (Fig. 1), owing to the relatively great burial depth and wider spacing of dissecting channel systems. Some 60 to 80% of the original surface in these sectors has been preserved.[89] Surface preservation is considerably poorer in the southwestern Netherlands (dense network of ingression channels) and in upstream parts of the Rhine-Meuse delta (shallower burial depth; channel belts of delta trunk rivers, from multiple rounds of avulsion in relatively narrow flood plain), but still represents approx. 55% of the original surface (Fig. 4).

Buried landscapes from time slice T1

During this second time slice, transgression proceeded and coastal landscape zones (beaches, tidal flats, inland coastal plain peat etc.) established themselves from the west, while terrestrial landscapes persisted in the most inland parts of the study area. The sea level rose from below -20 m to about -5 m NAP during T1 (7000 to 3400 BC). In the western Netherlands, the maps show a still very recent barrier coastline, with a narrow beach and coastal dune zone and a broader back barrier tidal zone. In the northern Netherlands, the embryonic barrier coastline of time slice T1 lay further offshore and the map features only a tidal back-barrier zone there. The southwestern and central sectors show a peatland fringe on the inland side. The Rhine-Meuse delta is shown as a freshwater flood basin area in which new networks of rivers were established through avulsion[90].

Time slice T1 was a major aggradation period, so Pleistocene surfaces between 20 and 5 metres below NAP, which had been at the surface in time slice T0, were now buried in the coastal plain. This applies both to the depressions in the former landscape such as the Late Glacial and Early Holocene brook valleys and river channels, and to higher features such as inland dunes and coversand ridges. Depending on the location and moment in time, burial took place due to deposition of flood plain river clay, local peat formation, or subaqueous muddy tidal sediments.[91] In the inland zones, sedimentation and peat growth was generally able to keep pace with the provision of accommodation space, so multiple land surfaces of the period were preserved, stacked on top of each other. Even in the inland zones, however, fenland and swampy flood plain 'wetland' environments dominated. Landforms suitable as hunter-gather camping grounds could be found only locally in the delta and coastal plain. They included natural levees along channels and flanks of half-buried Pleistocene relief,[92] including the infamous T0-inherited inland dunes, many of which are rich Mesolithic and Neolithic sites.[93] Owing to the aggradational conditions, the buried surface of time slice T1 is fairly well preserved throughout the study area. If the western open water fringe is excluded from the calculations, preservation exceeds 50% of the original surface in the southwestern sectors and inland Rhine-Meuse delta (for the same reasons as discussed for T0), and exceeds 75% in the other sectors. This includes shallow subaquatic landscape zones such as intertidal environments ('wadden'), reed-rimmed lakes and other types of fen and marsh wetlands.

87 Vandenberghe 1995; Berendsen *et al.* 1995; Van Huissteden & Kasse 2001.
88 Hijma *et al.* 2009; Cohen *et al.* 2012; Isarin *et al.* 2015.
89 Cohen *et al.* 2017a,b.
90 Berendsen & Stouthamer 2001; Hijma & Cohen 2011.
91 Jelgersma 1961; Van de Plassche 1982; Van der Woude 1984.
92 Louwe Kooijmans 1974; Van der Woude 1983.
93 E.g. Hazendonk and Swifterbant cultures.

Buried landscapes from time slice T2

In this time slice, rates of sea-level rise had reduced greatly and the coastal configuration approached equilibrium conditions.[94] The sea level rose from approximately 5 to 1.5 m NAP during time slice T2 (3400 to 1500 BC). The beach barrier and low coastal-dune system widened considerably in the western sectors and amalgamated into a complex interrupted by estuarine tidal outlets only (all back barrier areas of tidal inlets lacking a hinterland river silted up, and the inlets themselves were plugged with beach barrier sand). In the northern Netherlands, the barrier system migrated to more or less the position it occupies today. The Pleistocene headland of Texel was subjected to wave erosion from the north and southwest, but still separated the back barrier tidal areas of the western and northern Netherlands. The Rhine-Meuse delta is shown as a freshwater flood basin area, with new networks of rivers (alluvial ridges) becoming established as a result of avulsion.[95]

Time slice T2 was a period of coastal plain stabilisation and consolidation (Fig. 3). Relative sea-level rise was only 3.5 metres and occurred at a more modest rate than before, meaning that tidal flood basins could silt up and lake and lagoon areas could be filled in with organics (reed fields and swamp forest expanding from the sides). Remaining inherited Pleistocene highs were buried under coastal plain and deltaic deposits, to levels slightly higher than contemporary open sea water levels, due to the gentle slope of the groundwater level and flood plains in the inland sectors of the study area.

