Faculteit Wetenschappen

The use of integrated process models in a geoarchaeological context

A proof of concept

Ann Zwertvaegher

Proefschrift voorgedragen tot het behalen van de graad van Doctor in de Wetenschappen: Geologie

2012

Promotor
Prof. Dr. Peter A. Finke (UGent)

Leden van de examencommissie
Prof. Dr. em. Marc Antrop (UGent)
Prof. Dr. Philippe Crombé (UGent)
Prof. Dr. Luc Lebbe (UGent)
Prof. Dr. Jan Sevink (UvA)
Prof. Dr. Marc Van Meirvenne (UGent)
Prof. Dr. Eric Van Ranst (UGent)
Prof. Dr. Jacques Verniers (UGent)

UNIVERSITEIT GENT

Faculteit Wetenschappen

Ann Zwertvaegher

The use of integrated process models in a geoarchaeological context: a proof of concept

Proefschrift voorgedragen tot het behalen van de graad van
Doctor in de Wetenschappen: Geologie

2012

Acknowledgments

Ghent, December 2012

Being at the end of this doctoral experience, it is time to overlook these past years and to be thankful for the fascinating things I have learned, for the stimulating experiences I have had, but most of all for the interesting people I have met.

I would like to start by thanking my promoter Prof. Dr. Peter Finke, who gave me the opportunity to work in the field of geoarchaeology. Not only did he introduce me to the world of modelling, programming and soil formation, moreover, he was always available to discuss my work and to give good advice. I hope that our collaboration has made me adopt some of the Dutch directness. I was lucky that my research was part of a larger, interdisciplinary project that was financially supported by the Special Research Fund (BOF) of Ghent University. Being part of this project gave me the opportunity to work in a team of various scientific disciplines. I thankfully mention Prof. Dr. Philippe Crombé (the project director) for helping to collect and explain archaeological literature and data. I am also grateful to Prof. Dr. Jacques Verniers, Prof. Dr. Marc Van Meirvenne, Prof. Dr. Philippe De Maeyer, Prof. Dr. Jean Bourgeois and Prof. Dr. em. Marc Antrop. All gave invaluable support and advice in the field, at various meetings and with several papers. The other doctoral students and researchers in this team deserve my gratitude for the instructive discussions and amicable collaboration: Machteld Bats, Mona Court-Picon, Jeroen De Reu, Philippe De Smedt, Vanessa Gelorini and Ilke Werbrouck.

I would like to express my gratitude to the members of my examination committee: Prof. Dr. em. Marc Antrop, Prof. Dr. Philippe Crombé, Prof. Dr. Luc Lebbe, Prof. Dr. Marc Van Meirvenne, Prof. Dr. Jan Sevink and Prof. Dr. Eric Van Ranst. They have thoroughly screened this manuscript and their suggestions have highly improved the quality of this work. I would also like to thank all other reviewers who, anonymously or not, have lent their time and knowledge to ameliorate this research.

The aid of all other researchers is also very much appreciated. Special thanks go to Prof. Dr. Luc Lebbe for his help with groundwater modelling and MODFLOW in particular; to Dr. Alexander Vandenbohede, who introduced me to the magic of Matlab and assisted me with programming and Fortran-obstacles; to Dr. Udaya Vitharana, with whom I set out on the road of Bayesian calibration. Machteld, Jeroen and Ilke: I have really enjoyed the times on the field with all of you! My gratitude goes out to Dr. Joris Sergant, Prof. Dr. Wim De Clercq and Dr. B. Davies for the use of their data; to Dr. Frank Mostaert and the people of WatLab; to all the archaeologists who were of assistance in the field and to all colleagues and students who have contributed to this work in one way or another.

It was a pleasure working with my colleagues at the S8 (both Geology and Geography Departments). Special thanks go to the team of the Laboratory of Soil Science. I would also like to mention Azam and Yan-Yan, whose company in the same office was very much appreciated. A warm thank you goes out to Amaury, Dries, Hans, Jan, Lieven, and Rindert, for relaxing coffee breaks and entertainment.

Finally, I would like to thank my family and friends for their support and very welcome distractions. My gratitude goes to my parents, Marc en Chris Zwertvaegher-Goethals, and to my sisters and their family (Ingrid, Karen, Lieven, Amber and the little boy or girl whom I am very curious to meet). Amaury deserves my special thanks for his company during lunch, for the electrical heating after office hours, for his help with the book cover, and much more. To Maaike and Christophe, the Manama, the Girls, the Geologen, Ginga Mundo, and all other friends: thank you all for the support, the fun we had and the good times we shared. I am looking forward to many more!

Table of Contents

Chapter 1
General introduction

1.1 Broader framework and problem statement

At present the archaeological heritage is seriously threatened by natural and human induced factors. The latter are the result of major planning schemes that often coincide with large construction works, but sometimes also of clandestine or unscientific excavations (Council of Europe, 1992). A lack of care and awareness can lead to the deterioration and ultimately even to the entire destruction and loss of these archaeological remains and/or of their scientific information for future generations. One must keep in mind that archaeological artefacts are the most direct evidence of the history of mankind. Especially for time periods that lack written sources they are often our only source of knowledge. They are therefore part of our public collective memory and should be treated accordingly, i.e. in a sustainable manner to preserve them for future generations. In this light, in Europe, the first steps towards the protection of our heritage were taken in 1969 at the European Convention on the Protection of the Archaeological Heritage, held in London (Council of Europe, 1969). This convention was revised and replaced in 1992 by the Valetta Treaty (Council of Europe, 1992), providing a framework of standards, principles and recommendations to be implemented in national policies. The convention was ratified by Belgium on the 8th of October 2010 (Vlaamse Regering, 2012). The treaty stresses the social value of the archaeological heritage and recommends a proper alignment between archaeology and spatial planning (Vlaamse Regering, 2012). In general, the implementation of the resolutions of the Valetta Treaty has led to increasing number of archaeological evaluations, the development of non-destructive techniques (for example geophysical prospection), and the renewed interest in spatial analysis techniques on archaeological find locati ons and the so-called predictive modelling (Meylemans and Vanderbeken, 2008).

Several of these aspects are incorporated in the project entitled 'Prehistoric settlement and land use systems in Sandy Flanders (NW Belgium): a diachronic and geoarchaeological approach'. This interdisciplinary project, a work in progress at Ghent University (Belgium) from 2008 onwards, combines archaeological research with GIS-based (Geographic Information System) geographical investigations, fieldwork, such as hand augering and trenching, non-destructive geophysical surveys, palaeoecological analyses, groundwater and soil-formation modelling, and land evaluation as a form of predictive modelling (Bats et al., 2009). This is performed by 5 major research activities (among them the presented work) at the departments of Archaeology (research group Prehistory and Protohistory), Geography (research group Landscape), Soil Management (research group Soil Spatial Inventory Techniques - ORBit) and Geology and Soil Science (research group Palaeontology and research group Soil Science). For more detailed information I refer to the project website (www.prehistoriclandscapes.ugent.be). The study region tackled by the project lies in the area of Sandy Flanders, which is mainly characterized by its sandy soils. The region is situated between the North Sea coast and coastal polder area in the west, the Scheldt polder area in the north and the Lower Scheldt River in the east and south. The region has a rich archaeological past. This already started with Middle Palaeolithic Neanderthals settling along the borders of the Flemish Valley some 300,000 years ago (Crombé and Van der Haeghen, 1994), followed by a long hiatus in the archaeological record. Towards the end of the last ice age, during the Late Glacial, the recolonization of the region began with the advent of Final Palaeolithic *Federmesser* hunter-gatherers (Crombé and Verbruggen, 2002). From then on the area became increasingly occupied and exploited, culminating in the Roman period (ca 60-260 CE).

More than two decades of systematic and thorough prospection and registering by means of fieldwalking, aerial photography and hand augering by the department of Archaeology of Ghent University and associated volunteers, has led to the creation of a large database of the archaeological sites and find spots in Sandy Flanders. An overview of the spatial distribution of the found Stone, Bronze and Iron Age sites revealed several areas with high site density, probably indicating a very intense and practically continuous occupation and exploitation from the Late Glacial onwards. However, areas almost completely devoid of archaeological traces were also present. It must be taken into consideration to what extent this spatial discrepancy is the result of an archaeological reality and not the result of biased sampling or different preservation conditions. But even after frequent archaeological investigations of these void areas (Crombé et al., 2011; De Reu et al., in press) no evidence of prehistoric exploitation of these regions was found. Therefore, the factors influencing this geographic and diachronic distribution must be identified. It is safe to assume that different economic, politic and socio-cultural factors, as well as the former landscape and its different components, have played a role in the occupation/exploitation of the region. The major focus of the project is on the palaeolandscape in a two-way interplay with the human occupation/exploitation of the Sandy Flanders region in pre- and protohistoric times starting from the Late Glacial till the beginning of the Roman period. This requires an interdisciplinary approach at different scales and the reconstruction of several components of the palaeolandscape.

1.2 Land evaluation and landscape reconstruction

Within the above mentioned interdisciplinary project, the study presented here tackles the relation between the human factor on the one hand and the landscape on the other hand based on an archaeological land evaluation. Land evaluation is defined by the FAO (Food and Agriculture Organization of the United Nations) as 'the process of assessment of land performance when used for specified purposes involving the execution and interpretation of surveys and studies of landforms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation' (FAO, 1976). The methodology was originally developed by soil scientists and is widely used, especially in Third World countries, to assess the potential of land for several types of use (Vink, 1975; Wright, 1987). The technique was introduced in archaeology by Kamermans et al. (1985). Archaeological information is combined with geo-information as a type of deductive predictive modelling (Kamermans, 2000). Present-day land characteristics can often be measured, although this is generally not the case for past land characteristics, thus implying the need for a reconstruction of the former components of the palaeolandscape. However, data are often largely scattered in a temporal and spatial sense. Therefore, the application of process models is proposed, which use equations or decision rules that describe physical and/or chemical processes representative of the behaviour of a system. The different components of the landscape that need to be reconstructed, are to be derived from the relevant variables and data requirements necessary to perform the land evaluation. As a consequence, the study focuses on the reconstruction of the depth of the phreatic groundwater and several soil properties.

The terminology used in the land evaluation refers to land: for example land utilization type, land use requirement, land quality. Here, land is defined as ‘an area of the earth's surface, the characteristics of which embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area including those of the atmosphere, the soil and underlying geology, the hydrology, the plant and animal populations, and the results of past and present human activity, to the extent that these attributes exert a significant influence on present and future uses of the land by man’ (FAO, 1976).

Landscape in this work is defined according to Berendsen (2005) as a part of the earth’s surface, characterized by a specific appearance (the physiognomy), a specific structure and development, particular dynamics and an internal coherence between the various landscape factors. These landscape factors, also called geofactors, correspond with sediments, topography, climate and air, soil, water, vegetation and fauna, including humans. All of these factors mutually interact in varying degrees and intensities (Berendsen, 2005). We are aware that other definitions for the term landscape also exist in literature, for example the one given by the European Landscape Convention held in Florence in 2000. Here, landscape is defined as ‘an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors’ (Council of Europe, 2000). However, with this landscape reconstruction in an archaeological context we mainly focus on the evolution of the landscape properties and the interrelations of the different components or factors of the landscape, and their development. We consider less the landscape physiognomy, i.e. its appearance and the resulting atmosphere because this is hard to assess and furthermore falls outside the scope of this study.

1.3 Objectives

The main theme of this study is the relationship between, on the one hand, land with is specific properties and, on the other hand, human presence, occupation and exploitation. The primary objective is to build a methodological framework to perform an archaeological land evaluation based and carrying capacity assessment on reconstructed landscape components and to test this for a study area in Sandy Flanders and for the time period starting in the Late Glacial and covering the entire Holocene. The study can be divided into several research themes, each with specific objectives, research questions and action points.

Research theme: reconstruction of the landscape components groundwater table and soil.

For the landscape component groundwater table, the specific objectives are:

- To select a model for the reconstruction of the groundwater table in the study area and period ;
- To collect or, when necessary, to reconstruct model boundary conditions on climate, vegetation, recharge to the groundwater table, location and characteristics of the hydrological network and topography, for the extent of the study area and period;
- To calibrate the model and to evaluate model quality;
- To collect or, when necessary, to reconstruct the required data to perform model calibration and model quality testing;
- To produce full-cover maps of the study area of the phreatic palaeogroundwater table depth, serving as input to the pedogenetic model, as well as the land evaluation.

For the landscape component soil, the specific objectives are:

- To select a model for the reconstruction of the soil characteristics in the study area and period;
- To collect or, when necessary, to reconstruct model boundary conditions on soil parent material, climate and vegetation, for the extent of the study area and period;
- To calibrate the soil-formation model and to evaluate model quality;
- To collect or, when necessary, to reconstruct the required data to perform model calibration and model quality testing;
- To produce full-cover maps of the study area of various soil characteristics that are to be used in the land evaluation.

Research theme: land evaluation and carrying capacity assessment. This has the following specific objectives:

- To define the different types of land use in the study area throughout the study period, and translate these into land utilization types;
- To define the land use requirements related to the applied land utilization types;

- To reconstruct the land characteristics and qualities at the time of the applied land use system;
- To define a suitability classification for the specific land characteristics and qualities;
- To produce land suitability maps for the different land utilization types and considered time periods;
- To perform a carrying capacity assessment.

1.4 Thesis outline

The objectives and action points listed above (section 1.3) are tackled in the subsequent chapters. A description of the study area is given in Chapter 2. This chapter provides important background information on the geological substrate and its hydrogeological characteristics, the Quaternary geomorphology, the pedology and pedogenetics, climate and vegetation. Furthermore, because humans are central to this work, a general overview of the archaeology of the region is given as well. For most of these aspects, the time frame covered in Chapter 2 corresponds with the extent of the study period, although for reasons of clarity this is not always the case. The same remark holds for the spatial extent. Because information exactly restricted to the study region can sometimes be too limited, information from other regions under similar conditions is used as well.

In Chapter 3, the predictive potential of the present-day landscape factors for archaeological site occurrence is firstly analyzed by a predictive modelling. This reveals the shortcomings in the use of present-day landscape characteristics when analyzing past distributions of human occupation, implying the need for a reconstructed palaeolandscape (or palaeolandscape components). This provides the onset for the rest of the chapter, in which the entire framework of process models to perform this reconstruction and subsequent land evaluation is conceptualized. In this conceptual methodology an idealized general workflow for the entire research is presented. The different required process models are clarified with several practical examples and remarks on model linkage and error propagation are made.

Chapters 4 and 5 deal with the reconstruction of past phreatic groundwater levels and the reconstruction of former soil properties, respectively. This is performed by modelling. The models MODFLOW and SoilGen2 are briefly introduced. The chapters report on the construction of required boundary conditions and the model calibrations and model quality testings. The land evaluation and subsequent carrying capacity is explained in Chapter 6. The general discussion (Chapter 7) reflects on the initial conceptual framework as presented in Chapter 3. Suggestions and outlook for future work are proposed. The general conclusions are presented in Chapter 8.

1.5 References

Bats, M. De Reu, J., De Smedt, P., Antrop, M., Bourgeois, J., Court-Picon, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Werbrouck, I., Zwertvaegher, A., Crombé, P., 2009. Geoarchaeological research of the large palaeolake of the Moervaart (municipalities of Wachtebeke and Moerbeke-Waas, East Flanders, Belgium). From Late Glacial to Early Holocene. Notae Praehistoricae 29, 105-112.

Berendsen, H.J.A., 2005. Landschap in delen; overzicht van de geofactoren. Van Gorcum, Assen.

Council of Europe, 1969. *European Convention on the Protection of the Archaeological Heritage, London, 6-5-1969. Council of Europe, European Treaty Series* 066.

Council of Europe, 1992. *European Convention on the Protection of the Archaeological Heritage (revised), Valletta, 16-1-1992.* Council of Europe, European Treaty Series 143.

Council of Europe, 2000. European Landscape Convention, Florence, 20-10-2000. Concil of Europe, European Treaty Series 176.

Crombé, P., Sergant, J., Robinson, E., De Reu, J., 2011. Hunter-gatherer responses to environmental change during the Pleistocene-Holocene transition in the southern North Sea basin: Final Palaeolithic-Final Mesolithic land use in northwest Belgium. Journal of Anthropological Archaeology 30(3), 454-471.

Crombé, P., Van der Haegen, G., 1994. Het Midden-Paleolithicum in noordwestelijk België. Archeologische Inventaris Vlaanderen, Buitengewone reeks 3. Archeologische Inventaris Vlaanderen vzw, Gent.

Crombé, P., Verbruggen, C., 2002. The Late Glacial and Early Post Glacial occupation of northern Belgium: the evidence from Sandy Flanders, in: Eriksen, B.V., Bratlund, B. (Eds.), Recent studies in the Final Palaeolithic of the European plain. Proceedings of a U.I.S.P.P. Symposium, Stockholm, 14-17 October 1999. Jutland Archaeological Society Publications. Jutland Archaeological Society, Stockholm, pp. 165-180.

De Reu, J., Deweirdt, E., Crombé, P., Bats, M., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Finke, P., Van Meirvenne, M., Verniers, J., Werbrouck, I., Zwertvaegher, A., Bourgeois J., 2011. Les tombelles de l'âge du bronze en Flandre sablonneuse (nord-ouest de la Belgique) : un status quaestionis. *Archäologisches Korrespondenzblatt* 41, 491-505.

FAO, 1976. A framework for land evaluation. Soils Bulletin 32. FAO, Food and Agriculture Organization of the United Nations, Rome, 94 pp.

Kamermans, H., 2000. Land evaluation as predictive modelling: a deductive approach, in: Lock, G. (Ed.), Beyond the Map. Archaeology and Spatial Techniques. Proceedings of the NATO Advanced Research Workshop, Ravello (Italy), 1-2 October. NATO Scientific Series. IOS Press, Amsterdam.

Kamermans, H., Loving, S.H., Voorrips, A., 1985. Changing patterns of prehistoric land use in the Agro Pontino, in: Malone, C., Stoddart, S. (Eds.), Papers in Italian Archaeology IV. Part i The Human Landscape. BAR International Series 243, pp. 53-68.

Meylemans, E., Vanderbeken, T, 2008. Onderzoeksbalans Onroerend erfgoed Vlaanderen – Archeologie, Hoofdstuk 12 Methoden en Technieken: Terreinprospecties en -evaluaties. (September 5, 2012) http://www.onderzoeksbalans.be/onderzoeksbalans/archeologie/

Vink, A.P.A., 1975. Land use in advancing agriculture. Advanced Series in Agricultural Science 1. Springer, Berlin.

Vlaamse Regering, 2012. Memorie van Toepassing. Ontwerp van decreet betreffende het onroerend erfgoed. Versie 17 februari 2012.

Wright, R.L., 1987. Integration in land research for Third World development planning: An applied aspect of landscape ecology. Landscape Ecology 1(2), 107-117.

Chapter 2
The study area

2.1 General setting

2.1.1 Geographical setting

The study area is situated in Flanders (Figure 2.1), a densely populated political region forming the northern part of Belgium. The three major cities are Antwerp, Ghent and Bruges (ADSEI, 2012). More specifically, the study area is situated in the sand area, which is one of the agricultural regions of Flanders and is also known as Sandy Flanders. This region is bordered by the polders of the river Scheldt in the north, by the coastal polders in the west and northwest and in the east by the Campine region. The sandloam and loam agricultural areas are found more to the south. Sandy Flanders is a flat, low-lying area with elevations ranging between 1 and 15 m.a.s.l. (De Moor, 1963), although major land forms are also present. To the west are the hills of Central-West Flanders with elevations up to 25 and even 50 m.a.s.l.; in the south are the interfluvia of the rivers Scheldt and Lyss that have elevations of 50 to 100 m.a.s.l.; and in the east lies the Cuesta of the Waasland with elevations up to 30 m.a.s.l. (De Moor and Heyse, 1978). Furthermore, a large dune complex consisting of several parallel ridges, stretches over a length of around 80 km in an east-west direction (width: 1-4 km; elevation: 5-10 m.a.s.l. on average; De Moor and van de Velde, 1995; Heyse, 1979). A part of this complex is referred to as the cover sand ridge of Maldegem-Stekene. Its asymmetric profile results in a rather steep southern border and a more gradually sloping northern flank (1-4% and 1-1.5% respectively; Heyse, 1979).

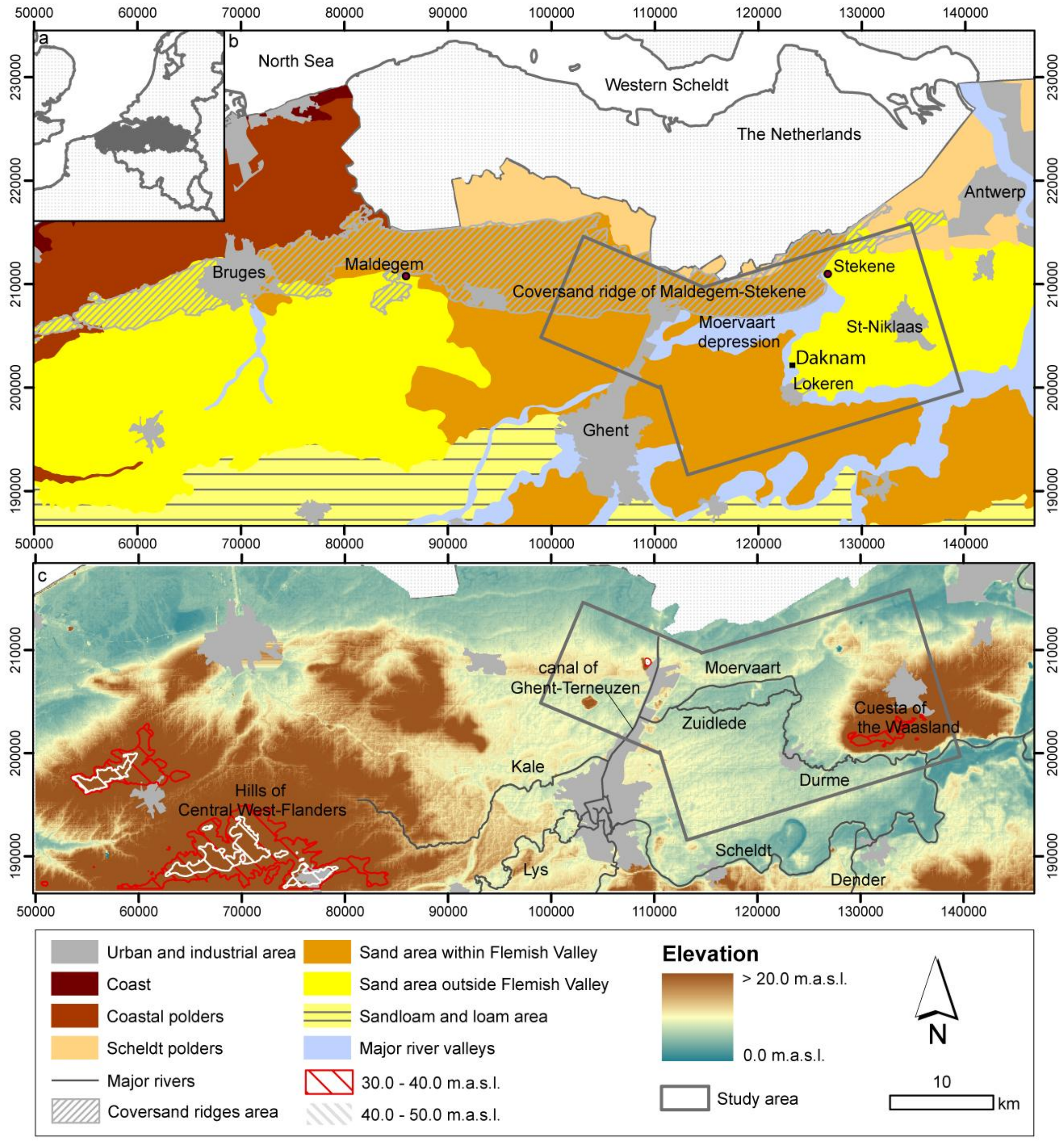

Figure 2.1 a: Indication of Flanders (in grey) within Belgium; b: Geographical regions in the northern part of Flanders (AGIV, 2001b; Antrop et al., 2002); c: Elevation of the northern part of Flanders based on the DEM (AGIV, 2008; Werbrouck et al., 2010); b-c: Indication of the study area (grey box), major cities, watercourses and geomorphological features.

The study area covers 584 km² and lies between Antwerp (to the east) and Ghent (to the southwest). It encompasses the cities of Sint-Niklaas and Lokeren. The industrial area along the canal of Ghent-Terneuzen crosses the study area in the west from south to north. To its north, the area is bordered by the Scheldt polders and to its south by the river Scheldt. Nowadays, the drainage system of the study region is part of the basin of the Canals of Ghent and also partly to the Lower Scheldt basin (HIC, 2012). The natural drainage is strongly altered by large constructions and interventions in the water management. For example, the canal of Ghent-Terneuzen separates the Durme from its upstream area formed by the Kale river (De Vos, 1958). Furthermore, the Durme at Lokeren was disconnected in the 1930s from its upstream canal, called the Moervaart. The latter is now draining into the canal of Ghent-Terneuzen (Vermeersch and Decleer, 2009). Other waterways in the study region are for example, the Zuidlede, the Lede, the Burggravenstroom, the Barbierbeek and many others.

2.1.2 Temporal setting

The study focuses mainly on the pre- and protohistoric times covering the Stone and Metal Ages. More recent historic Roman and Medieval times lie outside the scope of the final objectives. However, due to calibration and quality testing of the models used, the simulated period covers a larger time frame starting during the Younger Dryas (at the end of the Late Glacial) and covering the entire Holocene.

2.2 Geological, hydrogeological and geomorphological context

2.2.1 Geology and hydrogeology

The geological substrate of a region provides the parent material for soil formation and influences by its lithological and structural characteristics the regional hydrogeology. All over the study region a layer of Quaternary sediments covers the underlying lithostratigraphical units. The thickness of the Quaternary sediments varies locally from only few meters (< 5 m) to more than 20 m (De Moor and van de Velde, 1995; Adams et al., 2002). Their origin covers a broad range: marine and estuarine, fluvial, alluvial, colluvial, aeolian and organic (De Moor and van de Velde, 1995). Generally, the Quaternary sediments found directly at the surface are of continental origin, except for a small area near the northern state border and near the eastern border of the study area consisting of marine/estuarine Holocene sediments (Bogemans, 2005b). All geological formations in the study area that are directly outcropping underneath the Quaternary cover are of Paleogene or Neogene age (Jacobs et al., 1993). Their origin is solely marine and it concerns mostly undisturbed and unconsolidated sediments (Jacobs et al, 1993). These deposits mainly consist of sand and clay, although a few more silty layers also occur. The layers are tilted with a dip of 1° in a northern-northeastern direction. Consequently, in a horizontal section underneath the Quaternary sediments, younger to older layers are found when going towards the south-southwest. The situation in the central part of the study area appears to be more complex as the combined result of the dipping layers and the more recent Quaternary erosion and formation of the Flemish Valley (Jacobs et al., 1996; Figure 2.1). No sediments of Mesozoic (secondary) and Palaeozoic (primary) age occur directly beneath the Quaternary cover (Jacobs et al., 1993, 1996). These are only present in the study region at considerable depths beneath the thick cover of younger Paleogene and Quaternary sediments. Therefore, the topography of the study region is largely the result of a complex Quaternary geomorphological evolution, except for some outcrops.

The geological strata were schematized based on their hydrological characteristics in function of the groundwater management in Flanders (Meyus et al., 2000). This resulted into a standardized hierarchical hydrogeological code called HCOV. Several of these HCOV-units are furthermore grouped in different groundwater systems amongst which practically no exchange of groundwater happens due to physical boundaries influencing the regional groundwater flow. Two groundwater systems cover the study area: the Central Flemish system (VMM, 2008b), taking up the largest part of the study area and the Central Campine system (VMM, 2008a), occurring in the eastern corner of the study area and topping the former one.

2.2.2 Quaternary geomorphological evolution

The present-day topography in the study area is basically the product of Quaternary processes that were mainly driven by climatic forces: erosion of sediments resulting in macrotopographical features, Quaternary infilling and smoothing of the relief, changing drainage patterns, and aeolian sediment transport. In this dynamic time period man firstly visited the region.

Glacial and interglacial cycles during the Pleistocene resulted in fluctuating sea levels giving rise to sequential periods of erosion and accumulation. Already in the Early and Middle Pleistocene (Figure 2.2 for all chronostratigraphical and archaeological periods) the regression of the North Sea accompanied by fluvial activity in a mainly northern direction led to the denudation of the marine sandy and clayey layers of the region (De Moor, 1963; De Moor and van de Velde, 1995). Due to the structural and lithological characteristics of the geological substrate, i.e. dipping layers towards the north-

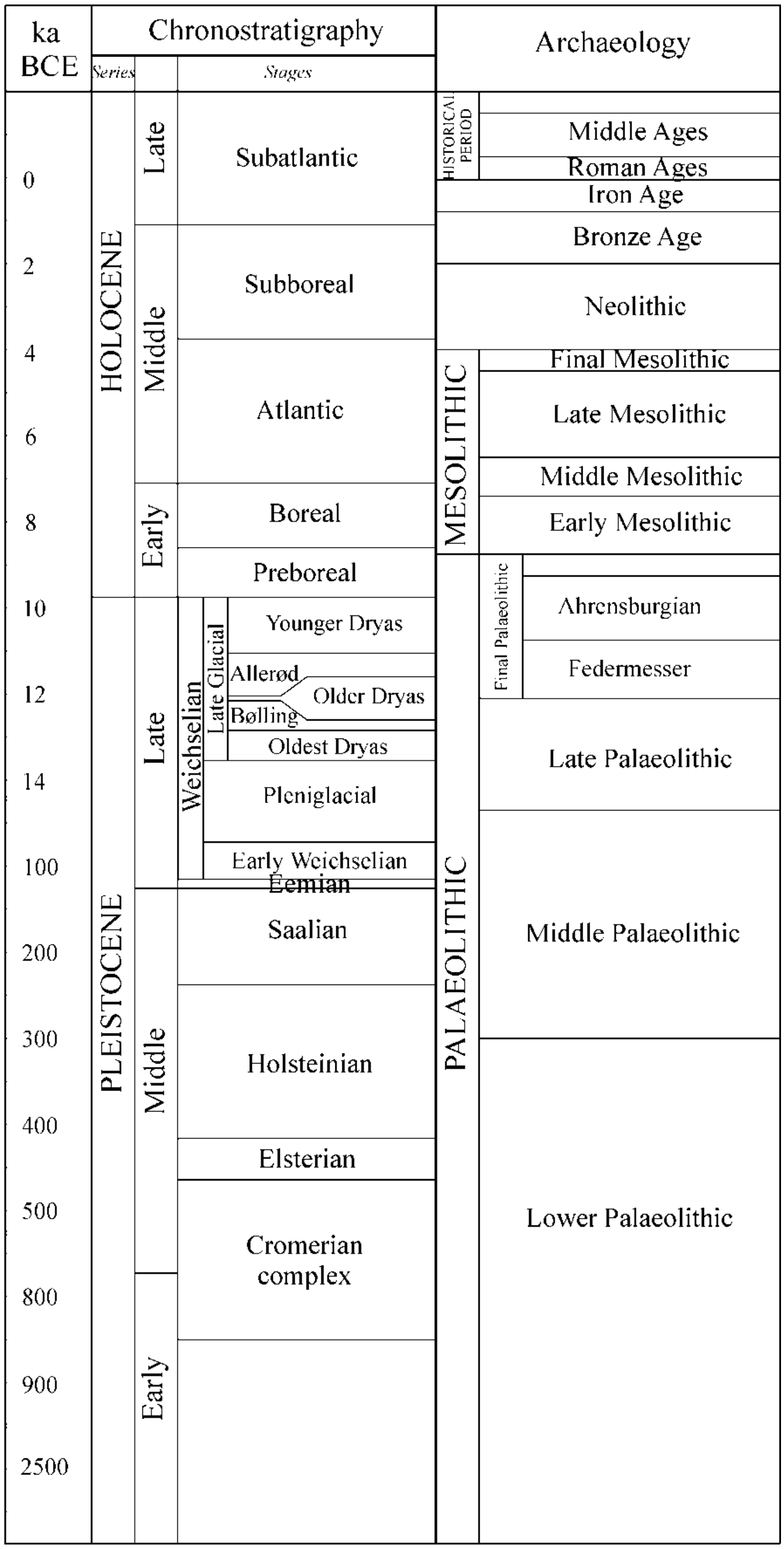

Figure 2.2 Time table listing the chronostratigraphical units and archaeological periods of the last 20 ka. Ages are expressed in BCE. Chronostratigraphy of the Holocene is based on Terberger et al. (2006); the subdivision of the Pleistocene is based on radiocarbon dated pollen diagrams for the Netherlands as revised by Hoek (2001). The time frame of the archaeological periods is expressed for the situation in Sandy Flanders. Note that at present no traces of the Late Palaeolithic and Ahrensburgian cultures have been reported in Sandy Flanders (Crombé and Verbruggen, 2002; Crombé et al., 2011).

northeast and alternation of less and more resistant layers respectively, the fluvial activity resulted in the formation of several asymmetrical cuestas (De Moor and Heyse, 1978; De Moor and van de Velde, 1995). For example, the presence of the Oligocene clay of Boom with its higher resistance against erosion resulted in the formation of the Cuesta of the Waasland. The gravel deposits of the alluvial floodplains became terraces, often serving as interfluvia, as the result of posterior erosion phases (De Moor and Heyse, 1978). The deepest incision and the main extension of the palaeovalley, called the Flemish Valley, occurred during the Saalian glaciation (De Moor and Heyse, 1978; Heyse, 1979), which was followed by a marine inundation in the Eemian. During the Weichselian, more exactly the Pleniglacial, fluvio-periglacial infilling of the valley by a braided river system draining towards the north-northwest was dominant. These mainly sandy deposits reach thicknesses up to 20 m or more (Jacobs et al., 1993; Figure 2.3).

From the Late Pleniglacial onward very cold and dry climatic conditions prevailed and vegetation was scarce (Hoek, 1997). Aeolian activity in the region increased and exposed fluvial sandy sediments were deposited into parallel east-west oriented dunes and dune complexes (De Moor and Heyse, 1974; Heyse, 1979). The southward moving sand was most probably halted by wetter zones and depressions fed by fluvial systems of reduced size (Heyse, 1979). Meanwhile the dune accumulation led to the gradual damming of this northwestward drainage and forced it towards a more eastern direction (De Moor and Heyse, 1978). The microrelief of parallel west-south-west oriented ridges (levees) and small depressions more to the south of the dune complex is most probably the result of this much reduced more eastward drainage system (De Moor and Heyse, 1978). The aeolian activity continued during the Late Glacial, however, intermittent periods of sediment stabilization and soil formation occurred. The drainage network evolved to a more meandering pattern with more deeply incised and fixated riverbeds (De Moor and Heyse, 1978). Local sand drifting occurred during the Late Glacial and Early Holocene. This resulted in the formation of two types of drift sand dunes (Figure 2.3). The local movement of the Weichselian cover sand resulted in the formation of inland dunes. These are located on top of the cover sand ridge of Maldegem-Stekene and on the southern border of the Cuesta of the Waasland. Blown out sand from river valleys gave rise to the formation of river dunes, for example the parabolic dune near Daknam in the valley of the Durme (De Moor and van de Velde, 1995). Although these drift sands can be several meters thick, they only cover 1.3% of the entire study area. Verbruggen (1971) mentions (natural and human induced) sand drift in more recent Roman and medieval times, for example at Stekene and Berlare. Generally, this concerns a very local displacement of the top of the dune towards its base (Verbruggen, 1971). The rest of the Holocene is considered to have been geomorphologically more stable. The establishment of a dense forest vegetation largely prevented aeolian activity. The fluvial activity was reduced and peat filled up the deeply incised riverbeds (Verbruggen, 1971). According to Verbruggen (1971) the absence of small peat-filled gullies proves the nonexistence of a secondary drainage network during the Late Glacial and the first part of the Holocene.

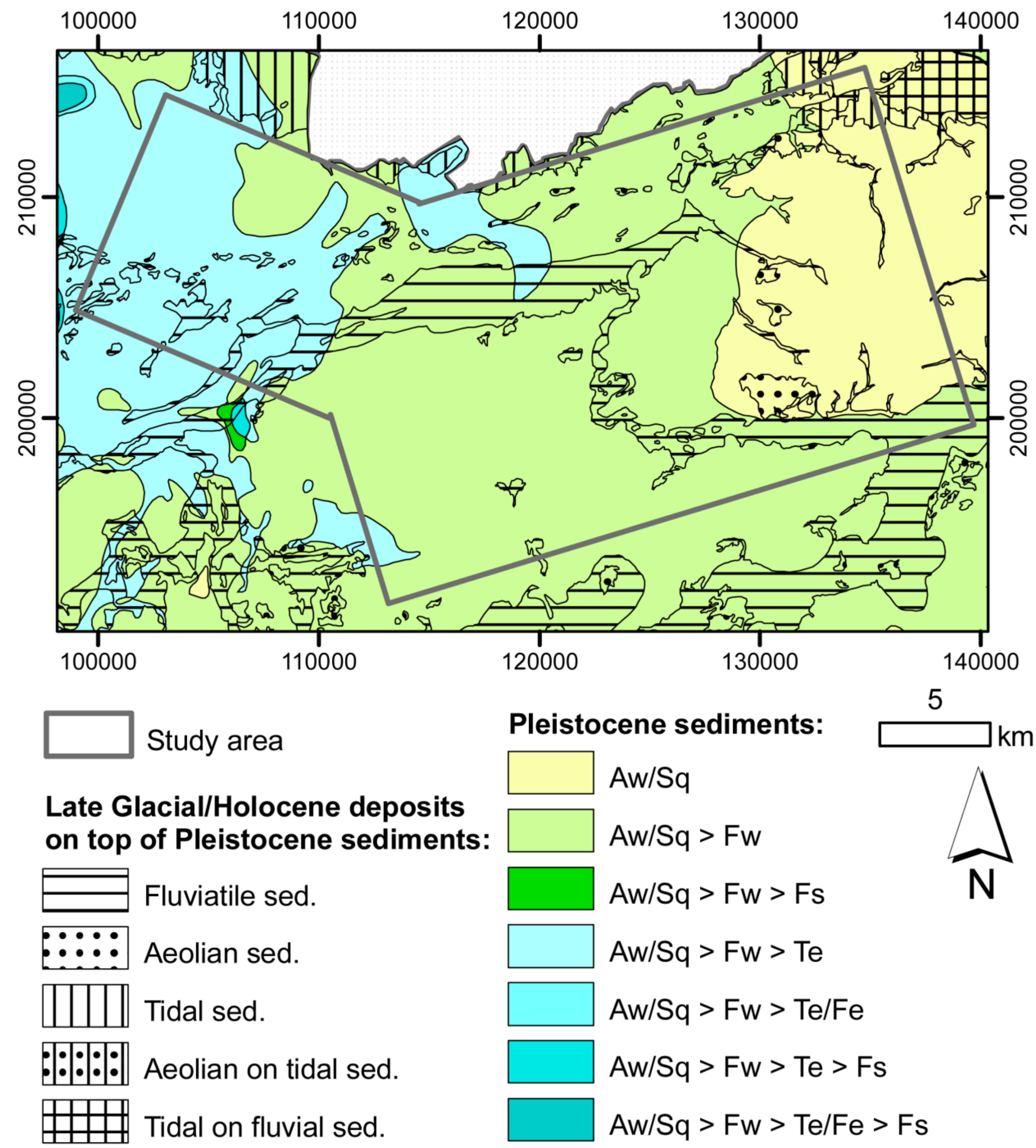

Figure 2.3 Quaternary deposits in the study area (Bogemans, 2005a). Aw: Aeolian deposits dating to the Weichselian (Late Pleistocene) or Early Holocene; Sq: Quaternary slope deposits; Fw: Fluviatile deposits dating to the Weichselian (Late Pleistocene); Fe: Fluviatile deposits dating to the Eemian (Late Pleistocene); Te: Tidal deposits (marine and estuarine) dating to the Eemian (Late Pleistocene); Fs: Fluviatile deposits dating to the Saalian (Middle Pleistocene); >: on top of. Drift sand dunes are indicated with dots (see legend: aeolian Late Glacial/Holocene deposits on top of Pleistocene sediments).

Rising sea level and the associated higher groundwater table resulted in the development of a large peat-covered area in the north (Heyse, 1979; Verbruggen et al., 1993; Vos and van Heeringen, 1997). The end of the peat growth and its exact southern extension are often the subject of discussion. Large peat excavations in medieval times have disturbed the physical evidence and are hampering the debate (Jongepier et al., 2011; Verbruggen and Semey, 1993). According to Verbruggen and Semey (1993) this Holocene peat had a thickness varying between 5 m in the north and 0.5 m in the south. The most southern limit of the Holocene peat extension was located to the north of the town of Zuiddorpe in the Netherlands (Jongepier et al., 2011; Verbruggen and Semey, 1993). This implicates that the peat expansion did not reach the study area. The same is confirmed by De Muynck (1976) for an area to the west of this study area. She places the most southern limit of the peat expansion 2.5 km to the north of the town of Assenede, although she mentions that small depressions to the south of this border could have contained local peat. Often the exact location, depth and thickness of these local peat-filled depressions are unknown. Their impact on the local hydrology was assumed to be minor due to their limited extent. Crombé et al. (in review) mentions a 0.5 m thick peat layer buried underneath medieval sediments in the eastern part of the Moervaart Depression. This peat is not yet dated, but there is indirect evidence to date its base to the transition of the Allerød to the Younger Dryas (Crombé et al., in review). This layer is missing at other locations in the Moervaart Depression, which makes its reconstruction highly uncertain.

The human presence in the region, however, had its impact even in earlier times. According to Verbruggen (1971) deforestations occurred from the Subatlantic onward. This influenced the natural drainage and led to the formation of a secondary drainage network. Furthermore, the acculturation of the land had its influence on the soil formation (Ameryckx, 1960).

2.3 Pedological context

The study area is dominantly characterized by sand (Figures 2.4.a and 2.5) textures ranging from moderately wet to moderately dry and loamy sand textures with drainage classes from moderately wet to wet (Tavernier et al., 1960). However, smaller inclusions of very dry to dry sandy soils do occur as well. Furthermore, (light) sandloam, clay, peat and marl are also present. The latter are mostly found in alluvial or semi-alluvial depressions and bound to predominantly wet to very wet, and even extremely wet locations (Tavernier et al., 1960). A distinct soil development is generally absent in these soils (Tavernier et al., 1960; Van Ranst and Sys, 2000). Regosols and Arenosols found in sandy textures with excessive drainage are often the result of recent sediment movement and re-deposition in dune contexts (Van Ranst and Sys, 2000). In these cases a buried Podzol is often found at a certain depth (Ameryckx, 1960). Several other stages of the soil development in the more sandy textures are found in the study region. These were defined in the pedogenetic chrono-biosequence of Ameryckx (1960), and correspond to the following WRB reference soil groups: Cambisols, Albeluvisols and Podzols (IUSS Working Group WRB, 2006).

Decalcification started in the calcium-rich sandy parent material after deposition. During the Bølling and Allerød the region was covered by a dense forest vegetation. Especially under deciduous forest vegetations in temperate climates a brown forest soil develops on decalcified materials (Duchaufour, 1982; Jacques et al., 2010). These Cambisols have a typical profile of *ABC*-horizons (FAO, 2001). The brown colour is due to a close association between the clay and the iron oxides (Duchaufour, 1982). An argillic horizon (Bt) is present when the clay migration is more pronounced. Often, this horizon is overtopped by a lighter coloured eluviation horizon (E). The typical soil profile in these Albeluvisols is *AEBtC* (FAO, 2001). In the study area with its poor sandy soils, the Bt-horizon is practically always degradated and iron concretions are often present. Podzols are formed by the transport of complexes (chelates) of aluminium, iron and organic compounds from the surface towards the deeper horizons together with percolating rainwater (Breemen and Buurman, 1998; FAO, 2001). The parent material is highly permeable and poor in base cations and iron (Sauer et al., 2007). The organic material produced as plant litter at the surface becomes mobilized under strong leaching conditions when depleted cations are not entirely replenished by the weathering of primary minerals (Jacques et al., 2010). Only under an acidifying vegetation that produces slowly degradable and nutrient-poor litter is the podzol profile (O(Ah)EBhsC; FAO, 2001) fully developed (iron-humic or humic Podzols; Duchaufour, 1982; Sauer et al., 2007). This is especially true for coniferous forest or heath vegetation with *Ericaceae*. In northwestern Europe the natural forest vegetation degraded due to human forest clearances. In the study area local heath growth is attested from pollen analysis from the second part of the Subboreal (Verbruggen et al., 1996). Forest Podzols, on the other hand, that developed under forest vegetation as well as Podzols that were formed under hydromorphic conditions are also present in the study area. The latter are controlled by an acid water table, which is (almost) permanent and is subject to a slow lateral flow (Duchaufour, 1982). Many Podzols in the study area, however, are strongly disturbed as the result of deep ploughing (Tavernier and Ameryckx, 1957).

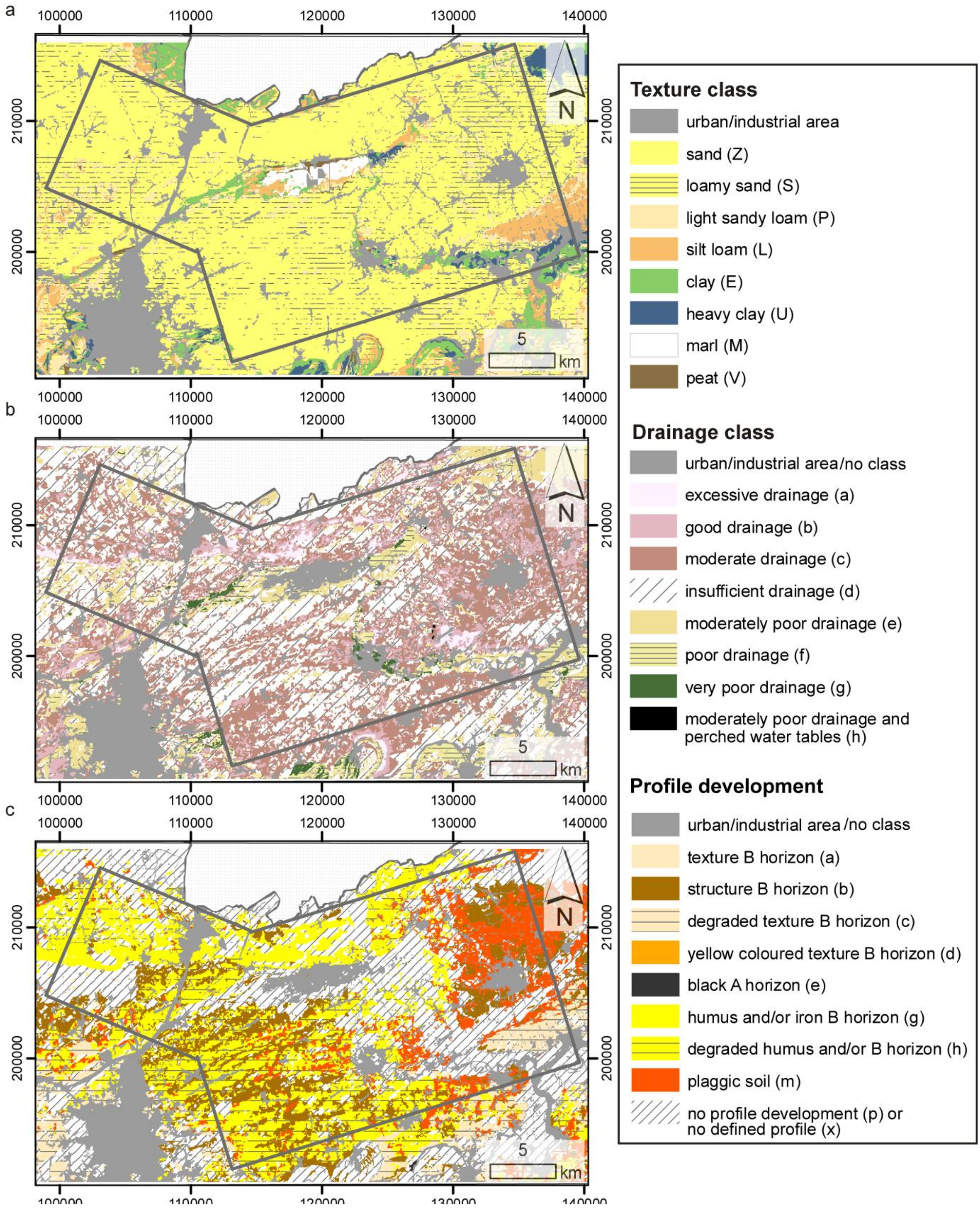

Figure 2.4 Texture class (a), drainage class (b) and profile development (c) in the study area (grey box) as recorded in the soil map (AGIV, 2001a). The codes for texture, drainage and profile development used in the Belgian classification are between brackets.

The Plaggic Anthrosol is also present in the study area. Its formation is the result of long-term human plaggen management: heath sods an/or forest litter were used as bedding material to the stables. Occasionally, the bedding together with the animal dung was removed and applied to the cultivated land as manure (FAO, 2001). The practice was locally introduced in the Early Middle Ages and became a regular management type on mineral poor sandy soils in medieval times (van Mourik et al., 2012). As a side-effect the land was heightened over time and lowered at the locations were the original sods were removed (Blume and Leinweber, 2004).

2.4 Climatological and vegetational context

Climatic conditions include amongst other things, the amount of precipitation, temperature and evaporation, influencing the vegetation of a region. All of these factors have an impact on soil formation and groundwater levels. Therefore, the general climatological and vegetational context is stated below. The temporal extent is restricted to the study period. Information on the climate and the vegetation development of the study area was generally provided by palynological investigations by Verbruggen (1971) and Verbruggen et al. (1996).

The Younger Dryas is considered to have been much colder than the preceding Allerød and was characterized by a decline of the pine-birch (*Pinus-Betula*) forest, which was fully established towards the end of the previous period. This was accompanied with the expansion of the herbaceous vegetation. From the Holocene onwards the forest regenerated due to the ameliorating climatic conditions. This started with the increasing and eventually dominating presence of birch. After the first warming phase, a short oscillation with colder temperatures during the Preboreal was accompanied with the sudden increase in *Gramineae* (grasses) (Verbruggen, 1971). Subsequently, climatic conditions improved permanent and were quickly followed by the increasing presence of pine resulting in the development of an almost closed pine-birch forest. From the beginning of the Boreal hazel (*Corylus*) occured and later on also oak (*Quercus*) and elm tree (*Ulmus*). Diversity increased with *Alnus* (alder), *Tilia* (lime) and *Fraxinus* (beech) towards the end of the Boreal. This was the onset towards the mixed-oak (*Quercetum mixtum*) forest, which was fully established from the Atlantic onward (Verbruggen, 1971) and especially present on the drier grounds, while alder (*Alnus*) occupied the wetter parts (Verbruggen et al., 1996). During the Subboreal lime (*Tilia*) and elm (*Ulmus*) declined, which was for the study region most probably attributed to human influence (Verbruggen, 1971). This coincided with the first continuous presence of ruderal plants. The second part of the Subboreal was characterized by the gradually increasing presence of beech (*Fagus sylvaticus*), although lower in concentrations than mentioned for neighbouring countries due to differing ecological conditions (Verbruggen, 1971). Human impact on the vegetation was initially displayed as very small open spots in the forest and the presence of *Cerealia*, however not continuous (Verbruggen, 1971; Verbruggen et al., 1996). Only on the cover sand ridges the forest was degraded further during the first part of the Subatlantic resulting in grassland with hazel and birch, and later on heathland with birch. Systematic clearances appeared from the Roman Age onwards, although a slight regeneration of the forest was observed during the medieval times. Afterwards the final clearances took place with the removal of the last patches of natural vegetation and the establishment of the cultural landscape.

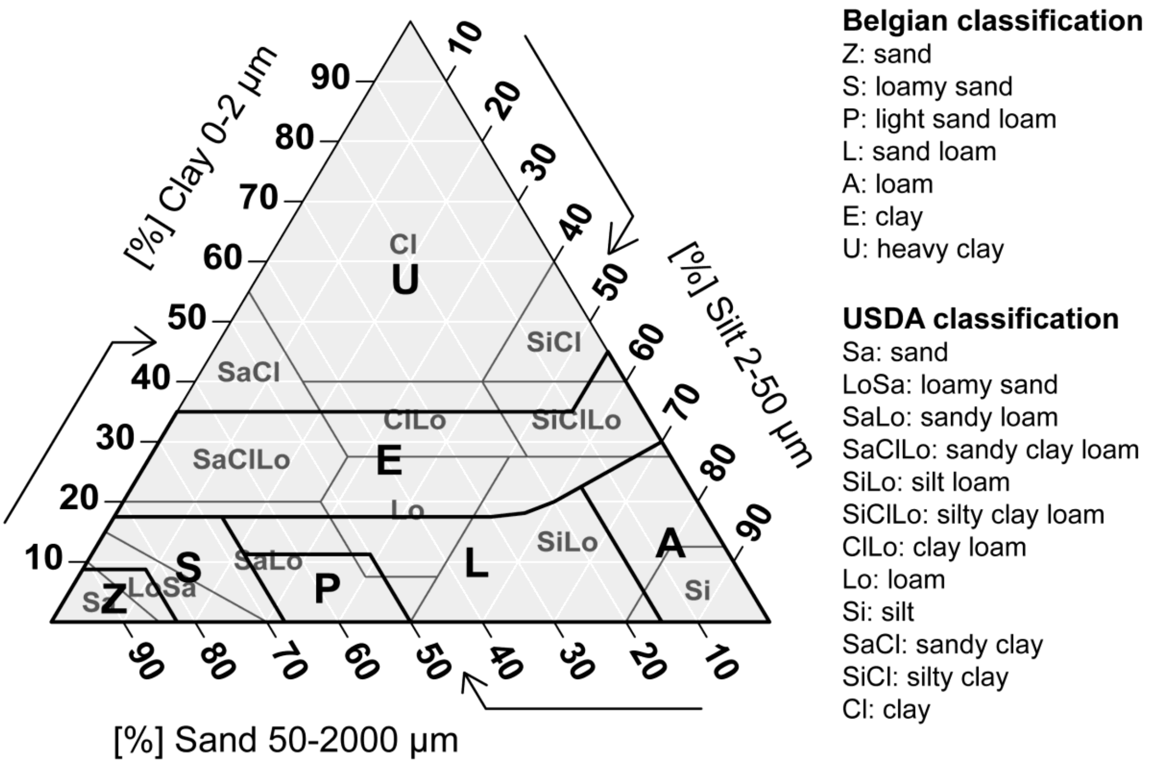

Figure 2.5 Texture triangle giving the relationship between the Belgian classification (ALEUZSP) and the USDA classification.

2.5 Archaeological context

The oldest archaeological evidence in Flanders dates to ca 300 ka BP at the transition from Early to Middle Palaeolithic (Kesselt 'Op de Schans'; Van Baelen et al., 2007). The oldest artefacts in Sandy Flanders are slightly younger (Ghent 'Blaarmeersen' and Ghent 'Port-Arthur'; Crombé and Van der Haegen, 1994). Above mentioned sites are attributed to the Neanderthal (*Homo neanderthalensis*) occupation. Modern man, known as *Homo sapiens sapiens*, only appeared in Europe around 40 ka BP, marking the transition between the Middle and Late Palaeolithic (Rensink, 2005). In Belgium the presence of Late Palaeolithic groups appears to be limited to the Ardennes (Deeben and Rensink, 2005), the Meuse basin (Charles, 1995) and the loess belt (Vermeersch, 1981). Remains of their presence are not found in the study region. Therefore, based on the current archaeological evidence the recolonization of Sandy Flanders after the Late Glacial Maximum appears to have started during the Allerød with Final Palaeolithic *Federmesser* groups (Crombé and Verbruggen, 2002).

Presently known *Federmesser* sites are mostly located on ridges and terraces on well-drained sands near open water, such as lakes and abandoned meanders, and preferably along their western and northern shores (Deeben and Rensink, 2005). River and stream valleys also seem a logical choice as attractive location. However, not many sites are found in these settings most probably due to erosion and superposition by alluvial sediments (Deeben and Rensink, 2005). For the study area as well, the highest concentration of *Federmesser* sites occurs on the southern rim of the cover sand ridge between Maldegem and Stekene (Figure 2.6a) near the border of the Late Glacial lake of the Moervaart Depression (Bats et al., 2010; Crombé et al., 2011). Hunting, gathering and fishing were the main means of subsistence. Information on the *Federmesser* diet and lifestyle can be derived from several settlements all over their territory. This is necessary because the organic remains are very poorly preserved on the sandy soils of the study area. Burnt bones collected from the Netherlands indicate a diet of meat and fat of elk (*Alces alces*), horse (*Equus* sp.), hare (*Lepus* sp.), beaver (*Castor fiber*) and most probably wild boar (*Sus scrofa*) and fish, such as pike (*Esox lucius*), salmonoids (*Salmonidae*) and cyprinoids (*Cyprinidae*) (Lauwerier and Deeben, 2012). No archaeological artefacts dating to the Younger Dryas are yet discovered in the study region suggesting it was uninhabited during the specific period (Crombé et al., accepted). Most probably, this is due to the hostile environment caused by intense aeolian activity and the possible disappearance of large water bodies (Bats et al., 2010; Crombé et al., accepted). However, the debate on the Younger Dryas occupation is still ongoing (Crombé and Verbruggen, 2002; Crombé et al., accepted) because signs of Ahrensburgian inhabitation are found in the surrounding regions (the southern

Netherlands, the Belgian Ardennes, the German Rhineland; Street, 1998; Deeben et al., 2000; Vermeersch, 2011; Weber et al., 2011).