Owing to the relatively shallow burial depth of the surface in time slice T2, the preservation of surfaces from this time period (with established Neolithisation in the coastal plain) is less complete than in time slice T1. Even with seaward open water fringes excluded from the calculations, preservation drops to below 35% of the original surface in seaward sectors, where the environments would have been dominated by difficult to dwell on salt marshes and peaty wetlands besides more habitable low dunes of the coastal barrier proper. In the inland sector of the Rhine-Meuse delta some 66% of the original surface is estimated to have been preserved, including considerable areas of alluvial ridge landscape. The central Netherlands sector (present-day ‘Flevoland’) and the perimarine sector of the Rhine-Meuse delta (today’s ‘Groene Hart’), have approx. 75% preserved, giving this sector the most complete preservation in this time slice.

Buried landscapes from time slice T3

From this time slice onwards, it is evident that the most recent phases of burial of coastal landscapes were not down to natural causes alone. The natural background conditions of a slowly sinking North Sea basin collecting sediment certainly continued to contribute, but from the Iron Age onwards sediment supply received from the Rhine and Meuse hinterland and human occupation strategies of the river[96] and coastal[97] flood plains had an increasing bearing on where and why old surfaces were buried (moderately, below approx. 1 metre of recent tidal or river levee clay) and where they were eroded (often completely, by channel bank and lakeshore migration processes).

Medieval storm surge ingressions (historic and proto-historic natural disasters), in particular, appear to be coastal system expansion responses to an excessive eagerness on the part of humans to occupy coastal land. This explains the relatively poor preservation of T3, T2 and T1 land surface area in the SW Netherlands (all <50%). The oldest ingressions are visible on the T3 map and occurred before organised embankment began. Storm surge ingression continued in time slice T4, interacting with dike raising and repair activities (see the relevant chapter). Surfaces from T3 are also poorly preserved in peatland areas of the northern (<60%), western (<50%) and central (<40%) sectors. This is due to ditch cutting and drainage activities in these areas since the end of time slice T3.[98]

The land surface is relatively well preserved in the Rhine-Meuse delta. The exception to this are zones immediately along rivers that were active during the last 2000 years, known to have been of strategic military and commercial importance in the Roman and Carolingian periods. Where these river branches continue to be active today, these zones have seen considerable erosion of T3 surfaces.[99] Where the branches were abandoned in Early Medieval times - a process that is associated with the final stages of increased deposition of overbank fines[100] - surface preservation in the Bronze Age, Iron Age, Roman Age and Early Medieval times is quite good, at 75%.

94 Hageman 1969; Beets & Van der Spek 2000; Vos 2015.
95 Berendsen & Stouthamer 2001; Hijma & Cohen 2011.
96 Willems 1986; Gouw & Erkens 2007; Pierik & Van Lanen 2017.
97 Vos & Van Heeringen 1997; Vos 2015; Pierik *et al.* 2017; This volume 3.2.
98 Vos 2015; Erkens, Van der Meulen & Niddelkoop 2016.
99 Willems 1986; Cohen *et al.* 2014; Pierik, Cohen & Stouthamer in prep.
100 Toonen, Kleinhans & Cohen 2012; Cohen, Toonen & Weerts 2016; Van Dinter *et al.* 2017.

3.4.6 Discussion

Use in archaeology
National-scale maps such as the landscape zone maps and palaeoDEMs in this paper compile abundant raw data on past landscapes (corings, datings, sections, specialist nomenclature) into a more accessible form. In previous cases, such maps have readily been used in applied (statutory), governmental (heritage management) and academic (thematic research) archaeology contexts[101] - regardless of what type of application the maps were originally intended for. Maps at a national scale are not intended to replace source maps at regional scale of the same actuality with legend and feature inclusion tailored to the region, but over time insights from regional mapping should percolate into national mapping, and vice versa.

The socioeconomic and governmental demand for such maps stems from the fact that the Holocene coastal and deltaic plain, especially the western Netherlands (Randstad) is densely populated and under constant pressure from infrastructural works, expanding urban and commercial activity, water management and so on. These works and activities are not restricted to the upper metres, but typically extend 5 to 8 metres below NAP, and even deeper in city centres (multi-storey underground parking), and in tunnels and harbours (navigation depth). Effective archaeological heritage management in the coastal plain must therefore consider the local age-depth relations of past landscapes when advice is given and building permits are issued (often at local authority level), and when prospecting for and analysing finds (in landscape archaeology, at a local to regional scale, e.g. for a municipality, province or city). This triggers decision-making processes that require information at the national, regional and local scales.

In the past, multiple map and cross-section products would need to be consulted in this process. Different sources would have to be used to answer questions on either 'past landscape', 'burial depth', or 'age of depositional and erosional features'. In some parts of the country this would be taken from dedicated regional studies, whereas in others it could be derived from national mapping products. The new maps provide a summarised entry point for such an exercise. The split landscape maps feature for subsequent periods may be a novelty to many local users. For parties dealing with archaeological projects in many different parts of the country and involving many different local authorities, the uniform legends of the buried and surficial landscape maps in the Predictions in Layers suite should eventually prove beneficial, however. After a period of using them as new products, shared experiences of the maps should speed up the process of starting up new local projects involving renewed comparison (or put more firmly: confrontation) with the national maps. Viewed in this light, perhaps the legend schematics, rather than the map visuals, might become a standard.

This mapping project was launched in response to the need for digital maps as part of a portal interface to archaeological information at a national scale.[102] In the 'Archaeology Knowledge Kit' portal, users can browse and query the maps and click through to other types of information linked to them, such as pointers to regional literature and datasets and texts on best practice for given archaeological periods. Such entry-level usage is envisaged in applied, governmental and academic contexts. The downloading of the actual GIS-dataset and supporting documentation may allow the map products to be used for more advanced purposes by GIS-trained professionals in applied or scientific research project teams.

Diverse applications are envisaged at the local scale, with users comparing the mapping process with that of earlier maps at provincial and municipal (i.e. local authority) scale. As a product of the implementation of the EU Valletta Convention, first-generation maps of this kind produced in the 2000-2010s are in widespread use and form part of the local decision-making structure for building permits, for example.[103] Many local authorities are considering revising these maps on the basis of new insights and experience of their use for administrative purposes. The national maps (and their legend schemes) can be used as starting points for such improvements.

Intercomparison of the national maps and the local maps would be a logical step, both when it comes to advising parties applying for building permits, and for the officials dealing with the applications, as well as for local

[101] E.g. Berendsen & Stouthamer 2001; Vos *et al.* (eds.) 2011; Cohen *et al.* 2012.
[102] Lauwerier 2017: this volume 1; Smit & Feiken 2017: this volume 3.5.
[103] Van Doesburg *et al.* 2017: this volume 5.

mapmakers. Intercomparison of the national and local mapping is likely to identify mismatches related to mapping errors or differences in conceptualisation, besides differences in scale and local data knowledge. Dealing with such mismatches and fixing those that are non-trivial will require consideration of the workload involved in updating, and how frequently this should be done. We attempted to reduce the former with an automated workflow (section 2). The latter will depend on the update cycles of the various base maps used, and on the level of archaeological usage and number of issues identified.

In addition to use at a local scale, the availability of systematically produced nationwide time-sliced landscape maps should be considered a great improvement in our ability to objectively assess landscape-archaeology relations. The potential for supporting such assessments with areal and other spatial statistics has been enhanced thanks to the uniform legend setup of the map and periodisation system, which actually provides a way of standardising such analyses. Spatial statistics will be useful for studying the distributions of actual finds, and how this may differ between regions and time slices (descriptive archaeology), as well as for defining and defending regional deviations from heritage management policy (predictive archaeology). Contributions elsewhere in this volume present further thoughts on archaeological applications.[104]

Use in earth sciences

The archaeological community are not the only users of the here described landscape maps and their underlying geological and geomorphological source maps. Other important users of the derived maps include engineers, water managers and ecologists, for example – and the earth science community itself is the prime contributor and user of the source maps. As said in section 1.2, in this age of increased digital data availability and computerized map production – synchronizing and integrating the information of the latest maps from different institutes is a constant quality management challenge, that the base map/ derived map approach and scripted map production are GIS-methodological responses to.

Of course one can only start compiling derived maps once a suitable base map has been created (one cannot start calculating from zero), and one still needs to edit base maps and/or scripts to update the derived map (maintenance is not zero). The potential benefit in the use of base maps to produce derived maps lies in the fact that a single instance of creation allows multiple use (economical for the person creating and updating maps), improves the reproducibility of the mapping results (traceable by reading the calculations in the scripts), and prevents the unintended introduction of mismatches when one zooms in too far (unit boundaries on derived maps are exact copies of those on input maps).