The transition towards the Holocene is characterized by an ameliorating and more hospitable climate. However, the population density of the region did not promptly increase with the beginning of the Mesolithic (Figure 2.6b; De Bie and Vermeersch, 1998). Many Early Mesolithic sites in the study area are situated at former *Federmesser* locations (Crombé, 2001), although most Early and Middle Mesolithic sites appear to be on new spots (Sergant et al., 2009). In general, the sites form extensive clusters (Sergant et al., 2009) in specific topographical settings, such as dry sand ridges close to open water (Crombé et al., 2011). The site-complexes now occur on the dry banks of river systems, such as the Kale/Durme river, as the Moervaart lake most probably had disappeared by then (Crombé et al., 2011). In other areas as well, such as the Campine region (De Bie and Van Gils, 2009; Vanacker et al., 2001), sites are found in similar contexts. The site density decreases during the Middle and Late Mesolithic, site-complexes no longer occur and campsites are more widely spaced. River banks, however, remain the most favoured settlement location (Crombé et al., 2011). The Late Mesolithic sites appear to be located on lower grounds. Furthermore, less reoccupation of former campsites occurs (Crombé et al., 2011): practically no *Federmesser* sites and only ca. 38% of the Early and Middle Mesolithic sites were reused during the Late Mesolithic (Sergant et al., 2009). Above-mentioned trends are also attested in other northwest European regions (Spikins, 1999) and attributed to vegetational changes: open coniferous forests harbouring evenly distributed resources during the Preboreal and Boreal in contrast to dense and dark broad-leaf forest (*Quercetum mixtum*) characterized by clustered resources from the transition to the Atlantic onwards (Crombé et al., 2008). The discrepancy between the Early Mesolithic on the one hand and the Middle and especially the Late Mesolithic on the other hand, is also detected in the use and the distribution of exotic raw materials such as the Tienen and the Wommersom quartzite (Crombé, 2002; Crombé et al., 2008). These trends might suggest interregional cultural and/or social differences (Crombé et al., 2008; Sergant et al., 2009). The Final Mesolithic in the study area (Swifterband culture) is currently only known from sites situated in the Lower Scheldt river floodplain in the vicinity of Antwerp (for example Doel 'Deurganckdok', Crombé, 2005; Crombé et al., 2000, 2004). They are located on narrow, elongated sand ridges that are nowadays covered underneath thick layers of peat and alluvial deposits (Crombé et al., 2002). In neighbouring regions as well, such as the Dutch Rhine-Meuse delta, the Final Mesolithic finds are restricted to wetland areas (Crombé and Sergant, 2008). According to Crombé and Sergant (2008) these Final Mesolithic groups focused on the wetland regions, but also marginally exploited the drier cover sand inlands. This most probably suggests a continuation of Late Mesolithic trends.

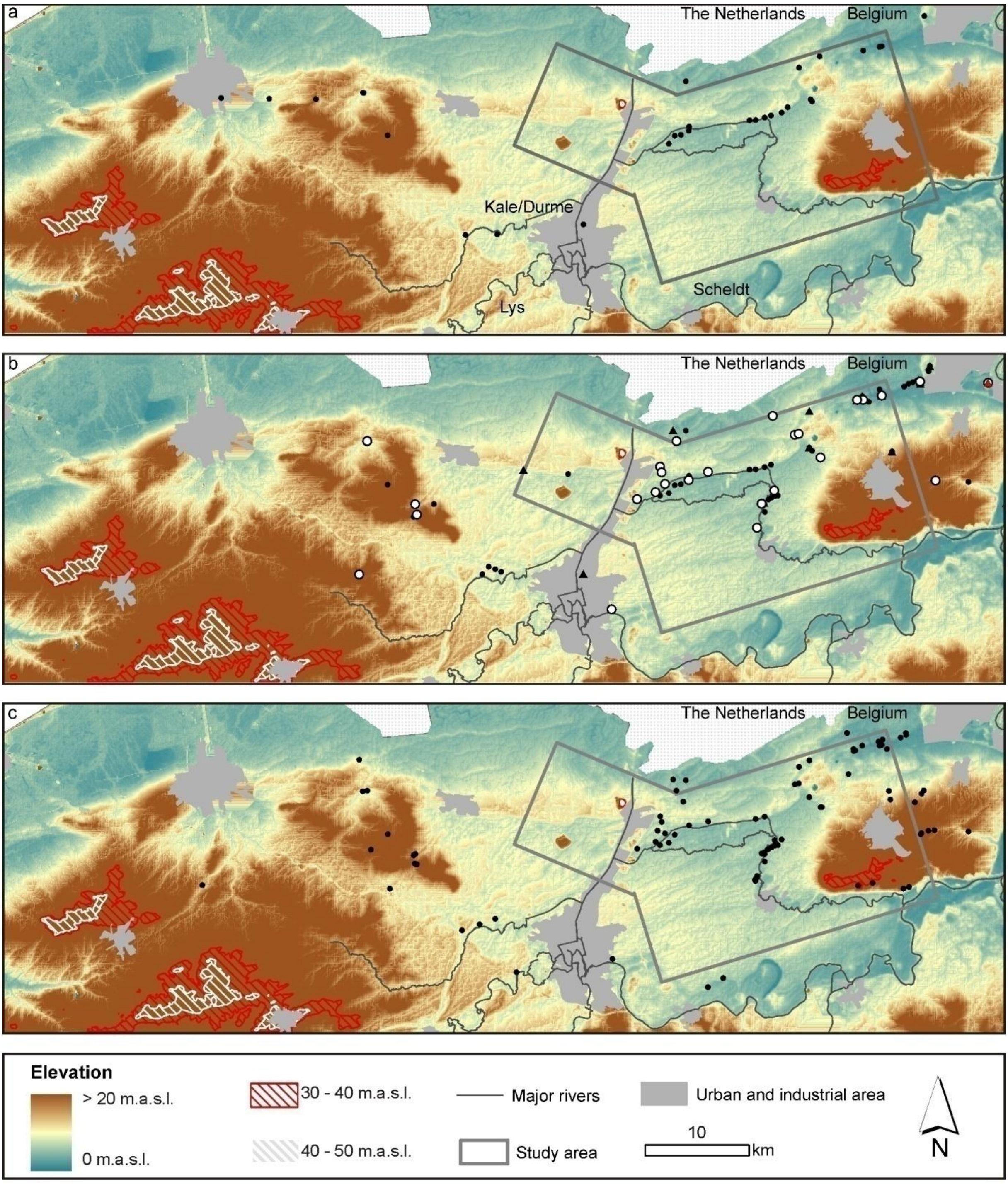

Figure 2.6 Elevation based on the DEM (AGIV, 2008; Werbrouck et al., 2010) and archaeological find spots in the study area and surroundings. a: Final Palaeolithic (black dots) sites; b: Early (black dots), Middle (black triangles), Late (white dots) and Final (red triangle) Mesolithic sites; c. Neolithic (black dots) sites. All archaeological Stone Age sites are provided by Sergant et al. (2009).

The poor preservation of organic material in dry sandy soils restricts the information on the Mesolithic diet to burnt, carbonized plant material and calcified bone fragments derived from hearth-pits. Most knowledge is derived from wetland settings with better preserved organic remains due to the reducing conditions in the soil (Verhart and Arts, 2005). However, to what extent these sites are representative of a broader Mesolithic context is yet uncertain. In general, the Mesolithic communities are known as hunter-gatherer-fisherman. Trees and plants were exploited as raw construction material, but also as a food source (Bakels, 2005). The range of edible seeds and fruits recovered from the Final Mesolithic site Doel 'Deurganckdok' resembles the assemblages listed from other Final Mesolithic/Early Neolithic sites in northwestern Europe. It concerns nuts from hazel, wild apples from crab apple (*Malus sylvestris*), sloe plums from blackthorn (*Prunus spinosa*), berries from hawthorn (*Crataegus monogyna*), and acorns from oak (*Quercus* sp.) (Bastiaens et al., 2005).

The transition from the Mesolithic hunter-gatherer towards the Neolithic agro-pastoral way of life in Sandy Flanders is still a matter of debate. However, it is clear that the neolithization process – the shift from an exploitative to a productive food economy (Verhart, 2000) – in the study area and in the sand area of Flanders in general, differs from the one seen in the loam area more to the south (Crombé and Vanmontfort, 2007). In the latter region the Neolithic started already 5.3 ka BCE with the presence of the *Linearbandkeramik* culture (Van Berg and Hauzeur, 2001). According to Bakels (2009), agriculture in the loess region arrived as a full package. In contrast, the integration of agriculture in the cover sand area more to the north appeared to be a more gradual process. Furthermore, the starting date of the neolithization process in the study area is set at 4 ka BCE based on the current archaeological evidence (Crombé and Sergant, 2008). Evidence of the preceding Final Mesolithic Swifterbant culture was found some twenty kilometres to the northeast of the study area at the site of Doel/Deurganckdok-sector B (Crombé et al., 2000, 2004; Crombé, 2005). However, no remains of domestic animals were found at the site (Van Neer et al., 2001, 2005) and only one cereal grain belonging to bread wheat (*Triticum aestivum*; Bastiaens et al., 2005). The grain was concluded as the result of import or exchange with contemporaneous Neolithic cultures rather than the product of local agriculture (Bastiaens et al., 2005). High amounts of *Hedera helix* seeds and *Viscum album* charcoal fragments were also found. The presence of these evergreen plants suggests their use as leaf fodder and is indirectly pointing to animal husbandry at the site (Bastiaens et al., 2005; Deforce et al., accepted). The recent discovery of uncarbonized animal bones, amongst which the remains of domesticated animals as dog, sheep/goat and pig, at the wetland site of Basel/Sluis (Perdaen et al., 2011), indicates that stockbreeding in the sand area of Flanders was already implemented in the Mesolithic broad-spectrum economy from 4300 cal BC. This is earlier than previously thought (Crombé, personal communication, 2012).

The Neolithic in the sand area of Flanders begins with the Middle Neolithic. The artefacts are most probably related to the Michelsberg culture or more specific to the Groupe of Spiere (Crombé et al., 2011). In general, Middle Neolithic artefacts are frequently found all over the study region (Figure 2.6c), although true concentrations are quite rare (Van Vlaenderen et al., 2006). It considers mostly stray finds or isolated artefacts at Mesolithic sites, which are often very hard to interpret or concentrations of artefacts that are mostly located in the Scheldt floodplain region (Crombé and Sergant, 2008). In general, these sites only display small assemblages of lithic artefacts as compared to the extensive concentrations found in the loess area with thousands of lithics covering several hectares (Crombé and Vanmontfort, 2007). According to some authors these are not to be associated with real occupations. Crombé and Sergant (2008) point out that the small sites in the sandy area might be comparable with some smaller sites found in the loess area, such as for example the site of Oudenaarde/Donk (Parent et al., 1987).

Furthermore, remains of the Late Neolithic Seine-Oise-Marne culture are only found in the Flanders region as dredged-up materials, although the sites at Eksaarde/Fondatie and Sint-Gillis-Waas may also be attributed to this culture (Crombé et al., 2011). The Final Neolithic as well, is characterized by new cultural traditions, belonging to the Deûle-Escaut group and the Single Grave culture, followed in time by the Bell-Beaker culture (Crombé, 1996). Very little of the Final Neolithic in the area is known. Generally, the finds concern single and isolated artefacts or finds in funeral contexts. However, for example at the site of Waardamme (Demeyere et al., 2004), a Final Neolithic house plan was uncovered. It concerns one single house plan, measuring 20.2 m long. According to Crombé and Vanmontfort (2007), this type of settlement might be a good representative of the average Neolithic settlement in the cover sand area. These were most probably relocated after several years. Such 'wandering farms' are also known in the sandy area dating to later periods especially the Early and Middle Bronze Age (Fokkens, 2005). Up till now, no actual occupation sites belonging to the end of the Neolithic, are found in the region. However, a large amount of intact beakers, as well as pot shards, give the impression of an intense occupation of the region by the Bell-Beaker culture (Crombé et al., 2011).

For the Bronze Age as well, findings belonging to funerary practices such as barrows (Figure 2.7a) and urnfields dominate the archaeological record. The Early and Middle Bronze Age barrows were built on the more prominent locations in the landscape (De Reu et al., 2011b) and they most probably served as anchor points during the Bronze Age, but also in later times. The knowledge on the settlement and subsistence and agricultural system is considerably restricted. This is of course related with the limited amount of settlement remains due to the typical low artefact concentrations at Metal Age sites and the low preservation potential of the used materials. The Early Bronze Age

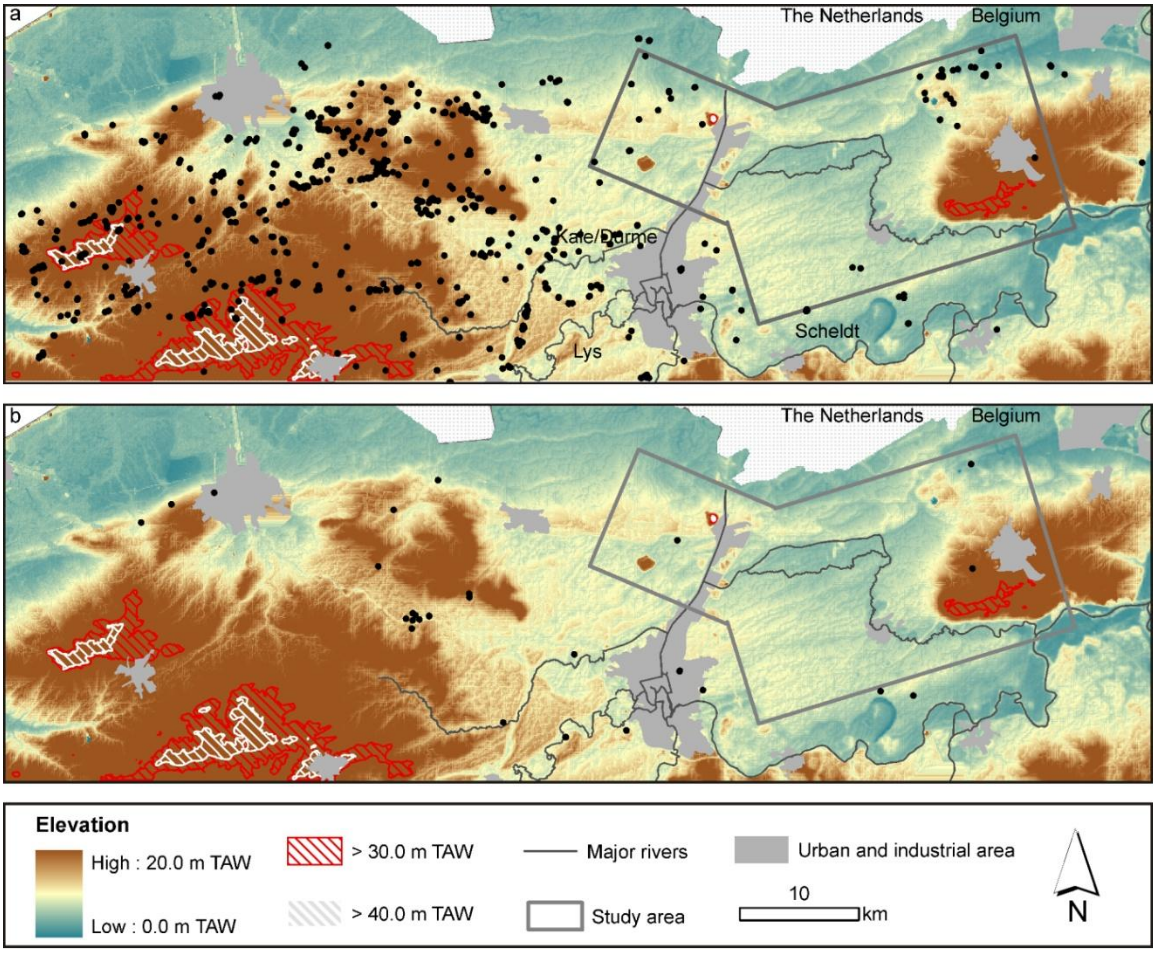

Figure 2.7 Elevation based on the DEM (AGIV, 2008; Werbrouck et al., 2010) and archaeological find spots in the study area and surroundings. a: Bronze Age barrows (black dots; Early and Middle Bronze Age; De Reu et al., 2011a,c); b: Late Iron Age (black dots) sites (De Clercq, 2009).

in particular is very much underrepresented. Considering the Middle Bronze Age, the sites at of for example Maldegem/Burkel (Crombé, 1993) and Sint-Gillis-Waas/Kluizenmolen (Lauwers and De Reu, 2011) display house plans of three-aisled longhouses. The longhouse is the traditional northwest European building type of the Metal Ages (Fokkens, 2003). According to several authors the longhouse with its stable and living part is strongly related with the subsistence system during the Bronze and Iron Age (de Hingh, 2000; Fokkens, 2003;). Floor plans of longhouses are also attested during the entire Iron Age as for example at the Early Iron Age settlement site of Sint-Gillis-Waas/Reepstraat (Bourgeois, 1993; Bourgeois et al., 1996). Several sites also display the remains of pits for underground storage called silos. Sometimes charred cereal remains were found in the pits. However, the presence of (pollen and grains of) cereals cannot be considered as evidence of local cereal cultivation. They provide only proof of cereal consumption and can be the result of import (Out, 2009). More direct evidence of agriculture in the sand area of Flanders, however, is currently only attested for the Late Bronze and Iron Ages. For example, Celtic field systems are known from the Belgian

Campine region (Creemers et al., 2011; Paesen et al., 2010). These parcel complexes are typical phenomena in northwestern Europe. The earliest are dated to the Late Bronze Age. They consist of several individual, more or less rectangular arable plots measuring 25 to 45 m in length and width (Kooijstra and Maas, 2008). The remains of an ard found at the Late Iron Age site of Zele/Zuidelijke omleiding are also an indication of agriculture (Bourgeois et al., 2009). The presence of a pool used for watering the cattle found at the Late Iron Age settlement of Ekeren/Salaadweg (Deforce and Minsaer, 2005) is evidence of stockbreeding.

In general, quite some sites dating to the Late Iron Age are known (Figure 2.7b): larger, fortified settlements such as the site at Kemmelberg in the Flemish Ardennes (Dalle, 2009; not in study area), but mainly smaller rural settlements. Nevertheless, our knowledge on Iron Age settlement organisation, agriculture and land use is still very limited.

2.6 References

Adams, R., Vermeire, S., De Moor, G., Jacobs, P., Louwye, S., Polfliet, T., 2002. Toelichting bij de Quartairgeologische kaart. Kaartblad 15: Antwerpen. Haecon and Universiteit Gent.

ADSEI, 2012. Statistieken, Statistieken - Bevolking, Statistieken - Download-tabellen. Algemene Directie Statistiek en Economische Informatie.

AGIV, 2001a. Vectoriële versie van de Bodemkaart (versie toestand 2001) 1/200,000. AGIV, IWT, Laboratorium voor Bodemkunde van de Universiteit Gent (GIS-Vlaanderen).

AGIV, 2001b. Vectoriële versie van de Traditionele Landschappen (versie 1.0) 1/50,000. MVG-LIN-AROHM-Monumenten en Landschappen (GIS-Vlaanderen).

AGIV, 2008. LIDAR-hoogtepunten (versie 1.0). MOW-Afd WL, VMM-Afd OW en AGIV.

Ameryckx, J., 1960. La pédogenèse en Flandre sablonneuse. Pédologie 10, 124-190.

Antrop, M., Van Eetvelde, V., Janssens, J., Martens, I., Van Damme, S., 2002. Traditionele Landschappen van Vlaanderen. Universiteit Gent, Vakgroep Geografie. http://www.geoweb.ugent.be/landschapskunde/projecten/traditionele-landschappen-vlaanderen (Geraadpleegd op 14 augustus 2012).

Bakels, C.D., 2005. Crops produced in the southern Netherlands and northern France during the early medieval period: a comparison. Vegetation History and Archaeobotany 14, 394-399.

Bakels, C., 2009. The Western European Loess Belt. Agrarian History 5300 BC - AD 1000. Springer.

Bastiaens, J., Deforce, K., Klinck, B., Meersschaert, L., Verbruggen, C., Vrydaghs, L., 2005. Features: Palaeobotanical analyses, in: Crombé, P. (Ed.), The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation projects. Volume 1: Palaeo-environment, chronology and features. Academia Press, Ghent, pp. 251-278.

Bats, M., De Smedt, P., Werbrouck, I., Zwertvaegher, A., Court-Picon, M., De Reu, J., Serbruyns, L., Demiddele, H., Antrop, M., Bourgeois, J., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2010. Continued geoarchaeological research at the Moervaart palaeolake area (east flanders, Belgium): preliminary results. Notae Praehistoricae 30, 15-21.

Blume, H.-P., Leinweber, P., 2004. Plaggen soils: landscape history, properties, and classification. Journal of Plant Nutrition and Soil Science 167, 319-327.

Bogemans, F., 2005a. Quartairgeologische overzichtskaart van Vlaanderen 1/200,000. In opdracht van Ministerie van de Vlaamse Gemeenschap, Afdeling Natuurlijke Rijkdommen en Energie.

Bogemans, F., 2005b. Technisch verslag bij de opmaak van de quartairgeologische overzichtskaart van Vlaanderen, VUB.

Bourgeois, J., 1993. De nederzetting uit de vroege ijzertijd van Sint-Gillis-Waas "Reepstraat" (O.-Vl.): 1991-1992. Lunula, Archaeologia protohistorica 1, 59-61.

Bourgeois, J., Crombé, P., Verlaeckt, K., 1996. De wereld van de levenden: nederzettingspatronene van vroege bronstijd tot vroege ijzertijd, in: Verlaeckt, K. (Ed.), Tussen heuvel en rivier. De bronstijd in Oost-Vlaanderen (ca. 2000-750 v.Chr.). Stadsbestuur Dendermonde, Dendermonde, pp. 19-27.

Bourgeois, I., De Clercq, W., Laloo, P., 2009. Onderdelen van een eergetouw op de vindplaats Zele-Zuidelijke Omleiding (provincie Oost-Vlaanderen, België). Lunula, Archaeologia protohistorica 17, 217-220.

Breemen, N., Buurman, P., 1998. Soil formation. Kluwer academic, Dordrecht.

Charles, R., 1995. A new Late Upper Palaeolithic engraving from the Trou de Chaleux, Province of Namur. NotaePraehistoricae, 15: 123-125.

Creemers, G., Meylemans, E., Paesen, J., De Bie, M., 2011. Laser altimetrie en de kartering van Celtic Fields in de Belgische Kempen: mogelijkheden en toekomstperspectieven. Relicta, Archeologie, Monumenten- en Landschapsonderzoek in Vlaanderen 7, 11-36.

Crombé, P., 1993. De nederzetting uit de midden-bronstijd te Maldegem "Burkel" (O.-Vl.). Lunula, Archaeologia protohistorica 1, 3-6.

Crombé, P., 1996. Het Finaal-Neolithicum: de voorbode van de bronstijd in Oost-Vlaanderen, in: Verlaeckt, K. (Ed.), Tussen heuvel en rivier. De bronstijd in Oost-Vlaanderen (ca. 2000-750 v.Chr.). Stadsbestuur Dendermonde, Dendermonde, pp. 15-18.

Crombé, P., 2001. The Mesolithic, in: Cauwe, N., Hauzeur, A., van Berg, P.L. (Eds.), Préhistoire en Belgique. Anthropologica et Praehistorica, pp. 49-62.

Crombé, P., 2002. Quelques réflexions sur la signification de la variabilité des industries lithiques Mésolithiques de Belgique. Préhistoire de la Grande Plaine du Nord de l'Europe. Actes du colloque chaire francqui interuniversitaire au titre étranger. (Université de Liège, 26 juin 2001), 99-114. Liège: ERAUL 99, pp. 99-114.

Crombé, P., 2005. The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation Projects. Volume 1: Palaeo-environment, chronology and features. Archaeological Reports Ghent University, 3. Academia Press, Ghent.

Crombé, P., Bats, M., Wuyts, F., Van Roeyen, J.-P., 2004. Een derde vindplaats van de Swifterbantcultuur in het Deurganckdok te Doel (Beveren, Oost-Vlaanderen, België). Notae Praehistoricae 24, 105-107.

Crombé, P., De Smedt, P., Davies, N.S., Gelorini, V., Zwertvaegher, A., Langohr, R., Van Damme, D., Van Strydonck, M., Antrop, M., Bourgeois, J., De Maeyer, P., De Reu, J., Finke, P.A., Van Meirvenne, M., Verniers, J., in review. Hunter-gatherer responses to the changing environment of the Moervaart palaeolake (NW Belgium) during the Late Glacial and Early Holocene. Quaternary International.

Crombé, P., Perdaen, Y., Sergant, J., 2008. La transition du Mésolithique ancien au Mésolithique moyen/récent dans le Nord-Ouest de la Belgique: Quelques réflexions concernant l'occupation du territoire, in: Ducrocq, T., Fagnart, J.P., Souffi, B.,Thévenin, A. (Eds.), Actes de la table ronde "Le Mésolithique ancien et moyen de la France septentrionale et des pays limitrophes", Amiens, Octobre 9-10, 2004., Amiens, pp. 194-204.

Crombé, P., Perdaen, Y., Sergant, J., Van Roeyen, P.-P., Van Strydonck, M., 2002. The Mesolithic-Neolithic transition in the sandy lowlands of Belgium: new evidence. Antiquity 76, 699-706.

Crombé, P., Sergant, J., 2008. Tracing the Neolithic in the lowlands of Belgium: the evidence from Sandy Flanders, in: Fokkens, H., Coles, B.J., Van Gijn, A.L., Kleijne, J.P., Ponjee, H.H., Slappendel, C.G. (Eds.), Between foraging and farming. An extended broad spectrum of papers presented to Leendert Louwe Kooijmans. Analecta Praehistorica Leidensia. Leiden University, Leiden, pp. 75-84.

Crombé, P., Sergant, J., Robinson, E., De Reu, J., 2011. Hunter-gatherer responses to environmental change during the Pleistocene-Holocene transition in the southern North Sea basin: Final Palaeolithic-Final Mesolithic land use in northwest Belgium. Journal of Anthropological Archaeology 30(3), 454-471.

Crombé, P., Van der Haegen, G., 1994. Het Midden-Paleolithicum in noordwestelijk België. Archeologische Inventaris Vlaanderen, buitengewone reeks, 3. Archeologische Inventaris Vlaanderen vzw, Gent.

Crombé, P., Vanmontfort, B., 2007. The neolithisation of the Scheldt and Basin in western Belgium. Proceedings of the British Academy 144, 261-283.

Crombé, P., Van Roeyen, J.P., Sergant, J., Perdaen, Y., Cordemans, K., Van Strydonck, M., 2000. Doel Deurganckdok (Flanders, Belgium): settlement traces from the Final Palaeolithic and the Early to Middle Neolithic. Notae Praehistoricae 20, 111-119.

Crombé, P., Van Strydonck, M., Boudin, M., Van den Brande, T., Derese, C., Vandenberghe, D., Van den haute, P., Court-Picon, M., Verniers, J., Gelorini, V., Bos, J.A.A., Verbruggen, F., Antrop, M., Bats, M., Bourgeois, J., De Reu, J., De Maeyer, P., De Smedt, P., Finke, P., Van Meirvenne, M., Zwertvaegher, A., accepted. Absolute dating (14C and OSL) of the formation of cover sand ridges occupied by prehistoric hunter-gatherers in NW Belgium. Radiocarbon.

Crombé, P., Verbruggen, C., 2002. The Late Glacial and Early Post Glacial occupation of northern Belgium: the evidence from Sandy Flanders, in: Eriksen, B.V., Bratlund, B. (Eds.), Recent studies in the Final Palaeolithic of the European plain. Proceedings of a U.I.S.P.P. Symposium, Stockholm, 14.-17. October 1999. Jutland Archaeological Society Publications. Jutland Archaeological Society, Stockholm, pp. 165-180.