In the case of the buried landscape map, the base maps that were available at the outset are updated as part of long-running programmes at TNO-GSN (national mapping / 3D modelling campaign) and UU (Delta Evolution research line) respectively. In this particular project, distinguishing between base maps and derived maps also helped formalise shared ownership and copyright on map products between the government and non-government parties involved. The scripted workflow and the T0123 output ownership have been transferred to the party that commissioned the study (RCE), while the input maps and the systematics behind them remain the institutional property of the parties that executed the project (TNO-GSN, resp. UU, Deltares).

One important property of the scripted production method is that it should allow for fairly fast execution of update rounds as far as generating time-sliced maps for the archaeological applications is concerned. One potential issue related to updates will be the revisions (partial or otherwise) of underlying base maps. The maintenance of base maps is partly covered in long-running national geological mapping programmes (TNO-GSN geological base map datasets) and over the past ten years academic and national-scale applied research project opportunities have emerged, generating additional funding (UU palaeogeographical base map datasets). If budgets continue to be allocated for the updating of geological and geomorphological base maps, updates of the time-sliced mapping will also benefit.

[104] Rensink *et al.* 2017: this volume 2.4; Smit & Feiken 2017: this volume 3.5.

3.4.7 Conclusion

A geological GIS-data recombination project produced a digital map that contains information on the Netherlands' former coastal and delta plain landscapes. The polygon maps are accompanied by a set of palaeoDEMs indicating the 'attention depth' for buried land surfaces and aquatic deposits. The user and/or interface developer can visualise the stack of maps in various ways, either in a desktop GIS or through the portal viewer. When used in this way, they are linked with other Archaeology Knowledge Kit products and activities.

The production workflow was stored in a series of scripts that document the map production process make it reproducible and maintainable, and lay the groundwork for the future release of updated map series. Technical production is a matter of combining and converting several geological map products and their legends, following a series of steps. In the methodological sections, this paper has highlighted conceptual dilemmas in the making of the maps. The production workflow is dependent on starting point decisions regarding the time slices (T0, T1, T2, T3, consistent with the periodisation system used throughout this volume), which were of unequal length and had breaks that matched important moments in the geomorphological evolution and resulting geological build-up of the coastal plain.

The conceptual decisions involved drawing a distinction between actively forming landscape zones and naturally fossilised and human-reclaimed landforms. The actively forming landscapes were needed to visualise transgressive coastal environments with dynamic tidal flats and organic wetlands undergoing successive development of marsh, fens, swamps and bogs. These types of landscapes dominate the buried coastal plains of time slices T1, T2 and T3. They buried landforms inherited from the Pleistocene which naturally fossilised owing to climate change (such as coversand dunes) and sea-level rise (buried valleys). A considerable proportion of the modern coastal plain landscape is a man-made reclaimed landscape. This is why, in the Holocene part of the Netherlands, the aforementioned 'Archaeological Landscapes Map' is fairly representative of the most recent archaeological period landscapes (T4, parts of T3), but conceals most landscape structures from preceding periods. Our additional buried landscape maps are therefore needed for the earlier periods (T0, T1, T2, T3).

Aided by the inclusion of the time-sliced buried landscape maps in the Archaeology Knowledge Kit portal, it is envisaged that the new national maps will be used in projects at the provincial and municipal scale. This is expected to generate topical feedback and drive a wish for future revision of the maps. In this respect, production and distribution of the maps is seen as a half cycle in a cyclical process of mapping improvement, with use and feedback comprising the other half. One important property of the scripted production method is that it should allow for fairly fast execution of update rounds as far as generating time-sliced maps for archaeological applications is concerned.

Acknowledgements
Thanks go out to our colleagues at the Cultural Heritage Agency, Utrecht University, Deltares, TNO - Geological Survey of the Netherlands, VU Amsterdam, the archaeology faculties of Dutch universities, municipal archaeology departments, and archaeological consultancy firms, who helped set up the inter-institutional mapping projects and sharing of data which were so vital to the success of our efforts to connect landscape geological and geomorphological mapping with archaeological prospection, discovery and protection: Bjørn Smit, Ellen Vreenegoor, Roel Lauwerier, Henk Weerts, Menne Kosian, Rik Feiken, Bert Groenewoudt, Eelco Rensink, Michel Lascaris, Esther Jansma, Rowin van Lanen, Esther Stouthamer, Wim Hoek, Hans Middelkoop, Marjolein Gouw-Bouman, Marieke van Dinter, Hans Renes, Peter Vos, Sieb de Vries, Bob Hoogendoorn, Freek Busschers, Geert-Jan Vis, Michiel van der Meulen, Ronald van Balen, Cees Kasse, Hessel Woolderink, Stijn Arnoldussen, Hans Peeters, Yftinus van Popta, Rien Polak, Philip Verhagen, Jurrien Moree, Ton Guiran, Maaike Sier, Michel Groothedde, Herre Wynia, Eric Graafstal, Peter van den Broeke, Eckhart Heunks, Rene Isarin, Jan-Willem Oudhof, Thijs Nales, Leo Tebbens, Nico Willemse, and many others.