Dalle, S., 2009. Visueel-ruimtelijke analyse van de ijzertijdsite op de Kemmelberg (provincie West-Vlaanderen, België). Lunula, Archaeologia protohistorica 17, 143-152.

De Bie, M., Van Gils, M., 2009. Mesolithic settlement and land use in the Campine region (Belgium), in: McCartan, S., Schulting, R., Warren, G., Woodman, P. (Eds.), Mesolithic Horizons. Papers presented at the Seventh International Conference on the Mesolithic in Europe, Belfast 2005, Oxbow books, Oxford, pp. 282-287.

De Bie, M., Vermeersch, P.M., 1998. Pleistocene-Holocene transition in Benelux. Quaternary International 49, 29-43.

De Clercq, W. (2009). Lokale gemeenschappen in het imperium Romanum. Transformaties in de rurale bewoningsstructuur en de materiële cultuur in de landschappen van het noordelijk deel van de civitas Menapiorum (Provincie Gallia-Belgica, ca. 100 v. Chr. - 400 n. Chr. Unpublished doctoral dissertation, Ghent University, Ghent.

Deeben, J., Dijkstra, P., Van Gisbergen, P., 2000. Some new ^{14}C dates from sites of the Ahrensburg culture in the Southern Netherlands. Notae praehistoricae 20, 95-109.

Deeben, J., Rensink, E., 2005. Het Laat-Paleolithicum in Zuid-Nederland, in: Deeben, J., Drenth, E., Van Oorsouw, M.-F., Verhart, L. (Eds.), De steentijd van Nederland (tweede druk). Archeologie 11/12. Stichting Archeologie, pp. 171-200.

Deforce, K., Minsaer, K., 2005. Onderzoek van het hout uit de IJzertijdnederzetting Ekeren - Salaadweg (An.). Lunula, Archaeologia protohistorica 13, 95-100.

Deforce, K., Bastiaens, J., Van Neer, W., Ervynck, A., Lentacker, A., Sergant, J., Crombé, P., accepted. Wood charcoal and seeds as indicators for animal husbandry in a wetland site during the late mesolithic - early neolithic transition period (Swifterbant culture, ca. 4600-4000 B.C.) in NW Belgium. Vegetation History and Archaeobotany.

de Hingh, A.E., 2000. Food production and food procurement in the Bronze Age and Early Iron Age (2000-500 BC): the organisation of a diversified and intensified agrarian system in the Meuse-Demer-Scheldt region (The Netherlands and Belgium) and the region of the river Moselle (Luxemburg and France). Archaeological Studies Leiden University, Leiden University, Leiden, 235 pp.

Demeyere, F., Bourgeois, J., Crombé, P., 2004. Plan d'une maison du groupe de Deûle-Escaut à Waardamme (Oostkamp, Flandre occidentale). Notae Praehistoricae 24, 167-173.

De Moor, G., 1963. Bijdrage tot de kennis van de Vlaamse Vallei, Ghent University, Ghent, 172 pp.

De Moor, G., Heyse, I., 1974. Lithostratigrafie van de Kwartaire afzettingen in de overgangszone tussen de kustvlakte en de Vlaamse Vallei in Noordwest België. Natuurwetenschappelijk Tijdschrift 56, 85-109.

De Moor, G., Heyse, I., 1978. De morfologische evolutie van de Vlaamse vallei. De Aardrijkskunde 4, 343-375.

De Moor, G., van de Velde, D., 1995. Toelichting bij de Quartairgeologische Kaart. Kaartblad 14: Lokeren, Universiteit Gent, Gent.

De Muynck, M., 1976. Het bedolven kultuurlandschap in de polders. Een rekonstruktie uitgaande van luchtfoto's toegepast op de Oost-Vlaamse en enkele Zeeuws-Vlaamse polders, Faculty of Science, Ghent University, Ghent, p. 266.

De Reu, J., Bats, M., Crombé, P., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Van Meirvenne, M., Verniers, J., Werbrouck, I., Zwertvaegher, A., Bourgeois, J., 2011a. Een GIS benadering van de bronstijdgrafheuvel in Zandig-Vlaanderen: enkele voorlopige resultaten (België). Lunula, Archaeologia protohistorica 19, 3-8.

De Reu, J., Bourgeois, J., De Smedt, P., Zwertvaegher, A., Antrop, M., Bats, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2011b. Measuring the relative topographic position of archaeological sites in the landscape, a case study on the Bronze Age barrow in northwest Belgium. Journal of Archaeological Science 38, 3435-3446.

De Reu, J., Deweirdt, E., Crombé, P., Bats, M., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Finke, P., Van Meirvenne, M., Verniers, J., Werbrouck, I., Zwertvaegher, A., Bourgeois, J., 2011c. Les tombelles de l'âge du bronze en Flandre sablonneuse (nord-ouest de la Belgique) : un status quaestionis. Archäologisches Korrespondenzblatt 41, 491-505.

De Vos, A., 1958. De Middeleeuwse loop van de Durme en haar bijrivier de Poeke. Oostvlaams verbond der kringen voor geschiedenis. Voorlichtingsreeks. Oostvlaams Verbond van de Kringen voor Geschiedenis, Gent.

Duchaufour, P., 1982. Pedology: pedogenesis and classification. Allan and Unwin, London.

FAO, 2001. Lecture notes on the major soils of the world. World soil resources reports 94.

Fokkens, H., 2003. The longhouse as a central element in Bronze Age daily life, in: Bourgeois, J., Bourgeois, I., Cherretté, B. (Eds.), Bronze and Iron Age communities in North-Western Europe. Paleis der Academiën, Brussel, pp. 9-38.

Fokkens, H., 2005. Woon-stalhuizen op zwervende erven. Nederzettingen in bekertijd en bronstijd, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 407-428.

Heyse, I., 1979. Bijdrage tot de geomorfologische kennis van het Noordwesten van Oost-Vlaanderen. verhandelingen van de koninklijke Academie voor Wetenschappen, letteren en schone kunsten van België, Klasse der wetenschappen. Paleis der Academiën, Brussel.

HIC, 2012. Hydrologisch Informatie Centrum (28 July 2012). http://www.waterstanden.be

Hoek, W.Z., 1997. Late-glacial and early Holocene climatic events and chronology of vegetation development in the Netherlands. Vegetation History and Archaeobotany 6, 197-213.

Hoek, W.Z., 2001. Vegetation response to the ~14.7 and ~11.5 ka cal. BP climate transitions: is vegetation lagging climate? Global and Planetary Change 30, 103-115.

IUSS Working Group WRB, 2006. World reference base for soil resources 2006. A framework for international classification, correlation and communication. World Resources Report No. 103, FAO, Rome.

Jacobs, P., De Ceukelaire, M., De Breuck, W., De Moor, G., 1993. Toelichtingen bij de geologische kaart van België - Kaartblad 14 Lokeren, Universiteit Gent, Geologisch Instituut, Gent.

Jacobs, P., De Ceukelaire, M., De Breuck, W., De Moor, G., 1996. Toelichtingen bij de geologische kaart van België, Vlaams Gewest. Kaartblad 22 Gent, schaal 1:50.000, Ministerie van de Vlaamse Gemeenschap, Afdeling Natuurlijke Rijkdommen en Energie, Brussel.

Jacques, D., Leterme, B., Beerten, K., Schneider, S., Finke, P., Mallants, D., 2010. Long-term evolution of the multi-layer cover. Project near surface disposal of category A waste at

Dessel. STB-NF – Version 1. NIROND-TR report 2010-03 E. Brussels: ONDRAF/NIRAS, Belgian agency for radioactive waste and enriched fissile materials.
Jongepier, I., Soens, T., Thoen, E., Van Eetvelde, V., Crombé, P., Bats, M., 2011. The brown gold: a reappraisal of medieval peat marshes in Northern Flanders (Belgium). Water History 3(2), 73-93.
Kooistra, M.J., Maas, G.J., 2008. The widespread occurence of Celtic field systems in the central part of the Netherlands. Journal of Archaeological Science 35, 2318-2328.
Lauwerier, R.C.G.M., Deeben, J., 2011. Burnt animal remains from Federmesser sites in the Netherlands. Archäeologisches Korrespondenzblatt 41, 1-20.
Lauwers, B., De Reu, J., 2011. Een midden-bronstijdbewoning te Sint-Gillis-Waas – Kluizenmolen (Oost-Vlaanderen, België). Lunula, Archaeologia protohistorica 19, 27-33.
Meyus, Y., Batelaan, O., Van Daele, T., De Smedt, F., 2000. Concept Vlaams Grondwater model (VGM). Technisch concept van het VGM. Deelrapport 3: Noodzakelijke gegevens en randvoorwaarden voor de opbouw van het VGM., Ministerie van de Vlaamse Gemeenschap, afdeling Water, AMINAL, Brussel.
Out, W.A., 2009. Sowing the seed? Human impact and plant subsistence in Dutch wetlands during the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC).Archaeological Studies Leiden University, Leiden University Leiden, 481 pp.
Paesen, J., Creemers, G., Meylemans, E., De Bie, M., 2010. Hernieuwd Celtic Fields onderzoek in de Limburgse Kempen (België). Lunula, Archaeologia protohistorica 18, 151-153.
Parent, J.P., Van der Plaetsen, P., Vanmoerkerke, J., 1987. Hypothesen over de betekenis van neolithische okkupaties te Oudenaarde-Donk, Notae Praehistoricae 7, 14-15.
Rensink, E., 2005. Het Midden-Paleolithicum in Zuid-Nederland, in: Deeben, J., Drenth, E., Van Oorsouw, M.-F., Verhart, L. (Eds.), De steentijd van Nederland (tweede druk). Archeologie 11/12. Stichting Archeologie, pp. 119-142.
Sauer, D., Sponagel, H., Sommer, M., Giani, L., Jahn, R., Stahr, K., 2007. Review Article. Podzol: Soil of the year 2007. A review on its genesis, occurrence, and functions. Journal of Plant Nutrition and Soil Science 170, 581-597.
Sergant, J., Crombé, P., Perdaen, Y., 2009. Mesolithic territories and land-use systems in north-west Belgium, in: McCartan, S., Schulting, R., Warren, G., Woodman, P. (Eds.), Mesolithic Horizons. Papers presented at the Seventh International Conference on the Mesolithic in Europe, Belfast 2005. Oxbow Books, Oxford, pp. 277-281.
Spikins, P., 1999. Mesolithic Northern England. Environment, population and settlement. BAR British Series 283. Archeopress, Oxford.
Street, M., 1998. The archaeology of the Pleistocene-Holocene transition in the northern Rhineland, Germany. Quaternary International 49/50, 45-67.
Tavernier, R., Ameryckx, J., 1957. Le postpodzol en Flandre sablonneuse. Pédologie 7, 89-96.
Tavernier, R., Maréchal, R., Ameryckx, J., 1960. Bodemkartering en bodemklassifikatie in België. Monografie van bodem en water in België. Ministerie van Landbouw, Nationaal Comité van de FAO, Gent, pp. 56.
Terberger, T., Barton, N., Street, M., 2006. The Late Glacial reconsidered - recent progress and interpretations, in: Street, M., Barton, N., Terberger, T. (Eds.), Humans, environment and chronology of the Late Glacial of the North European Plain. Proceedings of Workshop 14 (Commission XXXII "The Final Palaeolithic of the Great European Plain / Le paléolithique Final de la Grande Plaine Européenne") of the 15th U.I.S.P.P. congress, Lisbon, September 2006, Verlag des Römisch-Germanischen Zentralmuseums, Mainz, pp. 189-207.
Vanacker, V.F., Govers, G., Van Peer, P., Verbeek, C., Desmet, J., Reyniers, J., 2001. Using Monte Carlo simulation for the environmental analysis of small archaeologic datasets, with the Mesolithic in Northeast Belgium as a case study. Journal of Archaeological Science 28, 661-669.

Van Baelen, A., Meijs, E.P.M., Van Peer, P., De Warrimont, J.-P., De Bie, M., 2007. An early Middle Palaeolithic site at Kesselt-Op de Schans (Belgian Limburg). Preliminary results. Notae Praehistoricae 27, 19-26.

Van Berg, P.L., Hauzeur, A., 2001. Le Néolithique Ancien. Anthropologica et Praehistorica 112, 63-76.

van Mourik, J.M., Seijmonsbergen, A.C., Jansen, B., 2012. Geochronology of soils and landforms in cultural landscapes on aeolian sandy substrates, based on radiocarbon and optically stimulated tuminescence dating (Weert, SE-Netherlands), in: Nawrock, D.M. (Ed.), Radiometric Dating, InTech, Croatia. http://www.intechopen.com/books/radiometricdating/geochronology-of-soils-and-landforms-in-cultural-landscapes-on-aeolian-sandy-substrates-based-onrad

Van Neer, W., Ervynck, A., Lentacker, A., 2005. Features: Archaeozoological analyses, in: Crombé, P. (Ed.), The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation projects. Volume 1: Palaeo-environment, chronology and features. Academia Press, Ghent, pp. 279-294.

Van Neer, W., Ervynck, A., Lentacker, A., Crombé, P., Sergant, J., Perdaen, Y., Van Strydonck, M., Van Roeyen, J.-P., 2001. Dierenresten uit een vroege Swifterbant-nederzetting te Doel-Deurganckdok (Vlaanderen, België): jachtwild, maar vooral veel vis. Notae Praehistoricae 21, 85-96.

Van Ranst, E., Sys, C., 2000. Eenduidige legende voor de digitale bodemkaart van Vlaanderen. Universiteit Gent, Gent.

Van Vlaenderen, J., Sergant, J., De Bock, H., De Meireleir, M., 2006. Steentijdvondsten in de Moervaartdepressie (Oost-Vlaanderen, België). Inventaris en geografische analyse. Archeologische Inventaris Vlaanderen, Buitengewone reeks, 9. Archeologische Inventaris Vlaanderen vzw, Gent.

Verbruggen, C., 1971. Postglaciale landschapsgeschiedenis van zandig Vlaanderen. Botanische, ecologische en morfologische aspekten op basis van palynologisch onderzoek, Rijksuniversiteit Gent.

Verbruggen, C., Denys, L., Kiden, P., 1996. Belgium, in: Berglund, B.E., Birks, H.J.B., Ralska-Jasiewiczowa, M., Wright, H.E. (Eds.), Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley and Sons, Chichester, pp. 553-574.

Verbruggen, C., Semey, J., 1993. Venen en moeren: fysisch-geografische benadering, in: De Kraker, A.M.J., Van Royen, H., De Smet, M.E.E. (Eds.), Over den Vier Ambachten: 750 jaar Keure, 500 jaar Graaf Jansdijk. Duerinck, Kloosterzande, pp. 61-65.

Verhart, L.B.M., 2000. Time fades away. The neolithization of the southern Netherlands in an anthropological and geographical perspective, Archeologische Studies Leiden University University of Leiden, Faculty of Archaeology, Leiden.

Verhart, L., Arts, N., 2005. Het Mesolithicum in Zuid-Nederland, in: Deeben, J., Drenth, E., Van Oorsouw, M.-F., Verhart, L. (Eds.), De steentijd van Nederland (tweede druk). Archeologie 11/12. Stichting Archeologie, pp. 235-260.

Vermeersch, P.M., 1981. Jong-Paleolithicum te Kanne en te Orp. Notae Praehistoricae 1, 13-15.

Vermeersch, P.M., 2011. The human occupation of the Benelux during the younger Dryas. Quaternary International 242, 267-276.

Vermeersch, S., Decleer, K., 2009. Verkennende ecologische gebiedsvisie voor de Moervaart en Durmevallei. Rapporten van het Instituut voor Natuur- en Bosonderzoek 2009 (rapportnr. 12). Instituut voor Natuur- en Bosonderzoek, Brussel.

VMM, 2008a. Grondwater in Vlaanderen: het Centraal Kempisch Systeem, Vlaamse Milieumaatschappij, Aalst.

VMM, 2008b. Grondwater in Vlaanderen: het Centraal Vlaams Systeem., Vlaamse Milieumaatschappij, Aalst.

Vos, P.C., van Heeringen, R.M., 1997. Holocene geology and occupation history of the Province of Zeeland, in: Fischer, M.M. (Ed.), Holocene evolution of Zeeland (SW Netherlands). Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen, 59. Netherlands Institute of Applied Geoscience TNO. National Geological Survey pp. 5-109.

Weber, M.-J., Grimm, S.B., Baates, M., 2011. Between warm and cold: Impact of the Younger Dryas on human behavior in Central Europe. Quaternary International 242, 277-301.

Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital elevation model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.

Chapter 3
Conceptual model framework

Abstract

Intensive archaeological investigations in Sandy Flanders (Belgium) revealed sites dating from the Final Palaeolithic to the Neolithic, showing a spatial and temporal discontinuous distribution. To improve the understanding of these occupational patterns a palaeolandscape reconstruction is proposed. A major problem in palaeolandscape reconstruction is that basic data are scattered in the temporal and spatial sense. Therefore, we propose the application of different process models in the soil-water-landscape reconstruction in an interdisciplinary approach. The process models include a digital elevation model, a hydrological, a pedogenetic, and a land evaluation model. A model framework is defined in which these discipline-specific models, which provide input to each other, are integrated. The focus lies on the methodological aspect of constructing the model framework and the questions one needs to answer in advance to facilitate the integration of the model results. Furthermore, it should not be ignored that errors occur within each individual model and propagate into the next step. We therefore emphasize the difficulties occurring when integrating these different models, such as scale and error propagation.

This chapter is based on Zwertvaegher, A., Werbrouck, I., Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, P., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the use of integrated process models to reconstruct prehistoric occupation, with examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal 25, 784-814.

3.1 Introduction

Geoarchaeological research is often motivated by the desire to understand observed occupational patterns. At first one must check how strong the evidence for these occupational patterns actually is. Data and knowledge driven predictive mapping techniques are valuable tools here. If predictive mapping based on find data and the current landscape does not provide strong evidence for any occupational pattern, possible reasons may be: (i) a non-systematic recording of presence/absence of finds; (ii) a biased sampling; (iii) the current landscape attributes do not explain past occupational patterns; (iv) the landscape attributes used for predictive mapping do not give a physical explanation for occupational preferences; (v) a deterministic approach based on the physical landscape cannot explain occupational patterns completely. Reason (iii) would motivate a palaeolandscape reconstruction; (iv) would motivate to search for biophysical factors that, with the land use at that time, give a physical-deterministic explanation for occupational patterns; (v) would motivate the inclusion of social, economic, cultural, ideological and ritual drivers that explain occupational patterns (Jordan, 2001; Thomas, 1993; Tilley, 1994, 2004; Zvelebil, 2003). By using the word occupation we emphasize that the location of favoured areas for prehistoric land uses is equally important in this study as the location of actual settlements. In situations where data collection possibilities are limited because of the available time and funds, dealing with issues (iii) to (v) of the above list appears to offer the best perspective to improve understanding of occupational patterns.

In this study we focus on landscape reconstruction methods and the derivation of relevant landscape attributes to tackle problem (iii). We propose land evaluation methods to obtain a motivation for occupational patterns (iv) and to decide which landscape attributes are relevant. Land evaluation includes the human factor (for example the cropping system reflects the farm size and the knowledge level of the farmer). It also includes the human perception of the landscape (for example the workability of the land). Therefore issue (v) is also partly considered. With Kamermans (2000, 2006) we see land evaluation as a form of deductive predictive modelling and our working hypothesis is that land evaluation based on reconstructed landscapes and land use will outperform predictive modelling based on the current landscape in the assessment of past occupational patterns.

We define landscape according to Berendsen (2005) and with landscape reconstruction in an archaeological context we mainly consider the evolution of properties and interrelations of the components soil, relief and vegetation over time and pay less attention to the physiognomic evolution as this is hard to assess without historical maps. However, historical maps can be used to filter the current cultural landscape to obtain the relief of the pre-existing near-natural landscape. Hence, part of the landscape reconstruction can be considered as a deconstruction of the current landscape. The preceding genesis of the natural landscape must be analysed with a forward temporal arrow, starting from an assumed initial landscape, taking the natural (deconstructed cultural) landscape as final reference and using local reconstructions based on sedimentological, palaeoecological and pedological research as benchmarks in space and time. Some models calculate the production and redistribution of soil material in – mainly alluvial – landscapes (Minasny and McBratney, 2001; Schoorl et al., 2002) and deal with some, but not all aspects of the above landscape definition. Most landscape reconstructions however, are knowledge assemblages. Several attempts in reconstructing the palaeolandscape have already been undertaken in the study area on a very local scale (Bats, 2007; Crombé, 2005). When looking at occupational distributions it is necessary to cover a larger research area (Chapter 2).

We approach landscape reconstruction as a spatio-temporal mapping problem based on the prediction of spatial patterns of variables at different time slices that are determinants for occupational patterns in a biophysical (deterministic, processualistic) sense. A time slice is a representative year for a certain period that is considered homogeneous in a climatic and archaeological sense. The variables of relevance follow from the data requirements of the land evaluation. In order to achieve this, these variables need to be defined and methods must be developed to map these values in the spatial and temporal domain of interest. We define a model as a set of equations or decision rules that mimic the behaviour of a system, for example the landscape, or subsystems such as the soil-vegetation or the groundwater-atmosphere system. The advantage of using models with data instead of only data, is that environments that change with varying speed, for instance in response to climatic variations, can be more reliably described with models built on process knowledge than with simple assumptions on for example linear change between dates on the time axis. Additionally, models apply the relations between variables such as precipitation, vegetation, water and nutrient uptake, soil moisture and leaching of soil components while the prediction of spatio-temporal patterns of these variables on a one-by-one basis may result in loss of co-variation. Therefore, we propose a model framework based on the integration of different models. The end product is not one single running model, but is a framework incorporating different models providing input to each other. Certain questions need to be answered in advance in order to facilitate the integration of the model results.

Furthermore, it should not be ignored that errors occur within each individual model and propagate into the next step. The focus of this chapter lies on the methodological aspect of constructing such a model framework and the difficulties occurring when integrating the different models.

3.2 Methodology

3.2.1 Predictive modelling

Predictive modelling based on the current landscape is applied to formalize the state of knowledge at the onset of the project. It is not a part of the proposed model framework, but the results can be compared in a later stage with a deductive predictive model obtained after the land evaluation, which is the last step in the model framework. Predictive modelling in archaeology is the activity that results in rules describing the geographical patterns of archaeological finds of predefined type. Often the end product is a map (Westcott and Brandon, 2000; further called expectation map) displaying the expectation of find occurrences that can be considered as an extrapolation of scattered finds to a presumed occupational pattern. The rules are based on inference, which may be of statistical nature, but may also be the condensation of expert judgment or a mixture of both. Usually, the type of inference gives the predictive modelling its name (Kamermans et al., 2004):

- The inductive approach is entirely data-driven and constructs inference using occurrence patterns of archaeological finds in combination with full-cover maps that describe for example soil, landscape and infrastructure.

- The deductive approach is knowledge-driven, as experts formulate the rules that link attributes such as soil, landscape and infrastructure to the occurrence of finds. Evidently, expert knowledge is to some extent based on field data as well, but it may originate from different geographical areas and is usually of a more informal kind. Predictive maps based on a land evaluation (suitability maps) would be the result of a deductive approach.

- Mixed approaches are also thinkable (Finke et al., 2008), where experts identify the geographic attributes that are of presumed relevance, but the classification of continuous values, such as wetness, grouping of nominal values (for example soil texture class) or the weighing of different attributes is optimized using field data and statistical techniques.

Ideally, expectation maps are verified with independent field observations before publication. Depending on the statistical part of the inference, it may be possible to display only those parts of the map that are strongly supported by evidence (Finke et al., 2008), which may be wise in a politically sensitive context.

In the case study at hand a mixed approach to predictive modelling using the current landscape with Bayesian inference to typical combinations of environmental attributes ('strata') was applied, as described by Finke et al. (2008). Expectation maps for the Final Palaeolithic, the Mesolithic and the Neolithic period were produced based on a number of 27, 193 and 91 find spots, respectively. A total of 151 non-find spots were also taken into account. This information was combined with present-day full-cover auxiliary information on different variables, such as elevation, slope, wetness index, wind exposure, visibility, distance to open water, natural drainage class, and texture class. In order to allow for Bayesian prediction, each of the chosen variables was divided into classes. Chi-squared statistics were used to check each class for its efficiency to distinguish between presence and absence of find spots. Classes with non-significant chi-squared statistics were merged with adjacent classes and only variables with two or more significant classes were retained to perform the rest of the predictive modelling. Based on this method, the variables altitude, slope, drainage and texture class, wetness index, distance to open water and wind exposure were selected for the Meso- and Neolithic. Based on the chi-squared statistics, equal variables except wind exposure, were chosen for the Final Palaeolithic. After selecting these variables and converting them into attribute maps, prior, conditional and posterior probability were calculated for each grid cell in the chosen study area. The prior probability reflects the degree of belief in a certain event, for example the occurrence of an archaeological find. The conditional probability represents the likelihood of the hypothesis to be true given the data. The outcome of the applied predictive modelling is the posterior probability, which is calculated using both prior and likelihood. Furthermore, following Finke et al. (2008) only those patterns that are strongly supported by the field evidence are displayed on the maps by the use of an evidence filter. This filter is based on the Bayes factor, which is the likelihood ratio of the probability of the data given the null hypothesis to the probability of the data given the alternative hypothesis (Finke et al., 2008). When the alternative hypothesis is the best-supported hypothesis, the likelihood ratio is minimal, which is indicative of the strongest evidence against the null hypothesis. This is called the Minimum Bayes Factor (MBF). Per pixel, only the posterior probabilities with an MBF lower than a fixed threshold pass the evidence filter. These thresholds were set by Finke et al. (2008). As a consequence, the results that did not meet this standard were not shown on the map.

3.2.2 Model framework for an integrative model-based landscape reconstruction

3.2.2.1 Rationale

The major problem in reconstructing past landscapes is that basic data usable for inference are scattered in both the temporal and geographical sense. Thus, to obtain a continuous or even a fragmented picture of past landscapes, methods are required to interpolate landscape characteristics in both space and time. Such interpolation can be entirely data-based (for example space-time kriging; Kyriakidis and Journel, 1999), but when information on for example rates of change and speed of processes is available, this can be used as well. When rates of change obey physical laws, process models can be particularly useful as deterministic interpolators in time and sometimes also in space (Heuvelink et al., 2006). We therefore propose the application of process models in the reconstruction of soil-water-landscapes to improve the understanding of occupational patterns as far as these can be explained by biophysical factors. The complexity of soil-water-vegetation processes and their interaction in the landscape enforce a multidisciplinary approach. Due to the multiple disciplines involved, a model framework must be defined in which various discipline-specific models are integrated.

Therefore, a conceptual framework was developed for the purpose of an environmental reconstruction in a postglacial and mainly alluvial landscape with mostly shallow water tables in Flanders. The next sections contain a description of the development of this framework and its model components with some explicatory, however not final, examples. Additionally, attention is paid to the transfer of inputs and outputs between the various models and associated issues of scale that have to be addressed.

3.2.2.2 Approach

As stated above, our objective is to predict, by using models, spatial patterns of biophysical variables that are considered to be of influence on occupational patterns at various time slices. A generic seven-step approach is proposed to reach this goal:

1. Define biophysical attractors for human occupancy and associate these with variables to be predicted by models. Examples of biophysical attractors are ‘suitable places for hunting’, ‘good soils for a particular type of agriculture’ or ‘a sheltered place that does not flood’. The third example corresponds to places with low wind exposure where in the wet season the groundwater table does not reach the surface and where stream floods do not occur. These places can be identified if the land qualities ‘wind exposure’, ‘wetness’ and ‘flooding hazard’ can be mapped for the

landscape in the relevant time slice. We propose land evaluation methods to translate these biophysical attractors into land qualities.

2. Define a model framework that can provide the required variables. In the above example wind exposure and drainage pattern can be mapped with a temporal Digital Elevation Model (DEM), while a hydrological model can calculate the water table fluctuations and flood-occurrence maps using the drainage pattern.

3. Define model dependencies in terms of data and knowledge flows at various scales. A hydrological model requires elevation data as input, but probably at lower resolutions than the DEM can provide because of computational limitations. This integration may involve upscaling activities before and during the hydrological modelling and downscaling of the obtained model results afterwards.

4. Prepare the individual models to run. The model components must be in optimal shape to produce plausible results. This means that wherever possible the individual models must be calibrated towards existing data and maps. Afterwards the quality of the model results should be tested with independent and preferably measured data. Additionally, model input data (that can be of spatial and of temporal nature) must be generated, possibly using other components from the model framework.