References

Alterra, 2006: *Kaart van de bodemopbouw in Nederland 1:50.000 onder INSPIRE.* https://data.overheid.nl/data/dataset/kaart-van-de-bodemopbouw-in-nederland-1-50-000-onder-inspire.

Beets, D.J. & A.J. van der Spek 2000: The Holocene evolution of the barrier and back-barrier basins of Belgium and the Netherlands as a function of late Weichselian morphology, relative sea-level rise and sediment supply, *Geologie en Mijnbouw* 79, 3-16.

Berendsen, H.J.A., 1982: *De genese van het landschap in het zuiden van de provincie Utrecht: een fysisch-geografische studie,* Utrecht (PhD thesis Universiteit Utrecht).

Berendsen, H.J.A., E.L.J.H. Faessen & H.F.J. Kempen, 1994: *Zand in banen - zanddiepte-attentie kaarten van het Gelders rivieren gebied,* Arnhem.

Berendsen, H.J.A., 2007: History of geological mapping of the Holocene Rhine-Meuse delta, the Netherlands, *Netherlands Journal of Geosciences* 8, 165-177.

Berendsen, H.J.A. & E. Stouthamer 2001: *Palaeogeographic development of the Rhine-Meuse delta, The Netherlands,* Assen.

Berendsen, H.J.A., T.E. Tornqvist & H.J.T. Weerts 1986: De geologisch-geomorfologische kaart van de Bommelerwaard, *Nederlandse Geografische Studies* 10, 15-20.

Cohen, K.M., 2005: 3D geostatistical interpolation and geological interpretation of palaeo-groundwaterrise in the coastal prism in the Netherlands, in: L. Giosan & J.P. Bhattacharaya (eds.), *River Deltas: Concepts, models, and examples*, Tulsa, Oklahoma: SEPM (Society for Sedimentary Geology), 341-364.

Cohen, K.M., 2017: *Beschrijving gebiedsindeling en legenda kaartlaag T0123: Begraven Hoofdlandschappen en Landschaps-zones*, Utrecht (Deltares report 1210450-000-BGS-0014).

Cohen, K.M. & J. Schokker 2014: *Geïntegreerd Plan van Aanpak: RCE-10A: Vervaardiging digitale paleo-hoogtemodellen voor de top van het Pleistoceen en tijdsnede 1, 2 en 3; RCE-10B: Landschapskartering van archeologisch relevante landschaps-eenheden, naar periode en diepte,* Utrecht.

Cohen, K.M., E. Stouthamer, W.Z. Hoek, H.J.A. Berendsen & H.F.J. Kempen 2009: *Zand in Banen - Zanddieptekaarten van het Rivierengebied en het IJsseldal in de provincies Gelderland en Overijssel,* Arnhem.

Cohen, K.M., E. Stouthamer, H.J. Pierik & A.H. Geurts 2012: *Digitaal Basisbestand Paleogeografie van de Rijn-Maas Delta / Rhine-Meuse Delta Studies' Digital Basemap for Delta Evolution and Palaeogeography,* Utrecht (Digital Dataset; https://doi.org/10.17026/dans-x7g-sjtw).

Cohen, K.M., S. Arnoldussen, G. Erkens, Y.T. van Popta & L.J. Taal 2014: *Archeologische verwachtingskaart uiterwaarden rivierengebied,* Utrecht.

Cohen, K.M., W.H.J. Toonen & H.J.T. Weerts 2016: *Overstromingen van de Rijn gedurende het Holoceen - Relevantie van de grootste overstromingen voor archeologie van het Nederlandse rivierengebied,* Utrecht.

Cohen, K.M., R. Dambrink, R. de Bruijn, J. Schokker & M.P. Hijma 2017a: *Vervaardiging van hoogtemodellen en landschapskaarten naar periode en diepte voor archeologisch gebruik in Holoceen-afgedekte delen van Nederland,* Utrecht (Deltares & TNO Geologische Dienst Nederland & Utrecht University).

Cohen, K.M., R. de Bruijn, V.C. Marges, S. de Vries, H.J. Pierik, P.C. Vos, G. Erkens & M.P. Hijma 2017b: *Vervaardiging van begraven landschapskaarten voor Holoceen afgedekt Nederland: Kaartlaag T0123 voor RCE's Kenniskaart-portaal,* Utrecht (Deltares).

Cohen, K.M., K. Westley, G. Erkens, M.P. Hijma & H.J.T. Weerts 2017: North Sea, in: N.C. Flemming, J. Harff, D. Moura, A. Burgess & G. Bailey (eds.), *Submerged Landscapes of the European Continental Shelf: Vol. 1 Quaternary Paleoenvironments.* New York, 147-186.

Dambrink, R., J. Stafleu, J. Schokker, K.M. Cohen & K. Koster 2015: *Vervaardiging digitale paleo-hoogtemodellen.* Utrecht

De Mulder, E.F., M.C. Geluk, I. Ritsema, W.E. Westerhoff & T.E. Wong (eds.) 2003: *De ondergrond van Nederland*, Groningen/Utrecht.

Erkens, G., M.J. van der Meulen & H. Middelkoop 2016: Double trouble: subsidence and CO2 respiration due to 1,000 years of Dutch coastal peatlands cultivation, *Hydrogeology Journal* 24, 551-568.

Gaffney, V.L., K. Thomson & S. Fitch 2007: *Mapping Doggerland: the Mesolithic landscapes of the southern North Sea*, Oxford.

Gouw, M.J.P. & G. Erkens 2007: Architecture of the Holocene Rhine-Meuse delta (the Netherlands) – A result of changing external controls, *Netherlands Journal of Geosciences* 86, 23-54.

Groenewoudt, B. & B. Smit 2014. *Archeologisch vierperioden systeem. Programma Kenniskaart: Project Best Practices Prospectie, Project Verwachtingen in lagen,* Amersfoort, (Internal report Cultural Heritage Agency).

Groenewoudt, B.G. & B.I. Smit 2017: Four-period system of archaeology, in: R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, B.P. Speleers & J. van Doesburg (eds.), *Knowledge for Informed Choices. Tools for more effective and efficient selection of valuable archaeology in the Netherlands*, Amersfoort (Nederlandse Archeologische Rapporten 55), 25-31.

Hageman, B.P., 1969: Development of the western part of the Netherlands during the Holocene, *Geologie en Mijnbouw* 48, 373-388.

Hijma, M.P. & K.M. Cohen 2011: Holocene transgression of the Rhine river mouth area, The Netherlands/Southern North Sea: palaeogeography and sequence stratigraphy, *Sedimentology* 58, 1453-1485.

Hijma, M.P., K.M. Cohen, G. Hoffmann, A.J.F. van der Spek & E. Stouthamer 2009: From river valley to estuary: the evolution of the Rhine mouth in the early to middle Holocene (western Netherlands, Rhine-Meuse delta), *Netherlands Journal of Geosciences* 88, 13-53.

Hijma, M.P., K.M. Cohen, W. Roebroeks, W.E. Westerhoff & F.S. Busschers 2012: Pleistocene Rhine–Thames landscapes: geological background for hominin occupation of the southern North Sea region, *Journal of Quaternary Science* 27, 17-39.

Isarin, R., E. Rensink, R. Ellenkamp & E. Heunks 2015: *Archeologische Verwachtingskaart Maasdal tussen Mook en Eijsden,* Amersfoort.

Jelgersma, S., 1961: *Holocene sea level changes in the Netherlands.* Leiden (PhD thesis Leiden University).

Koomen, A.J.M. & G.J. Maas 2004: *Geomorfologische Kaart Nederland (GKN); Achtergrond-document bij het landsdekkende digitale bestand*, Wageningen.

Koster, K., J. Stafleu & K.M. Cohen 2016: Generic 3D interpolation of Holocene base-level rise and provision of accommodation space, developed for the Netherlands coastal plain and infilled palaeovalleys, *Basin Research*, 10.1111/bre.12202.

Lauwerier, R.C.G.M. 2017: Knowledge for informed choices. Tools for decision-making in archaeological heritage management in the Netherlands, in: R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, Speleers, B.P. & J. van Doesburg (eds.), *Knowledge for Informed Choices. Tools for more effective and efficient selection of valuable archaeology in the Netherlands*, Amersfoort (Nederlandse Archeologische Rapporten 55), 11-24.