5. Run the models within the framework to obtain space-time coverage with the required variables identified in the first step.

6. Integrate the results so that the selected biophysical attractors are mapped, and the reconstructed landscapes at various time slices can be evaluated for optimal places to live, to hunt, to fish or to farm.

7. Matching of the resulting maps with the occupational data from archaeological finds to identify to what extent biophysical-deterministic reconstructions can explain these patterns, and to what extent other, socio-economic attractors play a role.

The model framework presented in the next sections illustrates the above generic approach in the context of a landscape reconstruction in the study area. The studied period stretches from the Final Palaeolithic to present times and thus covers a variety of climates, vegetations (Verbruggen et al., 1996) and types of land use (Crombé, 2005). The biophysical attractors to be defined in step 1 of the above approach should reflect the variety of environmental conditions and land use. By analysing the data needed to perform a land evaluation at the various time slices, the attractors and associated land qualities are revealed at the parameter level (step 1; Table 3.1). The source for each of these parameters is defined, which motivates the use of the model instruments inside the model framework (step 2). The framework includes a temporal DEM, a hydrological model and a pedogenetic model. The next two sections address these model instruments – including also the land evaluation method, explaining more in detail the choice of the biophysical attractors – and their connection in the landscape-reconstruction study in the study area (steps 3-6).

3.2.3 Components of the model framework

3.2.3.1 Elevation model

Settling conditions such as wind exposure and wetness, or hunting conditions such as visibility, are highly influenced by the relief. This motivates the incorporation of a DEM in the model framework. Since the relief has changed over time by natural and anthropogenic actions, it is necessary to not only consider the current topography, but also to take palaeotopographies into account.

The present-day DEM was generated by Werbrouck et al. (2011) and was based on high precision airborne LiDAR (Light Detection and Ranging) data with an average sample density of one point per 2 m^2. The altimetric accuracy ranges from 0.07 m on a concrete surface to 0.20 m on vegetation cover (AGIV, 2003) which is significantly better than the planimetric accuracy with a typical value in the order of 0.50 m (Drosos and Farmakis, 2006). This exceptional accuracy at centimetre level and the regular scan pattern allows the production of a high quality DEM (Axelsson, 1999; Drosos and Farmakis, 2006; Liu, 2008; Lohr, 1997). Here, the term DEM is used in the context of a Grid DEM which represents the relief as a two-dimensional regular grid where each grid cell contains one elevation value. Given that a higher ground resolution results in an increasing ability to record features but also increases the size of the datasets, a resolution of 2 m x 2 m was chosen to obtain an optimal combination of efficiency and accuracy of terrain representation. However, the DEM derived from the original LiDAR data contained data points representing not only terrain elevation but also objects like vegetation and buildings as well as current disturbances of the natural topography by artificial features like road banks and waste dumps, which are no part of the natural topography. To generate a DEM exclusively representing the natural topography, three filtering steps were executed involving the use of topographical vector maps and aerial photographs for the filtering, slope analysis for identifying remaining extreme non-natural relief features and interpolation to refill the grid. These steps were performed by Werbrouck et al. (2011).

Table 3.1 Parameters needed for the land evaluation. P: Pedogenetic model; D: Temporal DEM; H: Hydrological model; NR: Not relevant in study area; RC: Reconstructed climate data; MLWT: mean lowest water table; MHWT: mean highest water table.

Biophysical attractors (in bold) and associated land qualities (in italics)	**Parameter**																
	Annual precipitation	Annual evapo-transpration	January temperature	July temperature	MLWT	MHWT	Soil texture	Bulk density	Stoniness	$CaCO_3$ content	Organic carbon content	Base saturation	pH	Reduced conditions in rooted zone	Surface water presence	Slope	Altitude
Rain-fed agriculture-potential production			X	X													
Moisture availability	X	X			X	X	X										
Oxygen availability	X	X			X	X	X										
Workability								X	X								
Nutrient availability										X	X	X					
Rootability								X	X								
Germination							X	X	X								
Flooding hazard	X	X													X		

Table 3.1 Continued

Toxicity													X	X			
Erosion hazard																X	
Soil degradation hazard							X			X	X		X				
Hunting, fishing																	
Surface water															X		
Visibility																X	X
Gathering																	
Ecological diversity					X	X	X			X			X		X	X	
Settling																	
Wind exposure																X	X
Wetness						X									X	X	X
Fresh water															X		
Parameter source (model)	RC	RC	RC	RC	H	H	P	P	NR	P	P	P	P	H	H	D	D
Accuracy (units)	<50 mm	<50 mm	2°C	2°C	<40 cm	<40 cm	<5 mass%	<0.25 kg/dm^3	NR	<2 mass%	<1 mass%	40%	<1 units	20% of cases	20% of cases	<1%	<0.5 m
Spatial grain (m^2)	10^8	10^8	10^8	10^8	10^4	10^4	1	1	NR	1	1	1	1	10^4	10^4	4	4

During the first step the LiDAR data were filtered for topographical objects. This is the most critical and difficult step in LiDAR data processing (Liu, 2008), because it creates filtering artefacts and some buildings and vegetation still remain. Also, artificial features disturbing the natural topography are not subjected to this filter method (Figure 3.1a). In order to meet these problems it is crucial to conduct a second filtering of the LiDAR ground point data to remove the filtering artefacts and the remaining artificial features (Figure 3.1b). This second filtering was conducted automatically using topographical vector data. As no automated filtering procedure is completely accurate, additional manual editing was necessary (Chen, 2007) to remove remaining artefacts. This was based on aerial photographs (Figure 3.1c). The filtering resulted in masked areas where new elevation values were created through interpolation using two different methods. Small confined areas were interpolated using surrounding data points with inverse distance weighted interpolation. The elevation values of large areas were estimated from contour lines on historical topographical maps of 1863 showing the landscape before the infrastructures were created. A third filtering of the elevation data aimed at extracting small artificial elements, such as small drainage ditches, remnants of former ditches bordering fields and convex shaped fields by circular ploughing. These remaining features are too small and too numerous to be removed manually during the second filtering step. The third filtering step implies a slope analysis followed by a removal of the elevation values for which the rate of the maximum change in *z*-value in a predefined radius of surrounding cells exceeded a defined threshold (Figure 3.1d). To avoid the removal of natural slopes, certain confined regions in the study area, exposing natural inclines exceeding this threshold, were assigned an adjusted threshold.

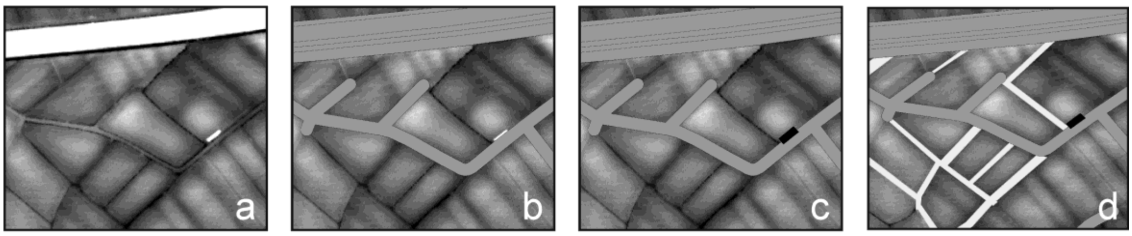

Figure 3.1 Removal of topographical objects from a DEM (AGIV, 2008; Werbrouck et al., 2011). a. After the first filtering of the point LiDAR data, artefacts may remain; b. Overlay with automatic mask (in grey) based on topographic vector maps; c. Manual checking (object indicated in black) by comparison with aerial photographs; d. Filtering of non-natural relief by slope analysis (indicated in light grey).

This filtered DEM corresponds to the natural topography. Creating a temporal DEM involves taking into account landscape changes occurring earlier. In the example study these changes were reported (Crombé, 2005) to be the transition of a Pleniglacial alluvial landscape into a landscape with niveo-aeolian deposits and cover sands from the Pleniglacial and Late Glacial. These changes were associated with the formation of Late

Glacial lakes and changed drainage patterns. At various point locations, such genesis can be reconstructed by palaeoecological research on undisturbed soil cores. At these points, the altitude and approximate dates of stable surfaces can be identified. By lithostratigraphic correlation of these undisturbed cores to georeferenced legacy soil profile descriptions, the number of point locations can be extended. These profiles include descriptions from the Flemish database on subsurface information (DOV), archaeological investigations and other literature sources (Figure 3.2) They facilitate interpretation and correlation of layers over larger areas. A number of 30,612 point locations was collected, although not all of them contain dated surfaces and not all are equally well described. Therefore a selection of useful point locations needs to be made. The temporal DEM can be constructed with space-time interpolation methods using the full-cover current natural DEM and the point reconstructions. Examples of such space-time interpolation methods are spatio-temporal kriging (Heuvelink et al. 1997; Kyriakidis and Journel, 1999) and space-time Kalman filtering (Heuvelink et al., 2006). Alternatively, process models called landscape evolution models (Schoorl et al., 2002) can be calibrated to the point reconstructions, although existing models mostly focus on the effects of tectonic and alluvial processes and less on aeolian landscape forming processes such as in the research area.

3.2.3.2 Hydrological model

In areas with shallow groundwater tables, such as Sandy Flanders, environmental processes like pedogenesis and vegetation development are strongly influenced by water table dynamics. The hydrological model supplies information directly to the pedogenetic model and therefore, indirectly to the land evaluation model. The model also provides input directly to the land evaluation model (Table 3.1). Wetness, for example, is influenced by the mean highest water table provided by the hydrological model.

The three-dimensional finite-difference groundwater model MODFLOW has a worldwide distribution and is known as the standard code for simulating groundwater flow in saturated zones (Schwartz and Zhang, 2003). In order to simulate groundwater flow, full-cover information on topography, drainage pattern, subsoil properties and recharge to the water table, is required as a model input. In a first step, a steady state simulation is performed, with a user-specified head as an initial estimation. This only affects the number of iterations required to converge to an acceptable approximation of the solution of the steady state flow equation and has no effect on the solution itself (Harbaugh, 2005). As a result, a mean water table (MWT) for every cell of the study area is produced. This gives information on the average wetness of a site through time, which will partly determine the suitability for settlement. Monthly minimum and maximum fluctuations influence soil formation and determine if a site is seasonally wet.

These fluctuations are calculated during a non-steady state flow simulation, in which the specific yield or storage coefficient near the water table, derived from soil characteristics, and the monthly recharge to the groundwater reservoir, obtained from meteorological data such as precipitation and evapotranspiration, are also taken into account. This leads to the production of monthly mean highest (MHWT) and mean lowest water table (MLWT) maps.

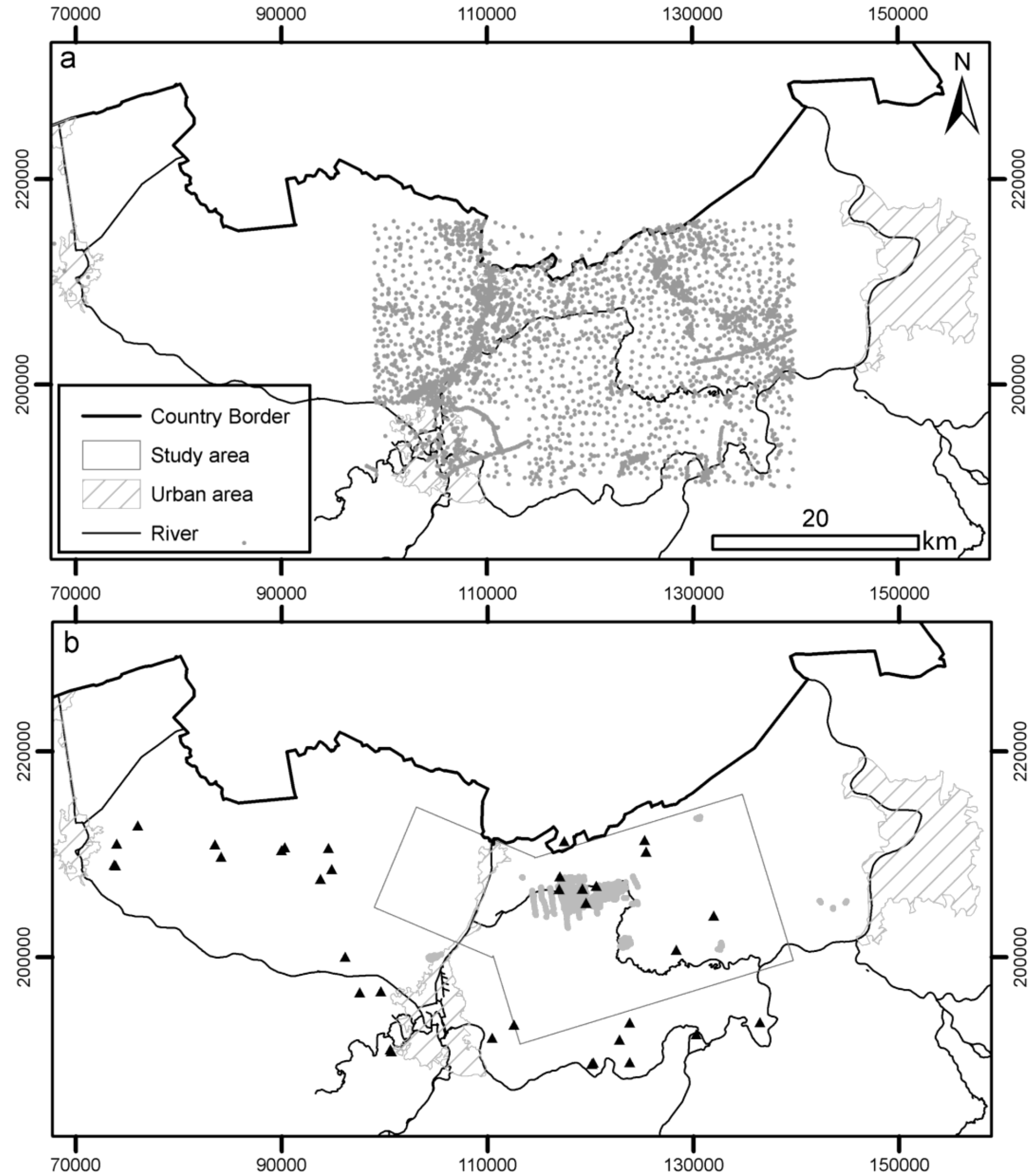

Figure 3.2 Point locations with described profiles collected for the reconstruction of a temporal DEM. a. Data provided by the Flemish database on subsurface information (DOV, 2009); b. Data collected from literature and corings performed in function of the project. Indication of dated (dark grey triangles) and undated profiles (pale grey circles). (Other maps used: AGIV, 2002).

Because of the large temporal extent of the period of interest computational limitations and constraints on data availability are encountered. To overcome these problems, water table dynamics can be calculated for time windows of 30 years, which correspond to a climatic period (Finke et al., 2004). Afterwards, a continuous set of groundwater heads can be obtained by means of interpolation. Furthermore, the spatial units considered are set to 100 m x 100 m grid cells. Data availability is mainly limited to present-day groundwater heads. This implies that calibration can practically only be performed on the present-day time window. Furthermore, calibration of the entire area based on measured heads proves to be hard because of the size of the study area and the restricted spatial distribution and temporal extent of the available data. Full-cover information, however, is present as drainage classes on the national soil map (scale 1:20,000), which was mapped in the study area during the 1950s. During this survey, next to soil profile and texture, information on the groundwater dynamics was recorded and translated into drainage classes. These drainage classes are related to MHWT and MLWT (Van Ranst and Sys, 2000), expressed as classes of depths below the surface. A MWT can be derived from the average values for the MHWT and MLWT per drainage class. Information on classes with boundaries beneath the maximum sampling depth of the national soil survey campaing (> 1.25 m) can be completed by means of a recent drainage class map of a part of the study area (Zidan, 2008). By comparing the results of the steady state simulation of the present time window with this MWT map and the results of the transient or non-steady state flow with the MHWT and MLWT maps, the model can be calibrated for the present time. By means of palaeoecological observations at different locations, simulated groundwater heads for previous time windows can be verified.

Another consideration that has to be made is that topography, river network and climate are variable, considering the long time periods involved. This as opposed to the geological layers and their hydrogeological properties, which are assumed to be continuous for the time considered. In order to take the changing climatic factor into account, present-day meteorological measurements are combined with palaeoprecipitation (Davis et al., 2003) and palaeoevapotranspiration anomaly series (Davis, personal communication, 2008) based on pollen data. As a consequence, a reconstruction of palaeotopography and palaeodrainage pattern, the latter derived from the palaeotopography, is required for each time window. This reveals the close interconnection between the different models presented.

3.2.3.3 Pedogenetic model

The main reason to include a pedogenetic model in the framework is that the natural chemical and physical fertility of the soil determines to a large extent the suitability for Neolithic and later types of agriculture. Liming was only introduced in the Iron Age. The suitability is determined in the land evaluation model, but this model needs information on a.o. soil pH, soil texture, calcium carbonate content and organic matter content at the relevant time slices. For a more detailed list of the model parameters and the associated land qualities, is referred to Table 3.1. A pedogenetic model is then needed to reconstruct these variables. Such model should take into account the effects of (changing) climate, vegetation, topographic position, parent material and human influence such as ploughing and erosion on the soil properties mentioned above. Soil processes involved include flow of water, chemicals and heat, chemical equilibration, carbon sequestration, physical and chemical weathering and perturbation of the soil by soil organisms and by ploughing. The model SoilGen, described in detail by Finke and Hutson (2008), has these abilities and produces annual values of the required variables for desired depths in the soil profile at point location.

The model needs initial values of soil properties at the starting year. These can be taken from chemical and physical analysis of C-horizons in the current soil. Furthermore, for the whole simulated period, values for precipitation, potential evapotranspiration, temperature, water table depth and type of vegetation must be available. Meteorological data can be generated using climate reconstructions based on quantitative analyses of pollen data like the ones from Davis et al. (2003) to obtain annual values for precipitation, evapotranspiration and January and July temperatures. The data of Davis et al. (2003) were calculated for six regions based on more than 500 sites covering Europe. These can be downscaled to local and daily values using a reference series based on local current measurements (Finke and Hutson, 2008), for example from weather stations, such as the one from Uccle (Belgium). Vegetation types can be reconstructed with local pollen diagrams (Verbruggen et al., 1996) and water table depths are supplied by the hydrological model. Additionally, the model handles erosion and sedimentation events, which can be derived from point-scale reconstructions using the temporal DEM and results from on-site pedological and palaeoecological research.

The reliability of the model outputs needs to be maximized. The underlying hypothesis is that if process rates and final state of the soil are well reproduced by the model, it is a suitable interpolator in time, i.e. it can give a reasonable estimate of soil conditions at different points in time. Model reliability is therefore maximized by (i) calibrating the model on measured soil data and (ii) by calibrating process rates to reproduce literature values (Egli and Fitze, 2001). Furthermore, individual model components such as water- and chemical-flow routines, decalcification rate and carbon sequestration need to be calibrated and verified. The above-mentioned model components in SoilGen have a good verification status (Addiscott and Wagenet, 1985; Dann et al., 2006; Finke and Hutson, 2008; Jabro et al., 2006; Jalali and Rowell, 2003; Smith et al., 1997). Ideally, the calibrated model is tested at independent locations in the study area as well. As the runtime for such model for temporal extents in the range of 15,000 BP to present is quite long, the number of geographic data points that can be simulated is limited. Therefore, obtained values must be spatially interpolated to obtain complete spatial coverage.

3.2.3.4 Land evaluation model

The aim of the land evaluation model is to delineate areas where in a chosen part of the temporal extent, the conditions for concomitant uses of land were optimal. Land evaluation is defined as 'the process of collating and interpreting basic inventories of soil, vegetation, climate and other aspects of land in order to identify and make a first comparison of promising land use alternatives in simple socio-economic terms' (Brinkman and Smyth, 1973). Early examples of land evaluation in archaeology were reported by Kamermans et al. (1985) and Finke and Sewuster (1987), focussing mostly on the agricultural aspect, although this needs not to be the case. Here we take, like Kamermans (2006) a broad interpretation of land use, i.e. also the use of land for hunting and gathering and as a comfortable place to live. The resulting maps provide a biophysical motivation for occupational patterns and can be considered as deductive predictive maps.

The first activity in an archaeological land evaluation is careful evaluation of the archaeological and palaeoecological record for prove of land uses, for example pollen, plant macroremains, artefacts and archaeological traces in the soil. This should, in combination with knowledge on the socio-economic organization, lead to identification of land use objectives and to a subsequent definition of land utilization types. The next step is the identification and mapping of relevant basic land properties (called land characteristics, for example soil pH) and compound land properties (called land qualities, for example moisture supply capacity). These properties must in our approach largely be derived from the models described earlier and they actually define the desired model functionality. The requirements of the land utilization type are then formalized and matched with the land characteristics and qualities at the considered period to result in maps indicating the suitability for the defined land utilization types. In instances where a fairly complete overview of the possible land utilization types is acquired and reasonable assumptions on the socio-economic system can be made, it is possible to make assessments of the population carrying capacity based on the suitability maps. Land evaluation has since the 1970s undergone an evolution from qualitative evaluation approaches towards approaches that quantify crop production with models and use trade-off analysis to define land use systems in detail (Stoorvogel et al., 2004). We consider such analysis as extensions of the proposed approach but do not pursue it in the case study at hand.

3.2.4 Concepts of scale

When different models are to be connected for integrated studies, such as geoarchaeological studies, it should be realized that the various models in the framework may not have the same spatial or temporal scale and may or may not cover the whole research area or time frame. In the context of scale, three concepts are of relevance (Bierkens et al., 2000):

- the *grain*, being the largest area (or volume) or time interval for which the property of interest is considered homogeneous. For example, in a DEM of 5 m x 5 m the spatial grain is 25 m^2, and the temporal grain of the civil calendar is one day. If a model framework contains models with different grains, and these models have to be connected, upscaling or downscaling methods must be applied to obtain results at the target grain. The choice of a grain affects the variability of the target property. At any grain, the within-grain variability is ignored as only the grain-average is considered. At a large spatial grain, less variability can be displayed on a map but one is more certain about the average values. Inversely, a small spatial grain allows displaying variability in detail but it may not be certain at all if these patterns are true. Ideally, the spatial grain is chosen based on an acceptable uncertainty threshold. In practice, choice of grain, spatial as well as temporal, is determined by the available data and analysis instruments such as models;

- the *extent* is the total area or time interval considered in a study. If two or more model components do not have the same extent, extrapolation (or singling out) is necessary to obtain results for equal extents;

- the *coverage* is the fraction of the extent for which there are data values (for a chosen grain). If a model operates on a small spatial grain, then many model runs must be done to obtain full coverage. In such a case the runtime of the model may be a limiting factor. If the applied models do not have the same coverage then interpolation is necessary to obtain equal coverage.

3.3 Results

3.3.1 Predictive modelling

The predictive modelling based on the current landscape, with and without evidence filter, resulted in maps for the Final Palaeolithic, the Meso- and Neolithic (Figure 3.3). By using the evidence filter, only those patterns that are strongly supported by field evidence are displayed on the map, while patterns supported by less strong evidence are not shown. The non-filtered (no evidence filter used) maps display the entire area investigated with the predictive modelling. The filtered (with evidence filter) map of the Final Palaeolithic also displays the entire area, while the filtered maps of the Mesolithic and Neolithic only display 3.3% and 49.7% of the modelled area respectively. All three filtered maps only display low probabilities of findings. Given the data at hand however, these appear to be the most reliable. The highest values on the filtered map of the Final Palaeolithic (Figure 3.3a), are located alongside river courses and the borders around the Depression of the Moervaart. However, these values are still very low. The filtered map of the Mesolithic (Figure 3.3b) displays certain, but low probabilities of findings in the polder areas in the west and alongside the borders of the Moervaart depression. Other regions show higher Bayesian probabilities. However, these appear to be less certain, since they are not displayed on the filtered map. Expectancy maps for the Final Palaeolithic and Mesolithic differ strongy from the one for the Neolithic (Figure 3.3c), in which a much broader area of low probabilities is displayed. Topographically higher lying regions show much higher probabilities on the non-filtered version. However, these appear to be highly uncertain and are therefore not displayed on the filtered map. This suggests less occupation on the lower-lying parts of the landscape during the Neolithic.

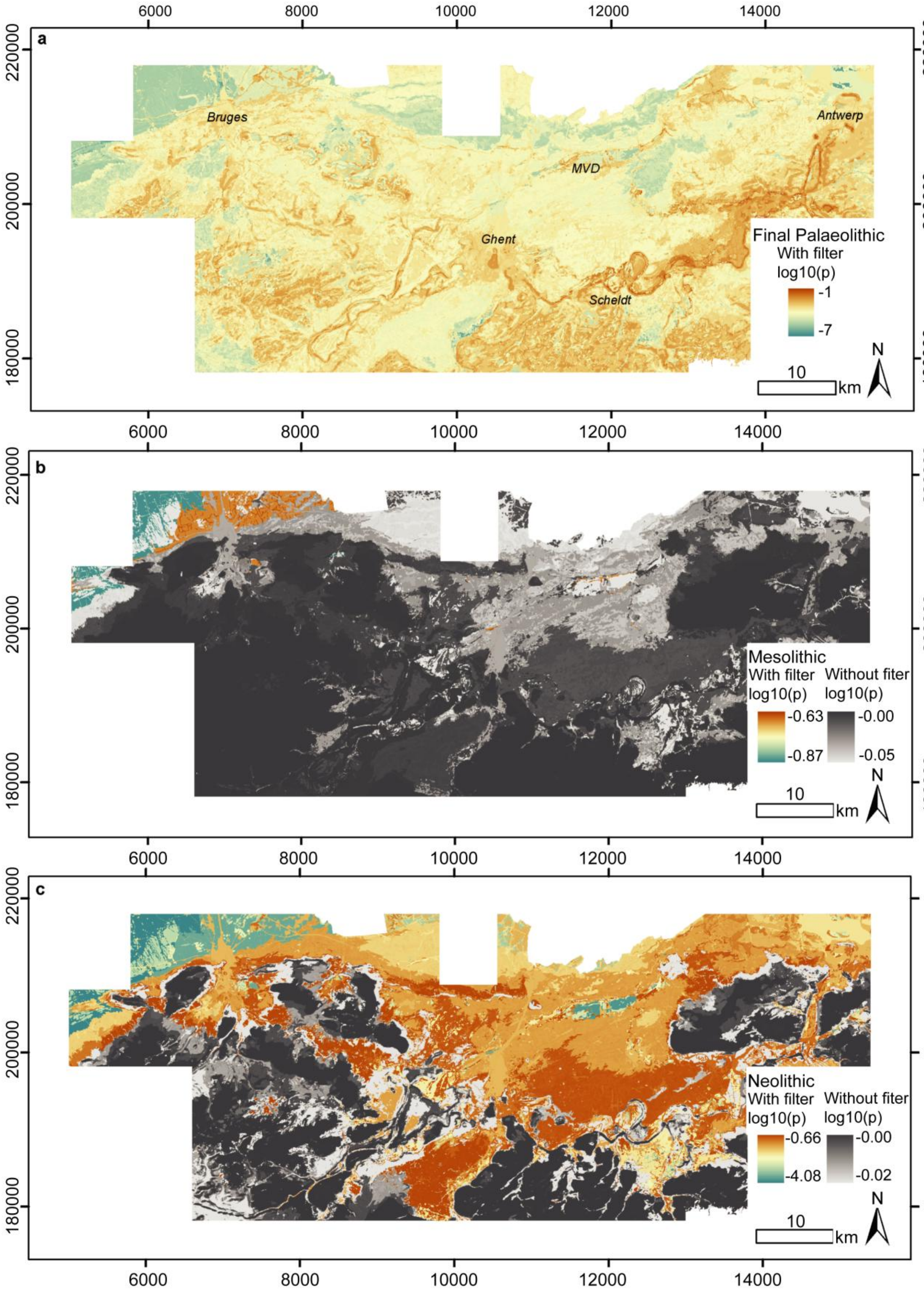

Figure 3.3 Maps of the (log-transformed) probability of finds obtained by Bayesian modelling: with evidence filter (colour scale) and without evidence filter (grey scale). a. Final Palaeolithic; b. Mesolithic; c. Neolithic. The maps with the evidence filter only display probabilities strongly supported by field evidence (p=0.001). Scale bars for the maps without evidence filter are adjusted for better visualisation: lowest values for the Meso- and Neolithic are respectively -1.09 and -4.68. (MVD = Moervaart depression).

3.3.2 Components of the model framework

3.3.2.1 Elevation model

As stated above, several DEMs are to be generated, as can be seen on the flowchart in Figure 3.4. Each DEM represents the terrain elevation for a different time slice. Starting from the original LiDAR data and after removal of vegetation and buildings, an elevation map of the current time (t = T) is provided. The resulting DEM has an accuracy equal to the one of the original LiDAR data set, which is 0.3 m in planimetrical view (x, y) and ranging between 0.07 and 0.20 m in altimetrical view (z). It also has a high resolution of 2 m x 2 m, which proves to be useful to detect archaeological and palaeoenvironmental features such as palaeochannels or filled ditches, even when other data sources give no indication of these features. The DEM is also useful for geophysical and palaeoecological field sampling and archaeological prospection (Werbrouck et al., 2010). Furthermore, it is used in calibrating the groundwater model with present-time data. By performing the stepwise filtering, a DEM exclusively representing the natural topography is generated ($t = T-\Delta_{hn}$). The accuracy equals the accuracy of the original LiDAR data, except in the interpolated parts where the minimum accuracy is 1 m. This is the maximum equidistance of the contours on the historical maps used for interpolation. The resulting DEM represents the natural topography free of artefacts caused by modern objects and infrastructures, corresponding to the post-medieval landscape.

3.3.2.2 Hydrological model

The flowchart of activities needed to run the hydrological model is given in Figure 3.5. The results discussed below are only preliminary. The example time window is situated between 1947 and 1976 CE (Current Era), a 30-year long time frame covering the period in which the soil survey in the area was executed. This took place between 1949 and 1953 (Van Ranst and Sys, 2000). A steady state flow simulation is performed for this time window with the average value of precipitation and evapotranspiration for the same period, calculating groundwater levels for cells of 100 m x 100 m. This results in a map of the MWT, expressed in absolute heights (Figure 3.6). As an outcome of the transient flow simulation, maps of the groundwater level are given for each month, covering the 30-year time window. For each year, the three months with the highest and with the lowest groundwater levels are selected and their 30-year average is calculated, giving maps of the MHWT and MLWT.

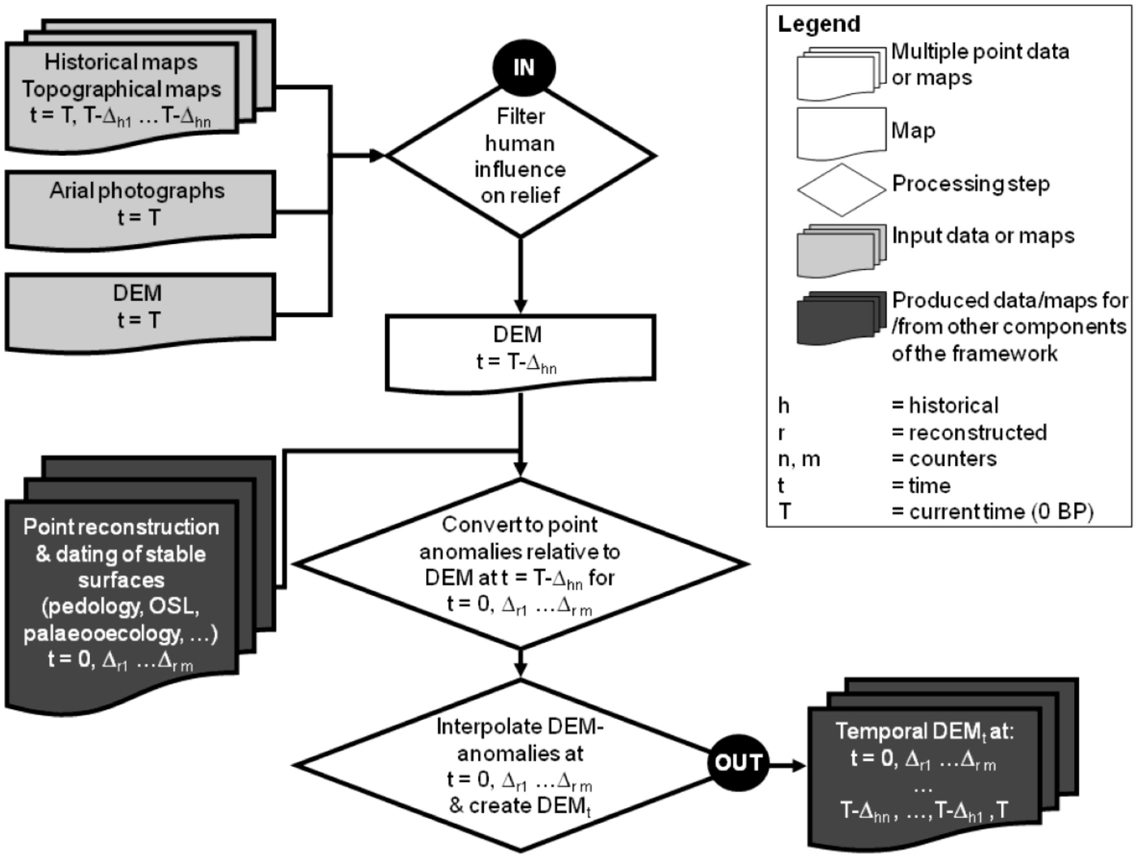

Figure 3.4 Flowchart for the construction of a temporal DEM. Solid lines indicate data flows, dotted lines indicate information flows (for model calibration and verification).

3.3.2.3 Pedogenetic model

The flowchart of activities needed to run the model for soil reconstruction is given in Figure 3.7. Obtaining meteorological input data from general climate evolution data is essential for running the model, as pedogenesis is strongly influenced by fluctuations in precipitation, evapotranspiration and temperature. In the figure these data are considered as available input which was the case for the presented model run, but may be laborious in other cases. As an example of the output of the pedogenetic model at the 1 m x 1 m spatial grain and one year temporal grain, Figure 3.8 shows the evolution of soil pH in soil depth and time. The effects on soil pH of calcareous aeolian dust additions in the Dryas periods are clearly visible. In deeply drained soils, the high Belgian precipitation surplus in combination with acidity produced by organic matter decomposition rapidly decalcifies the soil, especially in the Holocene. In such soils the conditions for agriculture without fertilization in the form of liming were unfavourable already from the start of the Neolithic. This effect is less marked in soils with shallow water tables. Other output data include the organic matter content and bulk density which are important to assess the chemical and physical soil fertility in the land evaluation model.

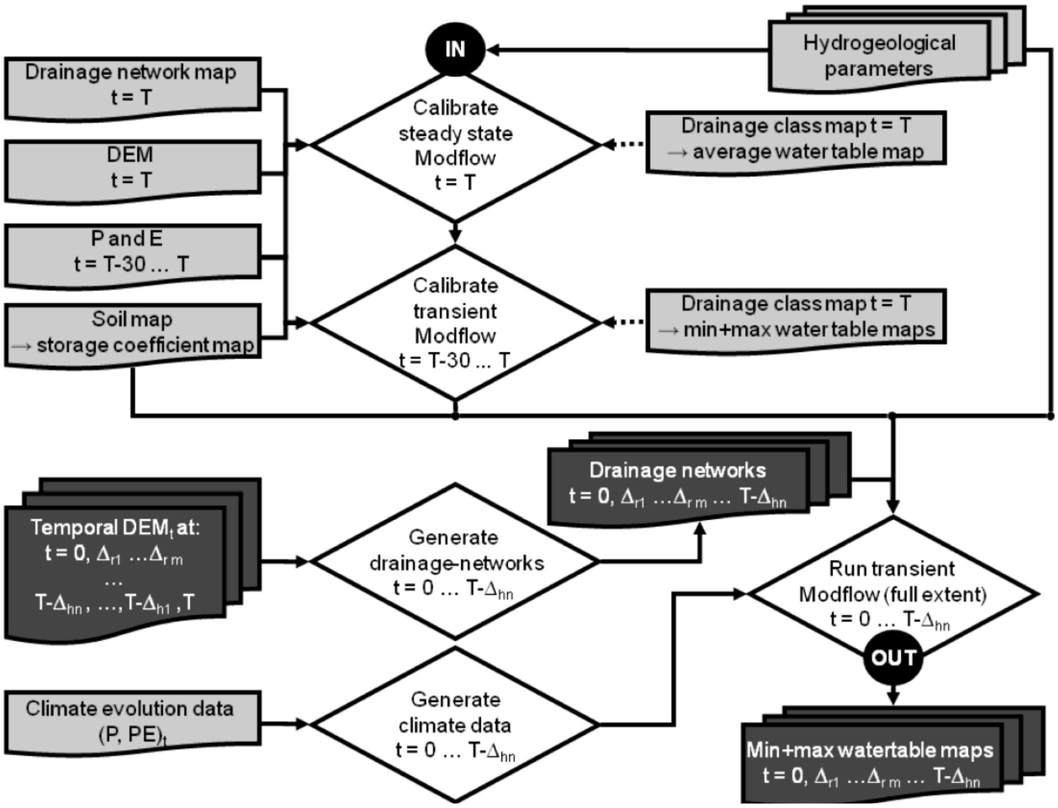

Figure 3.5 Flowchart for the construction of the hydrological model. For the legend, see Figure 3.4. Solid lines indicate data flows, dotted lines indicate information flows (for model calibration and verification).

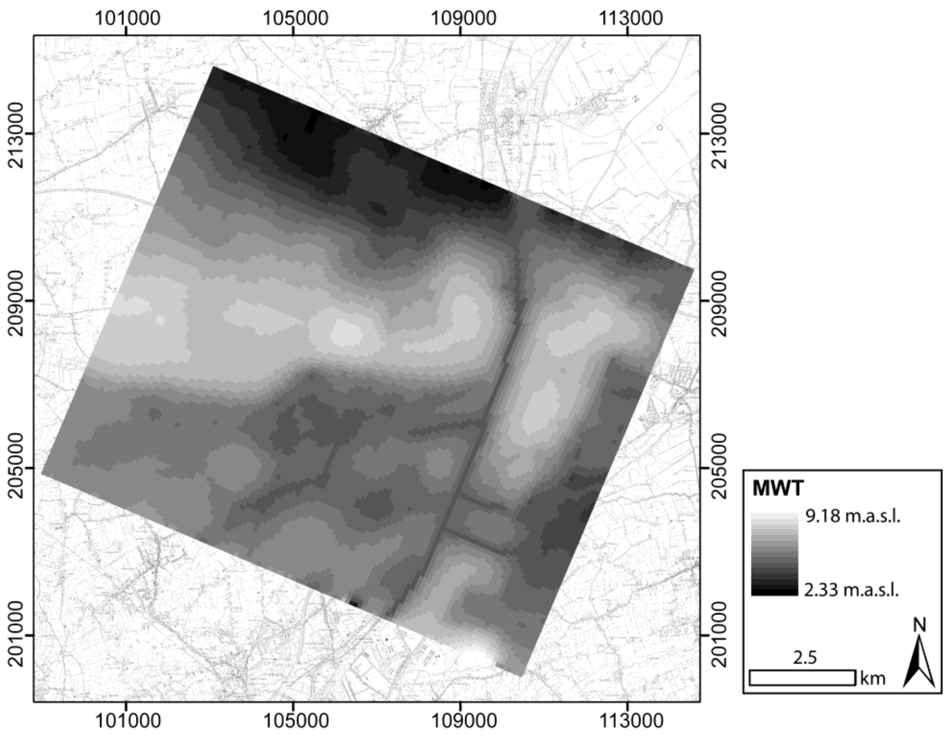

Figure 3.6 Simulated mean water table (MWT, greyscale) level in the most western part of the groundwater modelling. The topographical map of the region (NGI, 2008) is also given.

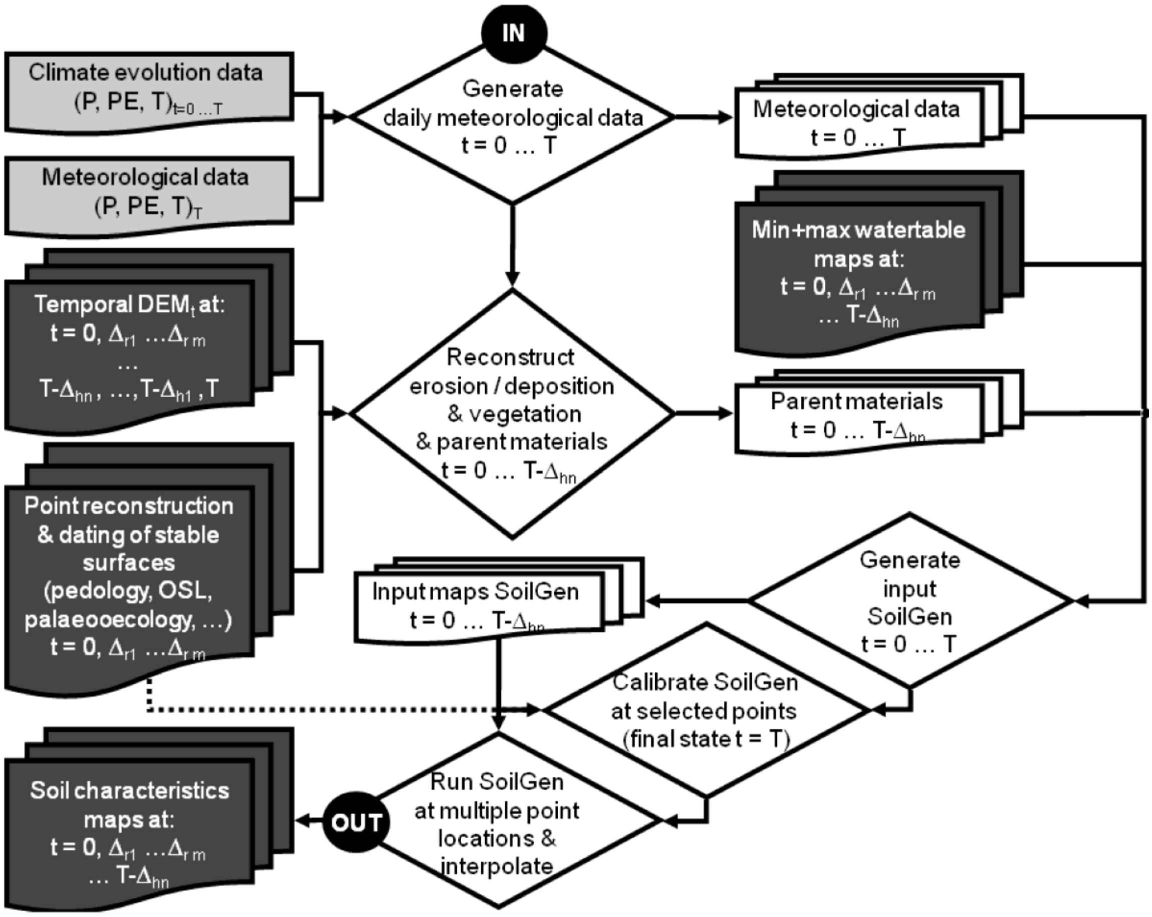

Figure 3.7 Flowchart of the pedogenetic model. For the legend, see Figure 3.4. Solid lines indicate data flows, dotted lines indicate information flows (for model calibration and verification).

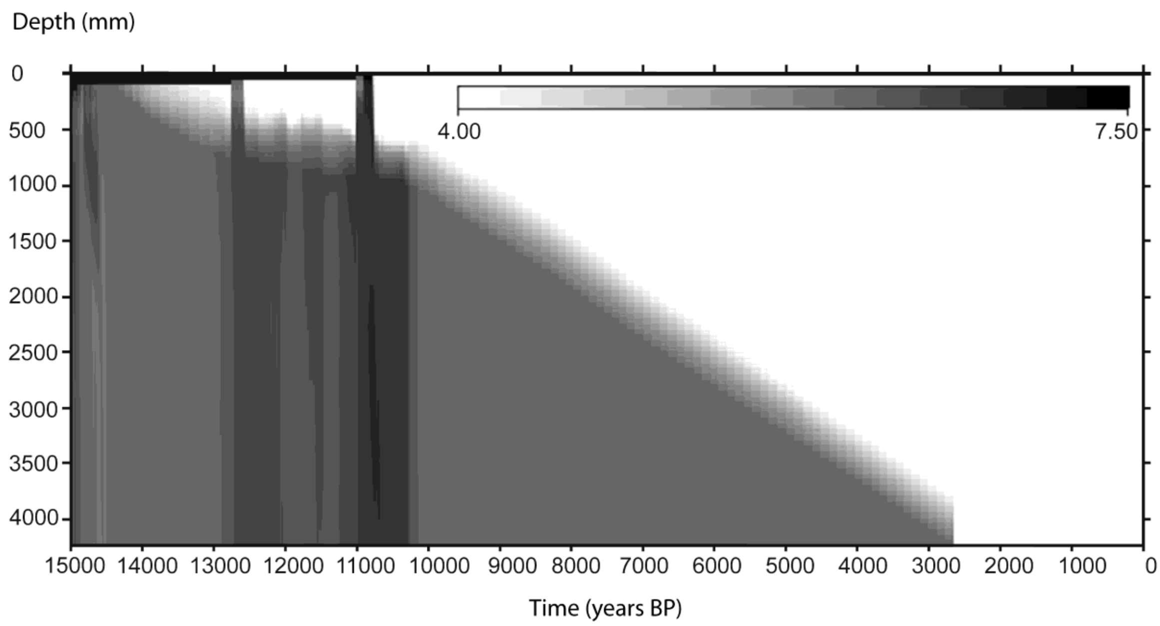

Figure 3.8 Simulated soil pH as a function of depth and time in a deeply drained silt loam soil in Flanders. The figure shows a drop of the pH through time and through the profile. The effects of calcareous aeolian dust additions in the Dryas periods are also clearly visible.

3.3.2.4 Land evaluation model

The land evaluation activities are depicted in Figure 3.9. Current emphasis is on evaluation of archaeological and palaeoecological data for more precise definition of land use types in the form of pollen, plant macroremains and archaeological artefacts and features. Within the area of Sandy Flanders, the earliest possible indication for agriculture was found at the site of Doel/Deurganckdok-sector B (Bastiaens et al., 2005). One charred cereal grain of *Triticum aestivum* (bread wheat) was recovered on the top of a sand dune, underneath a peat layer (Crombé and Vanmontfort, 2007). The beginning of the peat growth was dated around 5050 ± 55 BP (sample KAI-12075: 3840 ± 130 cal BCE; Crombé, 2005). Artefacts linked with agricultural land use activities were discovered at Kluizen and Zele. In Kluizen, three ardshares were found in the revetment of a well, dating to the Early Iron Age (Laloo et al., 2009), while in Zele, two fragments of an ard were found in a Late Iron Age well (Bourgeois et al., 2009). At the excavations of Bronze and Iron Age sites at Sint-Gillis-Waas, pollen of *Cerealea* were collected in wells, indicating agricultural activities in the vicinity (Gelorini, 2001). Based on these observations (locations indicated on Figure 3.10b), parameters needed for the land evaluation can be identified (Table 3.1). We presume 3 broad land utilization types: rain-fed agriculture, hunting and fishing, gathering and also formulated criteria relevant for settling. For rain-fed agriculture we define the data needs for 10 land qualities that were used in previous land evaluations (Finke et al., 1994; Van Joolen, 2003) for emmer (*Triticum dicoccon*), spelt (*Triticum spelta*) and barley (*Hordeum vulgare*). For hunting and fishing the data needs on the land qualities are based on ‘presence of surface water’ and ‘visibility’. For gathering we define an attractor ‘ecological diversity’, with associated landscape characteristics. Finally for housing we define the comfort-related qualities ‘wind exposure’, ‘wetness’ and ‘nearby fresh water’. Table 3.1 shows the associated parameters, which practically all can be provided by the hydrological model, pedogenetic model and temporal DEM. Additionally, climate reconstruction data (notably annual precipitation, potential evapotranspiration and temperatures in January and July) need to be known. These can be obtained using studies such as those by Davis et al. (2003). The spatial object of land evaluation should correspond to the smallest unit of land use or land management, assuming this management was homogeneous. We consider agricultural fields of 40 m x 40 m reasonable. A period of one year is considered a reasonable temporal scale as the crop growth, hunting and gathering cycles take one year to complete.

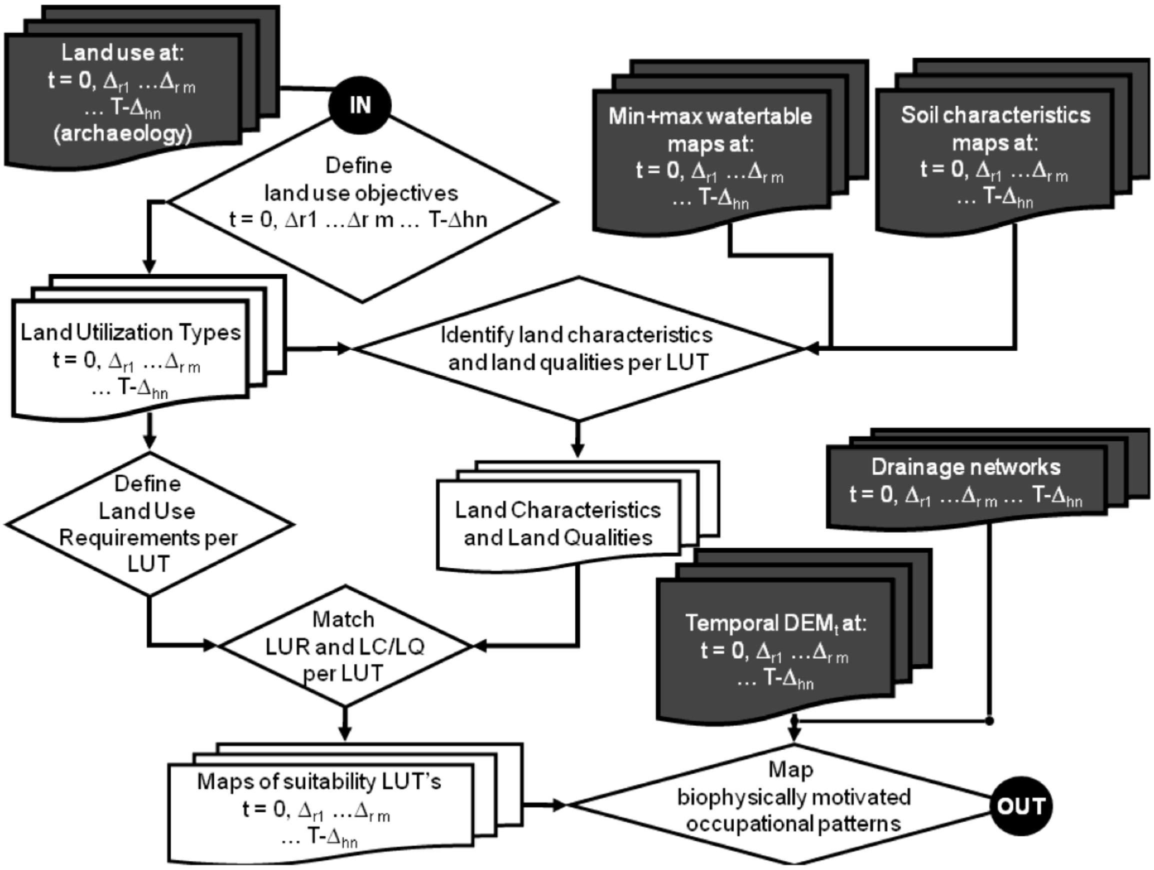

Figure 3.9 Flowchart for the land evaluation model. For the legend, see Figure 3.4. Solid lines indicate data flows, dotted lines indicate information flows (for model calibration and verification).

3.3.3 Model framework and compontent integration

The proposed general model framework (Figure 3.11) connects the four models in a sequence: DEM > hydrological model > pedogenetic model > land evaluation model. This was actually designed in the reverse order to ascertain that all the data needed by the land evaluation model can be generated with the model instruments earlier in the model chain. The identified model components cannot be directly connected because of scale issues: as the grain sizes of the DEM, hydrological model, pedogenetic model and land evaluation model differ, upscaling and downscaling steps must be added to the chain. Furthermore, interpolation is necessary to obtain full coverage of the soil properties. Thus, the model framework is integrative in the sense that it combines process knowledge from various disciplines and integrates the result to predictive maps with chosen spatial and temporal grains. From such a framework, protocols can be derived that specify data and information flows between involved research groups,

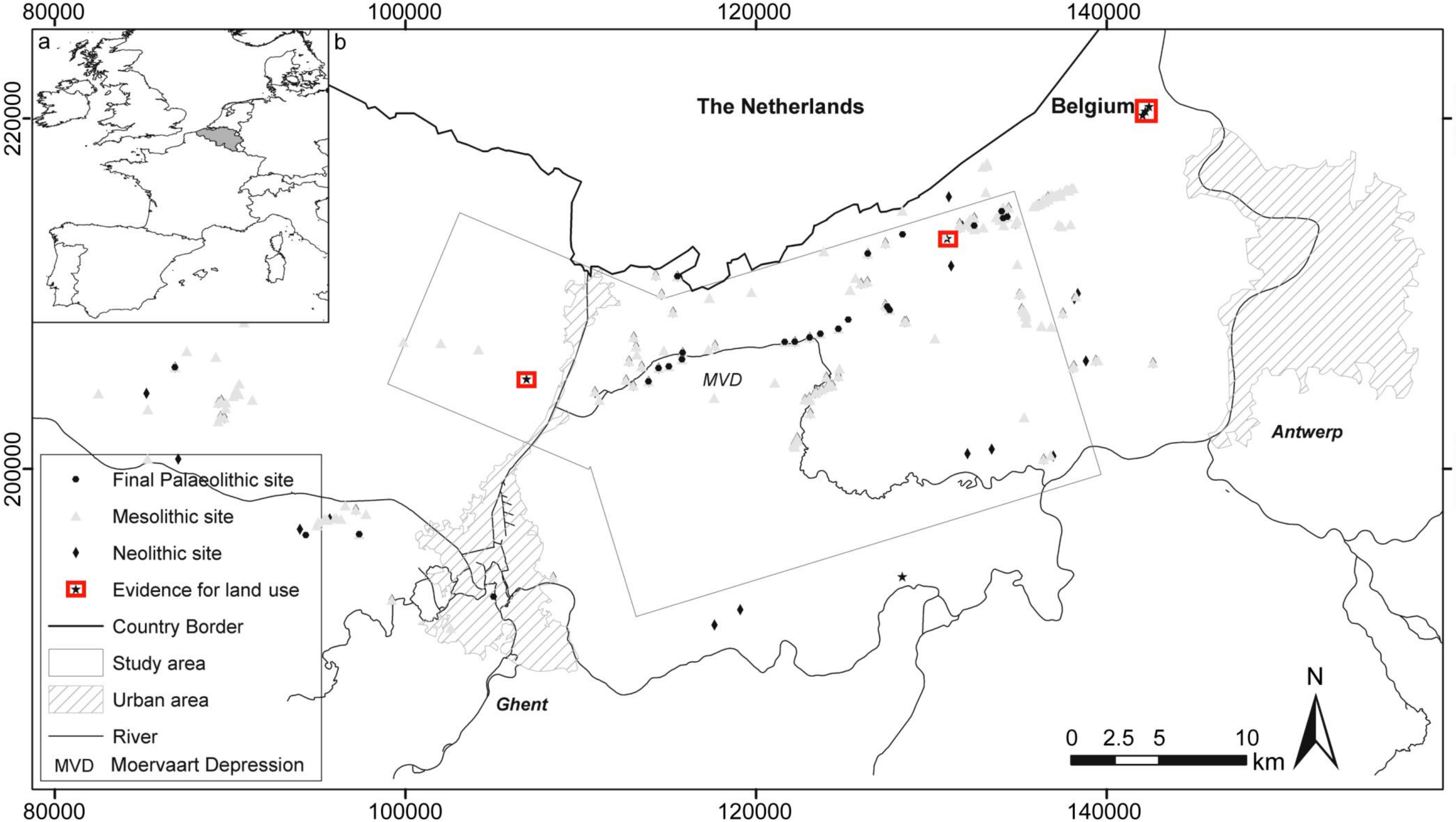

Figure 3.10 a. Belgium (grey) within Europe; b. Location of known archaeological sites for the Final Palaeolithic, the Meso- and the Neolithic (Sergant et al., 2009). Sites with prove of land use are also indicated. (Other maps used: AGIV, 2002).