Louwe Kooijmans, L.P., 1974: *The Rhine/Meuse delta: four studies on its prehistoric occupation and Holocene geology,* Leiden (PhD thesis Universiteit Leiden).

Maarleveld, G.C., J.A.M. ten Cate & G.W. de Lange (eds.) 1977: *Geomorfologische kaart van Nederland schaal 1: 50 000. Legenda en Toelichting op de legenda.*

Moree, J.M., & M.M. Sier (eds.) 2015: *Interdisciplinary Archaeological Research Programme Maasvlakte 2, Rotterdam: Twenty metres deep! The mesolithic period at the Yangtze Harbour site-Rotterdam Maasvlakte, the Netherlands,* Rotterdam (BOOR reports 566).

Peeters, J.H.M. & K.M. Cohen 2014: Introduction to North Sea submerged landscapes and prehistory, *Netherlands Journal of Geosciences* 93, 3-5.

Peeters, H., P. Murphy & N. Flemming (eds.) 2009: *North Sea prehistory research and management framework (NSPRMF)*, Amersfoort.

Pierik, H.J., K.M. Cohen & E. Stouthamer 2016: A new GIS approach for reconstructing and mapping dynamic Late Holocene coastal plain palaeogeography, *Geomorphology 270*, 55–70.

Pierik, H.J., K.M. Cohen & E. Stouthamer in prep.: Natural levee evolution in the Rhine-Meuse delta during the first millennium CE. *Peer-reviewed academic journal / chapter in upcoming PhD thesis by Pierik* (PhD thesis Universiteit Utrecht).

Pierik, H.J. & R.J. van Lanen 2017: Roman and early-medieval occupation patterns in a delta landscape: The link between settlement elevation and landscape dynamics. *Quaternary International*, 10.1016/j.quaint.2017.03.010.

Pierik, H.J., K.M. Cohen, P.C. Vos, A.J.F. van der Spek & E. Stouthamer 2017: Late Holocene coastal-plain evolution of the Netherlands: the role of natural preconditions in human-induced sea ingressions, *Proceedings of the Geologists' Association* 128: 180-197.

Pons, L.J. & A.J. Wiggers 1959-1960. De Holocene wordingsgeschiedenis van Noord-Holland en het Zuiderzeegebied, *Tijdschrift Koninklijk Nederlands Aardrijkskundig Genootschap* 76, 104–152, continued 77, 3-57.

Rensink, E., H.J.T. Weerts, M. Kosian, H. Feiken & B.I. Smit 2016: *Archeologische Landschappenkaart van Nederland: Methodiek en kaartbeeld*, Amersfoort (Internal report Cultural Heritage Agency).

Rensink , E., H.J.T. Weerts, M. Kosian, R. Feiken & B.I. Smit 2017: The Archaeological Landscapes Map of the Netherlands. A new map for inventory and analysis at the archaeology-landscape interface, in: R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, B.P. Speleers & J. van Doesburg (eds.), *Knowledge for Informed Choices. Tools for more effective and efficient selection of valuable archaeology in the Netherlands*, Amersfoort (Nederlandse Archeologische Rapporten 55), 36-47.

Smit, B.I. & H. Feiken 2017: Land Use in Layers. A digital insight into the complex occupation history of the Netherlands, in: R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, B.P. Speleers & J. van Doesburg (eds.), *Knowledge for Informed Choices. Tools for more effective and efficient selection of valuable archaeology in the Netherlands*, Amersfoort (Nederlandse Archeologische Rapporten 55), 94-107.

Stafleu, J., D. Maljers, F.S., Busschers, J.L., Gunnink, J. Schokker, R.M. Dambrink, H.J. Hummelman & M.L. Schijf 2012: *GeoTop modellering*, Utrecht.

Stouthamer, E., K.M. Cohen & W.Z. Hoek 2015: *De vorming van het land: Geologie en geomorfologie.* Utrecht.

Toonen, W.H.J., M.G. Kleinhans & K.M. Cohen 2012: Sedimentary Architecture of Abandoned Channel Fills, *Earth Surface Processes and Landforms* 37, 459-472.

Vandenberghe, J., 1995: Timescales, climate and river development, *Quaternary Science Reviews* 14, 631-638.

Van de Plassche, O., 1982: *Sea-level change and water-level movements in the Netherlands during the Holocene.* Haarlem/ Amsterdam (PhD thesis Vrije Universiteit Amsterdam).