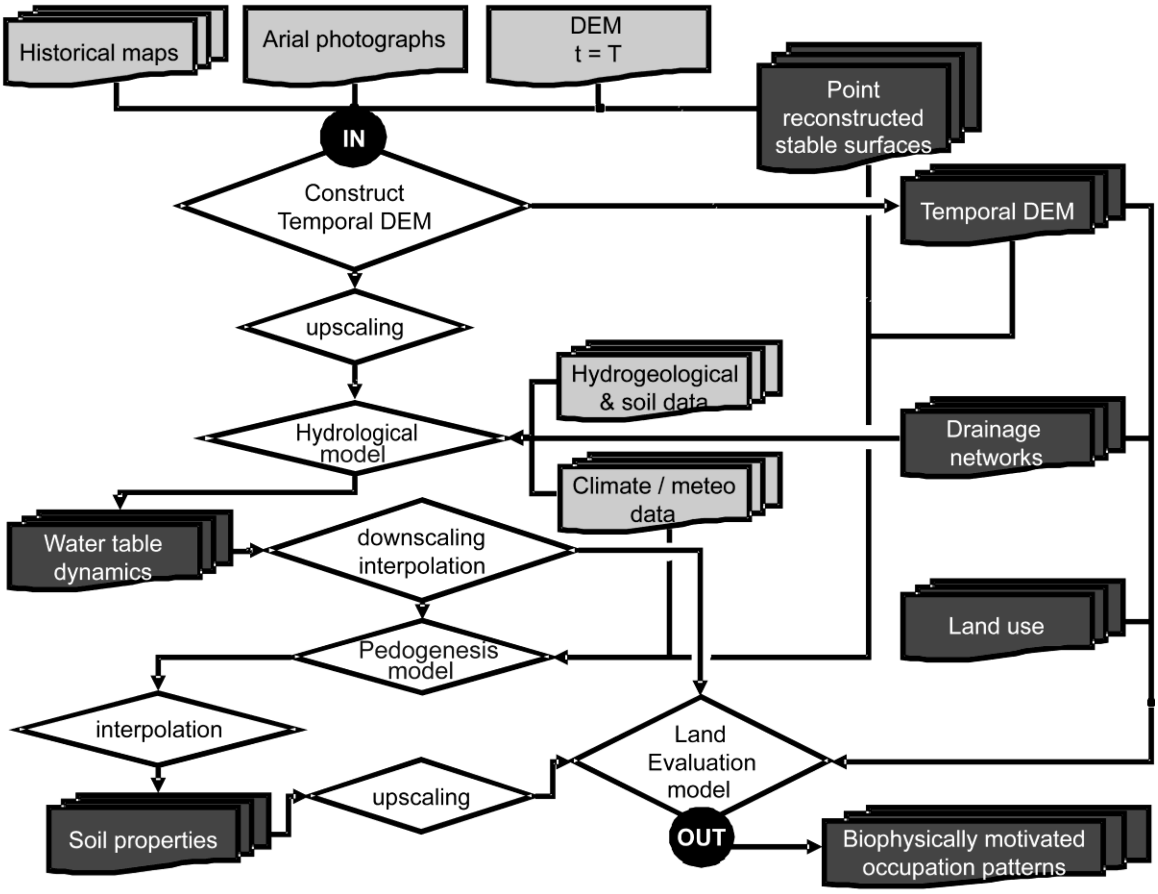

Figure 3.11 Model framework incorporating the different model instruments (DEM, groundwater model, pedogenetic model and the land evaluation model). For the legend, see Figure 3.4Figure 3.4.

which will be of great value when several disciplinary groups cooperate. The model framework is generic in the sense that it is portable to other landscapes, especially in regions with shallow water tables. However, the processes to be included (or not) in the various models partly depend on the geographic setting. For instance the construction of a temporal DEM in a tectonically active area or an area undergoing strong erosion may involve inclusion of additional processes.

3.4 Discussion

3.4.1 Predictive modelling

A predictive modelling was conducted based on a mixed inductive-deductive approach with Bayesian inference to typical combinations of environmental attributes of the current landscape. The dataset consisted of recorded absence and presence of finds, furthermore the data were geographically scattered and clustered per surveyed field. This last configuration causes poor performance of geostatistical methods but does not hinder the prediction to geographical strata. Based on this data configuration, a mixed inductive-deductive approach to predictive modelling was chosen. This approach has proven to be the most favourable for a similar data configuration in another study area (Finke et al., 2008). The predictive modelling resulted in filtered maps displaying only certain but very low probabilities of archaeological findings. The observed site distributions did not match the predictive maps based on our knowledge of the current landscape and the chosen biophysical attractors. In this way, more insight was obtained in the state of knowledge at the beginning of the project. This has led to the motivation of an integrative landscape reconstruction.

3.4.2 Model linkage over different scales

All models must produce their final outputs at full extent (the complete study area), full coverage (no empty areas) and at the spatial and temporal grains of the land evaluation model. The spatial and temporal grains and coverages of the different model instruments as mentioned above are listed in Table 3.2. Most of the model instruments operate at the entire coverage of the study area. The pedogenetic model is an exception here, because it simulates pedogenesis at the point scale. Because of the long runtime of this model, it is only possible to perform simulations at a restricted number of locations. The same restrictions count for the temporal coverage of the DEM and the hydrological model. To reach the grain of the land evaluation model, up- and downscaling actions are necessary and the full coverage is attained by interpolation. This is illustrated in Figure 3.12. This figure is a simplification of reality since the models do not only contribute to the land evaluation model but also to each other, which may involve more upscaling, downscaling and interpolation activities. We refer to Bierkens et al. (2000) and Heuvelink and Pebesma (1999) for an extensive review of up- and downscaling methods in the context of modelling. The former publication also gives protocols to choose appropriate scale transfer methods for specific situations.

In the context of upscaling, the choice of method depends on the question if the model responds linearly to its input parameters. If this is the case, one can upscale (for example spatially average) the model inputs and run the model at the coarser grain to directly obtain results at the target grain. Usually, in hydrological and pedogenetic models this is not the case. Then the model has to be run at many locations at a fine grain, and the model results have to be upscaled. The latter method has the disadvantage that many more model runs need to be made, which can be time consuming. Considering downscaling one can utilize fine-grain auxiliary information to obtain plausible patterns at the finer grain. The auxiliary information should then be relevant for the process studied. For modelling purposes, the DEM with the 4 m² grain needs to be re-sampled to the resolution of the hydrological model, which is 100 m x 100 m. Taking into account possible remaining peaks in the DEM, the median value is used to upscale the grid size. As the DEM exclusively represents the natural terrain elevation it can also be used for downscaling the results of the hydrological model in a later phase, because the water table depth is known to be related to micro-relief.

Table 3.2 Spatial and temporal grain and coverage of the DEM, hydrological, pedogenetic and land evaluation models. The temporal coverage is expressed as a percentage of the temporal extent (here taken as 15,000 years). n is the number of time slices.

Model	Spatial Grain	Spatial Coverage	Temporal Grain	Temporal Coverage
DEM	4 m² (2 m x 2 m)	100%	4 years	0.027% * n
Hydrological model	10,000 m² (100 m x 100 m)	100%	1 month	0.2% * n
Pedogenetic model	1 m² (1 m x 1 m)	0.000017%	1 day	100.00%
Land evaluation model	1,600 m² (40 m x 40 m)	100%	1 year	100.00%

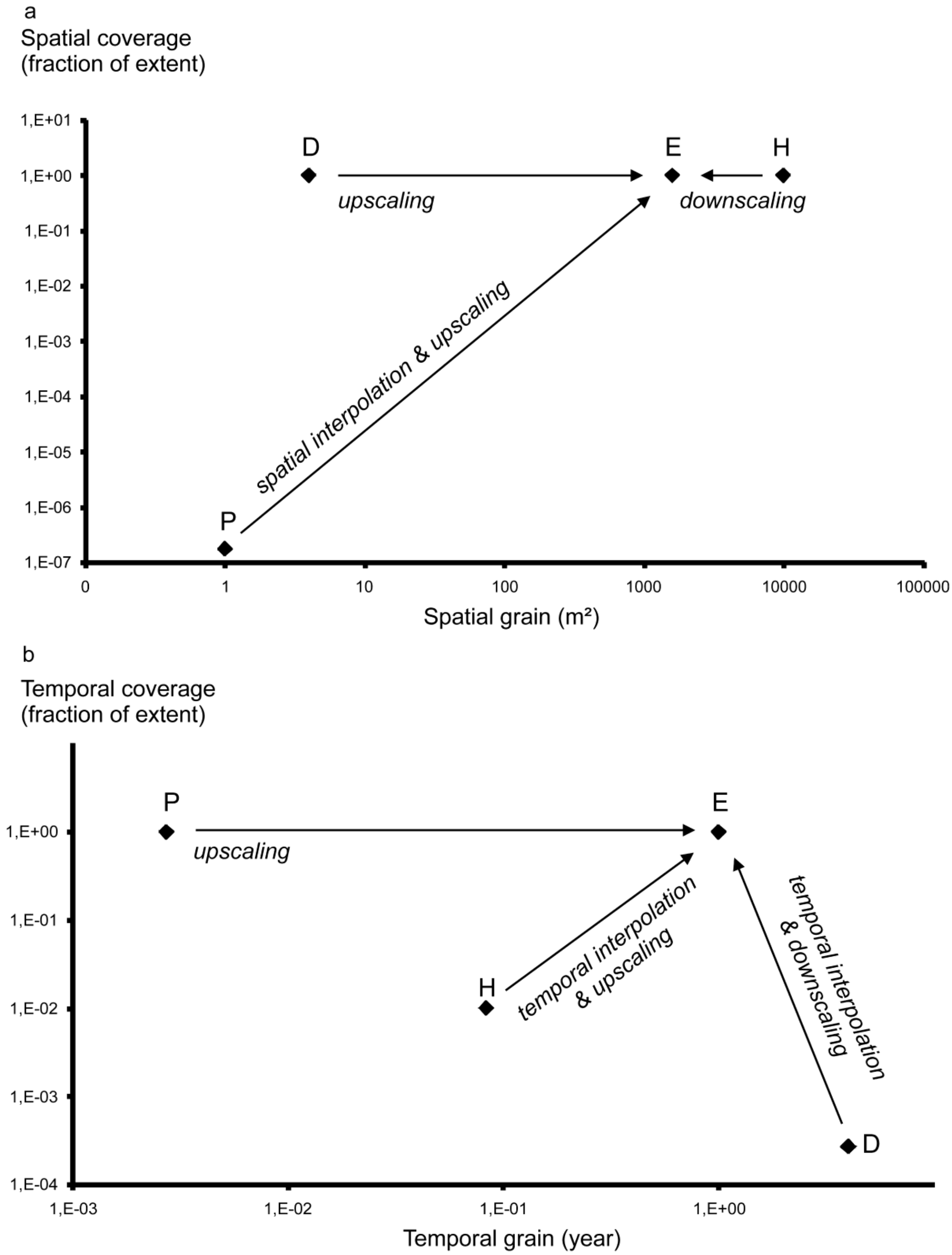

Figure 3.12 Grain versus coverage of model components: a. spatial; b. temporal. Temporal coverages of the DEM and the groundwater model are dependent on the amount of time slices and need to be multiplied with the number of time slices to get the correct value. Spatial and temporal up- and downscaling are necessary to bring the model outputs at the same grain as the land evaluation. Spatial and temporal interpolations bring the model outputs to the 100% coverage. P: Pedogenetic model; D: Temporal DEM; H: Hydrological model; E: Land evaluation model.

3.4.3 Model errors and error propagation

The accuracies of the different models (Table 3.1) are derived from studies where model results were confronted with measurements (AGIV, 2003; Finke and Hutson, 2008). Within each individual model, errors occur and propagate into the next step. For the DEM, accuracy of the original LiDAR data is reduced after filtering and interpolation. Interpretation and correlation of profiles comprises uncertainties that are enhanced in a later step of space-time interpolation, when creating the full-cover temporal DEM. Within the hydrological model, errors are already present in the input, derived from the DEM, the soil map and the climate data. Even after calibration, uncertainties are present. This is because the calibration is based on the drainage classes of the soil map, made in the 1950s, instead of present-day measurements of the water table level. Using the soil map however, allows estimations of the water table dynamics on a full-cover scale. Furthermore, using present-time data imposes current activities of pumping and draining on the model, while a natural situation without these activities is pursued. The soil map represents a semi-natural situation, close to the intended situation. In the pedogenetic model, soil parameters are simulated at different depths through the profile, starting from a parent material and going forward in time. A good assessment of the characteristics of the parent material is therefore of great importance for the outcome of the simulations. However, this is not always feasible. This is, for example, the case with the initial calcite content of the parent material of the soil.

It is clear that even after calibration models are not free of error. As a result, the land evaluation is subject to uncertainty as well. This would however be equally true for less formal ways of landscape reconstruction where errors would be unquantifiable. Ideally, the propagation of errors through the chain of models and upscaling, downscaling and interpolation steps would be studied by techniques such as Monte Carlo analysis (Heuvelink, 1998). Given the complexity of the models and their runtime this seems unfeasible. A more realistic option would be to estimate model errors such as given in Table 3.1 and repeat the land evaluation procedure for perturbations of the parameters that reflect these errors. This would allow identifying the persistent patterns in suitability for the land use given the model errors.

3.5 Conclusions

The identification of occupational patterns benefits from landscape reconstructions, since the current landscape often does not provide essential information, as may result from evidence-filtered predictive modelling. The development and subsequent application of model instruments provide the tools to interpolate various landscape characteristics in space and time, using process knowledge supplemented by empirical interpolation methods. This approach allows to predict, with models, spatial patterns of biophysical variables that are considered to be of influence to occupational patterns at various time slices. A land evaluation method is proposed, in order to translate these biophysical attractors into parameters, that can be provided by models. The first step of the approach is thus to define the requirements of the land evaluation, followed by the choice of the models that can provide the necessary parameters. We propose the following components as model instruments for the landscape reconstruction:

1. A temporal DEM derived from a current DEM, historical maps, point reconstructions of palaeosurfaces and interpolation methods;

2. A hydrological model applied at various time slices to reconstruct the water table dynamics and flood hazard areas;

3. A pedogenetic model applied at various point locations to reconstruct relevant soil characteristics such as pH, organic matter content, followed by spatial interpolation of the results for time slices;

4. A land evaluation model to identify areas of land per time slice that provided favourable conditions for the land uses at that time.

All these model components need input data that only palaeoecological, sedimentological and pedological on-site research can provide. Next to this, the model components also provide input to each other. Since the model components operate at different spatial and temporal grains and coverages, upscaling and downscaling methods as well as interpolation methods should be part of the integrated framework. Errors are present in the initial input data and in the model instruments and propagate through the model framework. As a result, the land evaluation is subject to uncertainty. The quality of model results needs to be estimated to assess how uncertain the land evaluation results are. It is clear that errors are present in this kind of landscape reconstruction, but this is equally true for other ways of landscape reconstruction, where errors would be unquantifiable.

3.6 References

Addiscott, T.M., Wagenet, R.J., 1985. Concepts of solute leaching in soils: a review of modelling approaches. Journal of Soil Science 36(3), 411-424.

AGIV, 2002. Vectoriële versie van de VHA-waterlopen & -zones (versie 22/10/2002) 1/5,000. Vlaamse Milieumaatschappij - Afdeling Operationeel Waterbeheer (AGIV).

AGIV, 2003. Digitaal Hoogtemodel Vlaanderen. Nieuwsbrief GIS Vlaanderen 16, 3–21.

AGIV, 2008. LIDAR-hoogtepunten (versie 1.0). MOW-Afd WL, VMM-Afd OW en AGIV.

Axelsson, P., 1999. Processing of laser scanner data - algorithms and applications. ISPRS Journal of Photogrammetry and Remote Sensing 54, 138–147.

Bastiaens, J., Deforce, K., Klinck, B., Meersschaert, L., Verbruggen, C., Vrydaghs, L., 2005. Features: Palaeobotanical analyses, in: Crombé, P. (Ed.), The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation projects. Volume 1: Palaeo-environment, chronology and features. Academia Press, Ghent, pp. 251-278.

Bats, M., 2007. The Flemish wetlands. An archaeological survey of the valley of the River Scheldt, in: Barber, J., Clark, C., Cressy, M., Crone, A., Hale, A., Henderson, J., Housley, R., Sands, R., Sheridan, A. (Eds.), Archaeology from the wetlands. Recent perspectives. Proceedings of the 11th WARP conference, Edinburgh 2005. . Edinburgh, Society of Antiquaries, pp. 93-100.

Berendsen, H.J.A., 2005. Landschap in delen; overzicht van de geofactoren. Van Gorcum, Assen.

Bierkens, M.F.P., Finke, P.A., de Willigen, P., 2000. Upscaling and downscaling methods for environmental research. Kluwer Academic Publishers, Dordrecht, 190 pp.

Bourgeois, I., De Clercq, W., Laloo, P., 2009. Onderdelen van een eergetouw op de vindplaats Zele - Zuidelijke Omleiding (provincie Oost-Vlaanderen, België). Lunula, Archaeologia protohistorica 17, 217-220.

Brinkman, R., Smith, A.J., 1983. Land evaluation for rural purposes. Summary of an expert consultation. Wageningen, The Netherlands, 6-12 October, 1972. International Institute for Land Reclamation and Improvement, Wageningen.

Chen, Q., 2007. Airborne LiDAR data processing and information extraction. Photogrammetric Engineering and Remote Sensing 73, 109–112.

Crombé, P., 2005. The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation Projects. Volume 1: Palaeo-environment, chronology and features. Archaeological Reports Ghent University, 3. Academia Press, Ghent.

Crombé, P., Vanmontfort, B., 2007. The neolithisation of the Scheldt and Basin in western Belgium. Proceedings of the British Academy 144, 261-283.

Dann, R.L., Close, M.E., Lee, R., Pang, L., 2006. Impact of data quality and model complexity on prediction of pesticide leaching. Journal of Environmental Quality 35(2), 628-640.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., data-contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 1701-1716.

DOV, 2009. Databank ondergrond Vlaanderen (DOV). http://dov.vlaanderen.be.

Drosos, V., Farmakis, D., 2006. Airborne Laser Scanning and DTM Generation, in: Manolas, E. (Ed.), Naxos International Conference on Sustainable Management and Development of Mountainous and Island Areas, Greece, pp. 206–218.

Egli, M., Fitze, P., 2001. Quantitative aspects of carbonate leaching of soils with differing ages and climates. Catena 46, 35-62.

Finke, P.A., Brus, D.J., Bierkens, M.F.P., Hoogland, T., Knotters, M., De Vries, F., 2004. Mapping groundwater dynamics using multiple sources of exhaustive high resolution data. Geoderma 123, 23-39.

Finke, P.A., Hutson, J.L., 2008. Modelling soil genesis in calcareous loess. Geoderma 145, 462-479.

Finke, P.A., Meylemans, E., Van de Wauw, J., 2008. Mapping the possible occurrence of archaeological sites by Bayesian inference. Journal of Archaeological Science 35, 2786-2796.

Finke, P.A., Sewuster, R.J.E., 1987. A soil survey and land evaluation in a Bronze Age context for the central Gubbio basin, Italy. University of Amsterdam, Laboratory for Physical Geography and Soil Science, Amsterdam.

Finke, P.A., Harding, J., Sevink, J., Sewuster, R.J., Stoddart, S., 1994. Site territories and landuse, in: Malone, C., Stoddart, S. (Eds.), Territory, time and state: the archaeological development of the Gubbio Basin. Cambridge University Press, Cambridge, United Kingdom.

Gelorini, V., 2001. Protohistorische waterputten palynologisch bekeken: site Sint-Gillis-Waas / Kluizemolen. VOBOV-Info 53, 2-12.

Harbaugh, A.W., 2005. MODFLOW-2005, The U.S. Geological Survey modular ground-water model - the Ground-Water Flow Process.

Heuvelink, G.B.M., 1998. Error propagation in environmental modelling with GIS. Taylor and Francis, London.

Heuvelink, G.B.M., Musters, P., Pebesma, E.J., 1997. Spatio-temporal kriging of water content, in: Baafi, E., Schofield, N. (Eds.), Geostatistics Wollongong '96, Volume 1. Kluwer Academic Publishers, Dordrecht, pp. 1020-1030.

Heuvelink, G.B.M., Pebesma, E.J., 1999. Spatial aggregation and soil process modelling. Geoderma 89, 47-65.

Heuvelink, G.B.M., Schoorl, J.M., Veldkamp, A., Pennock, D.J., 2006. Space-time Kalman filtering of soil redistribution. Geoderma 133, 124-137.

Jabro, J.D., Jabro, A.D., Fox, R.H., 2006. Accuracy and performance of three water quality models for simulating nitrate nitrogen losses under corn. Journal of Environmental Quality 35(4), 1227-1236.

Jalali, M., Rowell, D.L., 2003. The role of calcite and gypsum in the leaching of potassium in a sandy soil. Experimental Agriculture 39(4), 379-394.

Jordan, P., 2001. Ideology, material culture and Khanty ritual landscapes in western Siberia, in: Fewster, J.J., Zvelebil, M. (Eds.), Ethnoarchaeology and hunter-gatherers: Pictures at an exhibition. BAR International Series 995. Archaeopress, Oxford.

Kamermans, H., 2000. Land evaluation as predictive modelling: a deductive approach, in: Lock, G. (Ed.), Beyond the Map. Archaeology and Spatial Techniques. Proceedings of the NATO Advanced Researhc Workshop, Ravello (Italy), 1-2 October. NATO Scientific Series. IOS Press, Amsterdam.

Kamermans, H., 2006. Problems in Paleolithic land evaluation: a cautionary tale, in: Mehrer, M.W., Wescott, K.L. (Eds.), GIS and Archaeological Site Location Modeling. CRC Press Boca Raton, Florida, USA, pp. 97-122.

Kamermans, H., Deeben, J., Halewas, D., Van Leusen, M., Verhagen, P., Zoetbrood, P. (Eds.), 2004. Deconstructing the crystal ball: The state of the art in predictive modelling for archaeological heritage management in the Netherlands.

Kamermans, H., Loving, S.H., Voorrips, A., 1985. Changing patterns of prehistoric land use in the Agro Pontino, in: Malone, C., Stoddart, S. (Eds.), Papers in Italian archaeology, Volume

4, Part 1: The human landscape. BAR International Series 243. Archaeopress, Oxford, pp. 53-68.
Kyriakidis, P.C., Journel, A.G., 1999. Geostatistical space-time models: A review. Mathematical Geology 31, 651-684.
Laloo, P., De Clercq, W., Perdaen, Y., Crombé, P., 2009. Het Kluizendokproject. Basisrapportage van het preventief archeologisch onderzoek op de wijk Zandeken (Kluizen, gem. Evergem, prov. Oost-Vlaanderen). December 2005 - december 2009. UGent Archeologische Rapporten, 20. UGent, Gent, 406 pp.
Liu, X., 2008. Airborne LiDAR for DEM generation: some critical issues. Progress in Physical Geography 32, 31–49.
Lohr, U., 1998. Digital elevation models by laser scanning. Photogrammetric Record 16, 105 –109.
Minasny, B., McBratney, A.B., 2001. A rudimentary mechanistic model for soil production and landscape development II: A two-dimensional model incorporating chemical weathering. Geoderma 103, 161-179.
NGI, 2008. Gescande topografische kaart (opname 2001-2006) 1/100,000, raster. Kaartblad 14.5-14.6.
Schoorl, J.M., Veldkamp, A., Bouma, J., 2002. Modelling water and soil redistribution in a dynamic landscape context. Soil Science Society of America Journal 66, 1610-1619.
Schwartz, F.W., Zhang, H., 2003. Fundamentals of ground water. John Wiley and Sons, New York.
Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long term experiments. Geoderma 81, 153-225.
Stoorvogel, J.J., Antle, J.M., Crissman, C., Bowen, W., 2004. The tradeoff analysis model: Integrated bio-physical and economic modelling of agricultural production systems. Agricultural Systems 80, 43-66.
Thomas, J., 1993. The politics of vision and the archaeologies of landscapes, in: Bender, B. (Ed.), Landscape: Politics and Perspectives. Berg, Oxford, pp. 1-17.
Tilley, C.Y., 1994. A phenomenology of landscape: places, paths, and monuments. Berg, Oxford.
Tilley, C.Y., 2004. The materiality of stone: Explorations in landscape phenomenology. Berg, Oxford.
Van Joolen, E., 2003. Archaeological land evaluation. A reconstruction of the suitability of ancient landscapes for various land uses in Italy focused on the first millennium BC. PhD dissertation. Rijksuniversiteit Groningen, Groningen, pp. 291.
Van Ranst, E., Sys, C., 2000. Eenduidige legende voor de digitale bodemkaart van Vlaanderen. Universiteit Gent, Gent.
Verbruggen, C., Denys, L., Kiden, P., 1996. Belgium, in: Berglund, B.E., Birks, H.J.B., Ralska-Jasiewiczowa, M., Wright, H.E. (Eds.), Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley and Sons, Chichester, pp. 553-574.
Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital elevation model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.
Westcott, K.L., Brandon, R.J. (Eds.), 2000. Practical applications of GIS for archaeologists: A predictive modelling kit. Taylor and Francis, London.
Zidan, Y.O.Y., 2008. Mapping phreatic water tables to update the drainage class map 1:20,000 in the Scheldt Valley near Ghent. Unpublished thesis, Department of Geology and Soil Science. Ghent University, Ghent, pp. 89.

Zvelebil, M., 2003. Enculturation of Mesolithic landscapes, in: Larsson, L., Kindgren, H., Knutsson, K., Leoffler, D., Åkerlund, A. (Eds.), Mesolithic on the Move. Papers presented at the Sixth International Conference on the Mesolithic in Europe, Stockholm 2000. Oxbow Books Ltd., Oxford, pp. 65-73.

Chapter 4
Reconstructing phreatic palaeogroundwater levels

Abstract

The complex discussion on prehistoric settlement decisions is at present no longer tackled from a purely archaeological perspective, but from a more landscape-oriented manner combined with archaeological evidence. Therefore, the reconstruction of several components of the former landscape is needed. Here, we focus on the reconstruction of the groundwater table based on modelling. The depth of the phreatic aquifer influences for example soil forming processes and vegetation type. Furthermore, it directly influences settlement by the wetness of a site. A palaeogroundwater modelling of the phreatic aquifer was executed to produce a series of full-cover maps of the mean water table depth between 10,766 BCE and 1953 CE in Flanders (Belgium). The research focuses on the reconstruction of the input data and boundary conditions of the model and the model calibration. The model was calibrated for the 1924-1953 CE time period using drainage class maps. Archaeological site data and occurrence data of podzols act as proxies for local drainage conditions over periods in the past and served as a control on the simulated phreatic palaeogroundwater levels. Model quality testing on an independent validation dataset showed that the model predicts phreatic water table levels at the time of soil mapping well (ME of 0.018 m; RMSE of 0.66 m). Simulated hydrological conditions were in agreement with the occurrence of archaeological sites of Mesolithic to Roman age at 96% of the validation locations and also with the occurrence of well-drained podzols at 97% of the validation locations.

This chapter is based on Zwertvaegher, A., Finke, P.A., De Reu, J., Vandenbohede, A., Lebbe, L., Bats, M., De Clercq, W., De Smedt, P., Gelorini, V., Sergant, J., Antrop, M., Bourgeois, J., De Maeyer, P., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Reconstructing phreatic palaeogroundwater levels in a geoarchaeological context: a case study in Flanders (Belgium). Geoarchaeology: An International Journal.

4.1 Introduction

It is generally agreed that the human occupation of a region in pre- and protohistoric times was influenced by the landscape, as well as by motivations of a more political, socio-economic and cultural nature (Jordan, 2001; Kamermans, 2006; Thomas, 1993; Tilley, 1994; Zvelebil, 2003). In this light, a more landscape-oriented point of view is often taken to examine the archaeological evidence in its spatial setting. Often however, the current state of the several landscape components deviates from their pre- and protohistoric one. Therefore, reconstructions of the palaeolandscape are needed. Several examples are found in literature that focus on the reconstruction of different landscape components such as hydrology (Gyucha et al., 2011), vegetation (Spikins, 1999, 2000) and topography (Orengo and Fiz, 2008).