Van de Plassche, O., B. Makaske, W.Z. Hoek, M. Konert & J. van der Plicht 2010: Mid-Holocene water-level changes in the lower Rhine-Meuse delta (western Netherlands): implications for the reconstruction of relative mean sea-level rise, palaeoriver-gradients and coastal evolution, *Netherlands Journal of Geosciences* 89, 3-20.

Van der Meulen, M.J., J.C. Doornenbal, J.L. Gunnink, J. Stafleu, J. Schokker, R.W. Vernes, F.C. Van Geer, S.F. Van Gessel, S. Van Heteren, R.J.W. Van Leeuwen, M.A.J. Bakker, P.J.F. Bogaard, F.S. Busschers, J. Griffioen, S.H.L.L. Gruijters, P. Kiden,

B.M. Schroot, H.J. Simmelink, W.O. Van Berkel, R.A.A. Van der Krogt, W.E. Westerhoff & T.M. van Daalen 2013: 3D geology in a 2D country: perspectives for geological surveying in the Netherlands, *Netherlands Journal of Geosciences* 92, 217-241.

Van der Woude, J.D., 1983: *Holocene paleoenvironmental evolution of a perimarine fluviatile area. Geology and paleobotany of the area surrounding the archeological excavation at the Hazendonk river dune (Western Netherlands),* Leiden (PhD thesis Universiteit Leiden).

Van Dijk, G.J., H.J.A. Berendsen & W. Roeleveld 1991: Holocene water level development in The Netherlands' river area; implications for sea-level reconstruction, *Geologie en Mijnbouw* 70, 311–32.

Van Dinter, M., K.M. Cohen, W.Z. Hoek, E. Stouthamer, E. Jansma, & H. Middelkoop 2017: Late Holocene lowland fluvial archives and geoarchaeology: Utrecht's case study of Rhine river abandonment under Roman and Medieval settlement, *Quaternary Science Reviews* 10.1016/j.quascirev.2016.12.003.

Van Doesburg, J., O. Brinkkemper, F.T.S. Brounen, I.M.M. van der Jagt, B.J.M. Jansen, M.A. Lascaris, E. Romeijn, M. Snoek & B.P. Speleers 2017: Mapping the Past for the Future. Local authority predictive maps and archaeological heritage management, in: R.C.G.M. Lauwerier, M.C. Eerden, B.J. Groenewoudt, M.A. Lascaris, E. Rensink, B.I. Smit, B.P. Speleers & J. van Doesburg (eds.), *Knowledge for Informed Choices. Tools for more effective and efficient selection of valuable archaeology in the Netherlands*, Amersfoort (Nederlandse Archeologische Rapporten 55), 155-164.

Van Huissteden, J., & C. Kasse 2001: Detection of rapid climate change in Last Glacial fluvial successions in The Netherlands, *Global and Planetary Change* 28, 319-339.

Verbraeck, A., 1984: *Toelichtingen bij de geologische kaart van Nederland 1:50.000. Blad Tiel West (39 W) en Tiel Oost (39 O)*, Haarlem.

Vos, P.C., 2015: *Origin of the Dutch coastal landscape. Long-term landscape evolution of the Netherlands during the Holocene, described and visualized in national, regional and local palaeogeographical map series.* Groningen/Utrecht (PhD thesis Universiteit Utrecht).

Vos, P.C., J.G.A. Bazelmans, H.J.T. Weerts & M.J. van der Meulen (eds.) 2011: *Atlas van Nederland in het Holoceen: landschap en bewoning vanaf de laatste ijstijd tot nu.* Amsterdam.

Vos, P.C. & S. de Vries 2013: *Tweede generatie palaeogeografische kaarten van Nederland*, Amersfoort.

Vos, P.C. & R.M. van Heeringen 1997: *Holocene geology and occupation history of the Province of Zeeland*, Haarlem (Mededelingen NITG-TNO 59).

Westerhoff, W.E., E.F.J. de Mulder & W. de Gans 1987: *Toelichting bij de geologische kaart van Nederland 1:50.000, blad Alkmaar west (19W) en blad Alkmaar oost (19O)*, Haarlem.

Willems, W.J.H., 1986: *Romans and Batavians. A regional study in the Dutch eastern river area.* Amsterdam (PhD thesis Universiteit van Amsterdam).

Wong, T.E., D.A. Batjes & J. de Jager 2007: *Geology of the Netherlands*. Den Haag.

Zagwijn, W.H., 1986: *Nederland in het Holoceen*. Haarlem.