The area of interest is situated in the Flanders region in northern Belgium, which is also known as Sandy Flanders because it mainly consists of sandy soils, and is elaborately handled in Chapter 2. The region was subject to extensive and systematic field research during the last decennia, which revealed areas rich in archaeological evidence, as well as void areas. Despite repeated archaeological surveys, the latter areas revealed little or no archaeological evidence (Crombé et al., 2011; Sergant et al., 2009). An interdisciplinary and landscape-oriented approach was suggested to unravel the possible implications for this apparently discontinuous population and exploitation of the region. In this light, a land evaluation based on reconstructed components of the palaeolandscape was proposed (Zwertvaegher et al., 2010; Chapter 3) and various biophysical attractors for occupation, such as suitable places for hunting, fishing, gathering, settlement and agriculture, were listed. These are associated with land qualities that relate to vegetation, soil, elevation, river network hydrology, as well as water table depth. For example, rain-fed agricultural potential production is influenced by moisture and oxygen availability in the soil, which are on their turn dependent on the depth of the groundwater table. Settlement is most probably largely determined by the wetness of a site, which is also affected by the water table depth. Because in geoarchaeological research, data are often limited in spatial and/or temporal sense, process models can be used for the reconstruction of the former state(s) of these landscape components. Such process models mimic the behaviour of a system using equations or decision rules built on knowledge of natural processes (Zwertvaegher et al., 2010). Furthermore, the simulated values from one process model can serve as input for another process model.

The objective of this study is to attempt a reconstruction of the phreatic palaeogroundwater levels for the defined study area in Sandy Flanders from the end of the Late Glacial and comprising the entire Holocene, encompassing a total of 12,720 years, by the use of a groundwater-flow model. This requires the reconstruction of boundary conditions, such as climate and vegetation, hydrological network and topography. The model is calibrated for a 1924-1953 CE period with full-cover observations derived from the soil map. Furthermore, we propose the use of archaeological and podzol evidence as proxies for local drainage conditions over periods in the past to serve as a plausibility check on the simulated phreatic palaeogroundwater levels.

4.2 Methodology

4.2.1 Available data sources

Several sources of information were available for the study region and were used in various steps of the research (Table 4.1). Present-day topographical information was supplied as a high-precision DEM (further called present DEM) constructed by Werbrouck et al. (2011) from high density airborne LiDAR data. Furthermore, artefacts caused by modern objects and infrastructure created since the 19th century were removed providing a DEM useful for historical geographical purposes (Werbrouck et al., 2011; further called post-medieval DEM). Information on texture class, drainage class and soil profile was recorded in the soil map (sampling density of 2 observations per ha). During the soil survey, thousands of profiles were analyzed and collected in the Aardewerk database (Van Orshoven et al., 1988). A more recent mapping of the drainage classes was performed by measurements of the water table in a small part of the study area (Zidan, 2008). Furthermore, the region is rich in historical maps dating between the 16th and 19th century. A total of 80 historical maps of the study area covering a large range of spatial extents and scales, was collected and scanned by the department of Geography of Ghent University. De Keersmaeker et al. (2001) constructed forest-distribution maps for the years 1775 CE, 1850 CE and 1930 CE based on well-documented maps of Ferraris, Vandermaelen and the 3rd edition topographical maps. Furthermore,

Table 4.1 Data used in the phreatic groundwater modelling and associated spatial and temporal resolution and typical errors or confidence levels. HC: high confidence, NR: not relevant.

Dataset	Source	Date	Data type	Resolution		Primary interest	Typical error or confidence
				Spatial	Temp.		
present DEM	Werbrouck et al. (2011)	2001-2004	raster	2 m x 2 m	Table 4.3	topography	<5 cm
post-medieval DEM	Werbrouck et al. (2011)	-	raster	2 m x 2 m	Table 4.3	topography	<10 cm
(pre)historic DEM	-	-	raster	2 m x 2 m	Table 4.3	topography; hydrology	<20 cm
coloured ortophotographs	AGIV	2002	raster	1:12,000	NR	hydrology	HC
soil map	AGIV	1949-1954	raster	1:20,000	NR	topography; calibr. & valid.	70% purity
hydrogeological maps	DOV	2002-2006	raster	100 m x 100 m	NR	hydrogeology	unknown
drainage class map	Zidan (2009)	2008-2009	raster	5 m x 5 m	30 year	calibr. & valid.	61% purity
historical maps	Ghent Univ.	1569-1870	raster	varying	NR	hydrology	unknown
forest-distribution maps	De Keersmaeker et al. (2001)	1771-1778; 1846-1854; 1920-1940	raster	1:20,000	Table 4.3	vegetation; recharge	HC
Flemish Hydrographical Atlas (FHA)	AGIV	1991-2010	vector	1:50,000	NR	hydrology	HC
Quaternary map	AGIV	1993-1999	vector	1:10,000	NR	topography	unknown
archaeological data	Ghent Univ.	1980-ongoing	vector	-	-	calibr. & valid.	HC
meteorological data	Royal Meteorological Institute Belgium	1977-2006	time series	-	1 day	climate; recharge	<1 mm day^{-1}
precipitation & temperature anomalies for central western Europe	Davis et al. (2003) ; Davis (pers. comm., 2008)	12,000 BCE – 1950 CE	time series	-	100 year	climate; recharge	<50 mm y^{-1} <2°C
Aardewerk database	Van Orshoven et al. (1983)	1950-1953, 1963	numerical point data	NR	NR	topography; calibr. &valid.	<10 cm

coloured orthophotographs, Quaternary geological and hydrogeological maps were available on the full extent of the study area. Vector data on the location and classification of the present-day watercourses of Flanders were collected in the Flemish Hydrographical Atlas (FHA). Archaeological data covering the study period were provided by the department of Archaeology of Ghent University. These concerned sites and/or find spots from the Meso- and Neolithic (Sergant et al., 2009), Bronze Age barrows (De Reu et al., 2011a,b) and Late Iron Age and Roman sites (De Clercq, 2009). Daily precipitation and evapotranspiration data in a 30-year time series (1977-2006 CE; from Merendree-Schipdonk and Melle weather stations), a one-year daily temperature series (2005 CE; from Uccle weather station), as well as temperature and precipitation anomalies (12,000 BP–1950 CE) for central western Europe provided by Davis et al. (2003) and Davis (personal communication, 2008) were also used.

4.2.2 Model description

The groundwater heads were calculated using MODFLOW, the three dimensional USGS groundwater model code (Harbaugh and McDonald, 1996) and known as the worldwide standard groundwater flow model, as evidenced by its application in a wide variety of groundwater studies (e.g. Wilsnack et al., 1999; Zhang and Hiscock, 2010; Zume and Tarhule, 2011). For computational reasons, the study area with a spatial extent of 584 km² was divided into 3 subareas (Figure 4.1) whose orientation and location were defined by the general direction of the groundwater streamlines and by large hydrological differences related to geomorphologic features in the landscape. The grid resolution was set at 100 m x 100 m. The temporal extent of the simulations was 12,720 years, starting at the end of the Late Glacial and covering the Holocene (10,766 BCE-1953 CE). Simulations were performed in the steady state mode of MODFLOW due to the large temporal extent of the study period. A temporal resolution of 30 years (i.e. a climatic period; Finke et al., 2004) was used. This resulted in maps of the MWT for a total of 424 simulation periods. The final results, provided as MWT depths below the surface, were constructed by subtracting the model output values (expressed in absolute heights) from the topography. Because topography in the study area varied during the simulated time period, several temporal DEMs were used and reconstructed when not available as an original data source.

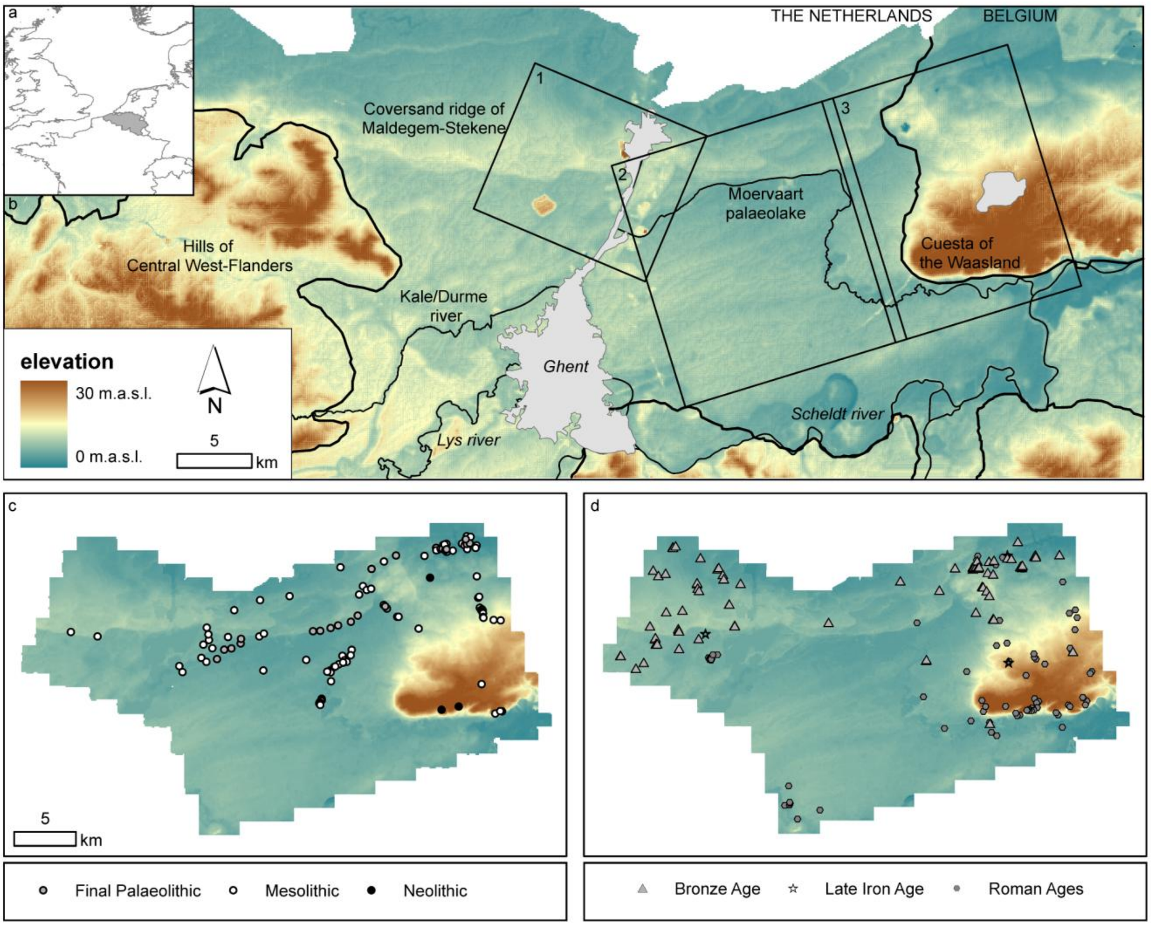

Figure 4.1 a: Indication of the study area (in red) within Belgium; b: Digital elevation model (AGIV, 2008; Werbrouck et al., 2011) showing the three partly overlapping subareas of the groundwater model are indicated with open squares (subareas 1, 2 and 3), several geomorphological units and the extent of the Flemish Valley (bold black line; based on De Moor and Heyse, 1978); c: Final Palaeolithic Federmesser, Mesolithic and Neolithic find spots (Sergant et al., 2009); d: Bronze Age barrows (Early and Middle Bronze Age; De Reu et al., 2011a,b) and Late Iron Age and Roman (De Clercq, 2009) sites. (Other maps used: AGIV, 2002).

Ranges of literature values for hydraulic characteristics of the different geological layers in the area are presented in Table 4.2. The depth of their base was derived from the hydrogeological maps, as provided by the Flemish Subsoil Database (DOV). The information on these layers was conceptualized as input to the groundwater model: the vertical discretisation was set at 15 computational layers of 5 m thickness and for each computation layer transmissivity, proportional to the horizontal hydraulic conductivity, and vertical hydraulic conductance divided by the layer thickness, was calculated. Model boundary conditions, such as the influence of the local hydrological network and the recharge to the groundwater table per simulation period, were reconstructed and supplied to the model via the MODFLOW packages. Furthermore, the drainage of the upper 0.20 m of the soil was also taken into account in accordance with the Dutch nutrient emission model STONE (Kroon et al., 2001). This is especially applicable in regions with shallow groundwater levels. Therefore, a uniform hydraulic conductance of the upper soil was applied to the entire study area.

Table 4.2 Hydrogeology of the study region: variation in lithology, horizontal hydraulic conductivity (Kh) and thickness of several layers in the study area (VMM, $2008_{a,b}$).

Hydrogeology	K_h ($m\ d^{-1}$)	Thickness (m)
Quaternary Aquifer System		
Pleistocene sediments	0.01-30	0-25
Pleistocene of the Flemish Valley		
Campine Aquifer System		
Peilstocene and Pliocene Aquifer		
Sandy top of Lillo	5-18	0-42
Miocene Aquifer System		
Sand of Kattendijk and/or bottom sand layer of Lillo	4-20	0-35
Boom Aquitard	10^{-8}	0-80
Oligocene Aquifer System		
Ruisbroek-Berg Aquifer		
Sand of Ruisbroek	0.03-5	0-20
Tongeren Aquitard		
Clay of Watervliet	10^{-4} - 10^{-5}	0-20
Under-Oligocene Aquifer System		
Clayey sand of Bassevelde	1-5	0-30
Bartoon Aquitard System		**0-50**
Clay of Onderdijke	10^{-4}-10^{-6}	
Sand of Buisputten	10^{-2}-10^{-6}	
Clay of Zomergem	10^{-5}-10^{-6}	
Sand of Onderdaele	0.2-1.7	
Clays of Ursel en/of Asse	10^{-6}-10^{-8}	
Ledo-Paniselian Brusselian Aquifer System		
Wemmel-Lede Auifer	0.6-3	0-30
Sand of Wemmel		
Sand of Lede		
Sand of Brussel	6	0-15
Sediments of the Upper-Paniselian	3	0-45
Sands of Aalter and/or Oedelem		
Sandy clay of Beernem		
Sandy sediments of the Under-Paniselian	0.8-6.7	0-30
Paniselian Aquitard System		**0-30**
Clay of Pittem	0.01-1	
Clay of Merelbeke	0.003	

4.2.3 Reconstructing model input and boundary condtions at the temporal extent of the study period

4.2.3.1 Topography

A modified assessment of the topography was applied for 3 different time periods (Table 4.3) called the present, post-medieval and (pre)historic DEM. The latter DEM is an adjustment of the post-medieval DEM in which plaggen soils and marine and alluvial Scheldt deposits were removed. Plaggen management was locally introduced in the Early Middle Ages and became a general management type in medieval times (van Mourik et al., 2012). Sods of heath and/or forest litter were applied in the stables as fresh animal bedding and at times, was spread out on the arable fields and served as manure (FAO, 2001). Average plaggen soil thickness in the study area was estimated at 0.40 m based on soil profile information from the Aardewerk database (Van Orshoven et al., 1988). The post-medieval DEM was stripped off this predefined amount in the areas with recorded plaggen soils on the soil map. Due to the nature of the evidence, the exact depth and the location of the plaggen extraction zones are generally not provided in literature. It is generally assumed that some 10 ha of heath land were needed to maintain the nutrient level of 1 ha of arable land (FAO, 2001). Based on these arguments (unknown location of the extraction sites and relatively low volume-to-surface ratio in the extraction areas), a positive correction (i.e. adding heights) for the extraction areas was not applied in the reconstruction of the (pre)historic DEM.

For areas affected by marine influence originating from storm surges and accompanying flood events from the 13th century onward (northern part of the area; Baeteman, 2006) or late medieval Scheldt influence (northeastern part of the area; Crombé, 2005; Soens, in press), the depth to the pre-alluvial material was derived from information books accompanying the soil map and their location was derived from the Quaternary geological map. The post-medieval DEM was stripped off this amount at the defined locations. Because the Holocene is considered a relative geomorphologically stable period this (pre)historic DEM was assumed representative for the time previous to 1114 CE. All DEMs were used at the same resolution of the groundwater model (100 m x 100 m).

Table 4.3 Reconstructed model input and corresponding time periods in the modelling.

Start year	End year	Topography	Vegetation	Recharge	Hydrology	Ditches	C_{DRAIN}
10,766 BCE	1113 CE	(pre)historic DEM	varying in time (Figure 4.1), spatially uniform	30-year averaged time series, spatially uniform	(pre)historic network, model parameters from 1924-1953 CE calibration period	-	spatially uniform, value calibrated on archaeological and recorded podzol evidence
1114 CE	1803 CE	post-medieval DEM	deciduous forest, grassland and shrubs	30-year averaged time series, spatially non-uniform	present network (FHA), model parameters from 1924-1953 CE calibration period	spatially uniform, model parameters from 1924-1953 CE calibration period	spatially uniform, value from 1924-1953 CE calibration period
1804 CE	1923 CE	present DEM					
1924 CE	1953 CE						

4.2.3.2 Hydrological network

Watercourses in the model were classified in 5 classes according to the size of their drainage area and following the legislative classification of watercourses as recorded in the FHA. River model parameters, such as water level, elevation of the bottom of the riverbed and hydraulic conductance of the riverbed material, were given a fixed value per class. Variable values were used for the class with navigable watercourses, the width was measured from coloured orthophotographs at several points along the course; water level (a fixed mark controlled by sluices) and water depth (taken as 0.5 m below the maximum allowed ship draught) were conducted from the statutory demands (NGI, 2006). Drainage of excess water is nowadays mostly performed by pipes, but for the pre-1950 period the pipes were absent. A network of artificial ditches served a two-fold function: drainage of excess water on the one hand, and re-introduction of water towards the groundwater on the other hand. Ditches were taken into account from 1114 CE onwards (Table 4.3). Depth (0.9 m below surface) and water level (0.05 m) in the ditches in the model was chosen based on a pilot study (Flemish Government Report, 2001).

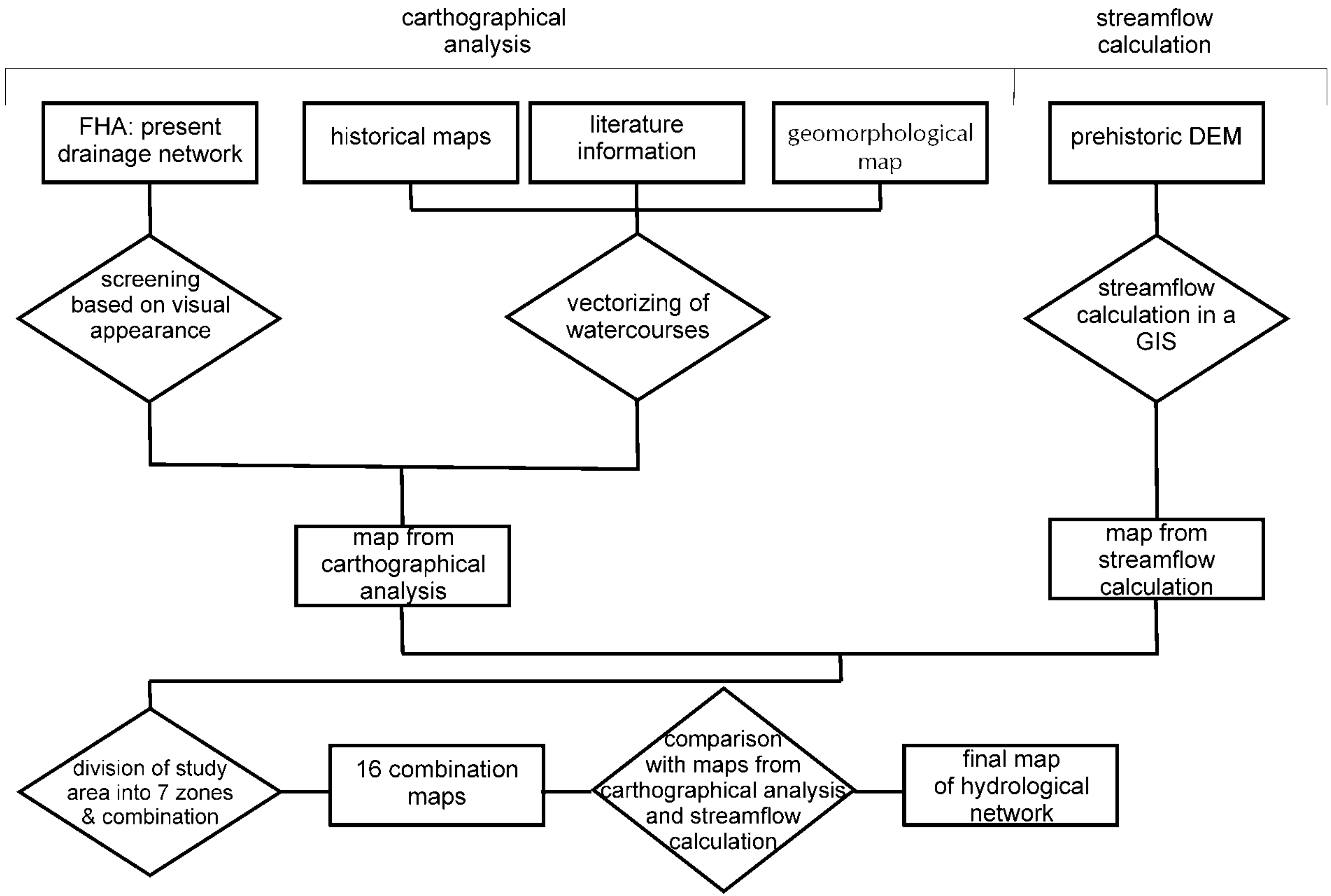

Figure 4.2 Flowchart of the hydrological network reconstruction based on cartographical analysis and streamflow calculation.

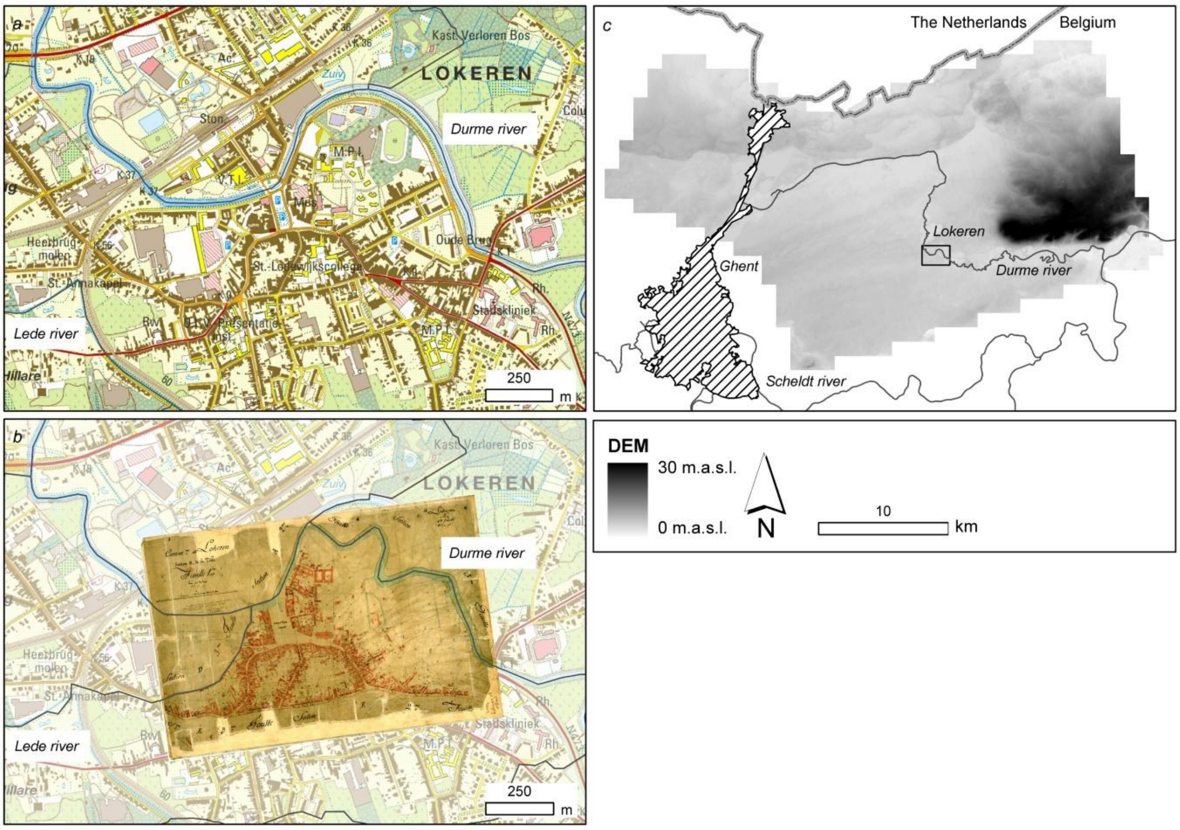

Figure 4.3 Man-made modifications of the river Durme at the city of Lokeren. a: The topographical map of Lokeren (scale 1:10,000; NGI, 2009) with indication of the present-day rivers Durme and Lede; b: Land register map from the 19th century (NGI, 2003), with indication of the former course of the rivers Durme and Lede; c: The Durme river (AGIV, 2002) and the city of Lokeren located on the DEM (AGIV, 2008; Werbrouck et al., 2011) of the study area.

The location of the present-day watercourses was taken from the FHA. However, existing watercourses were modified and new canals were constructed during the past decades, resulting in a present-day river network strongly deviating from the natural system present during prehistoric times. Therefore, a reconstruction of this natural system was conducted based on a two-fold analysis: a cartographical analysis and a streamflow calculation, both executed in a GIS. The workflow is presented in Figure 4.2. In the cartographical analysis the present-day hydrological network as recorded in the FHA, was classified into straight/unnatural and curving/natural looking waterways in a GIS based on a visual screening. Georeferencing of the historical maps was executed whenever possible, although in most cases this was not feasible and a rough localization of the watercourses was performed based on the available place names. A total of 61 separate waterways located inside the study area were vectorized on the historical maps. The added value provided by the historical maps was especially situated in the geographical reconstruction of reaches in a GIS, which are nowadays hidden underground (especially in urban areas), or which are in disuse due to straightening and

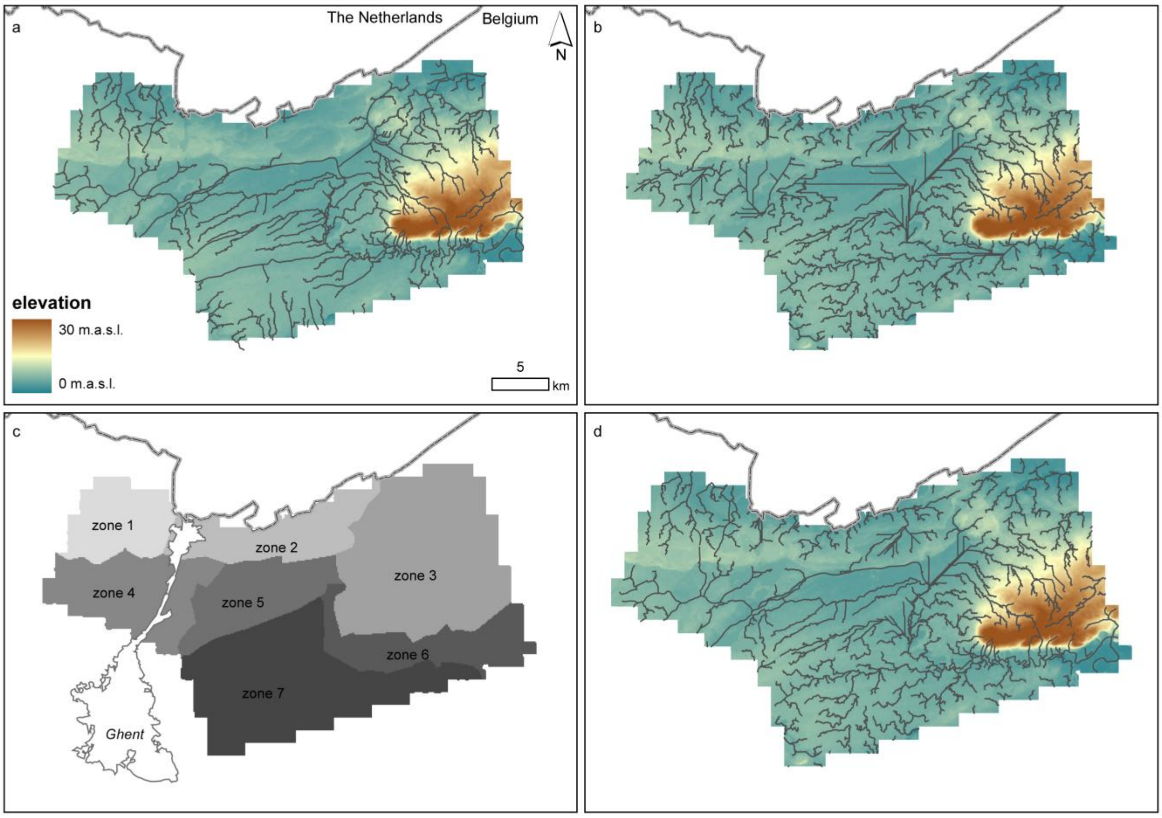

Figure 4.4 a & b: Maps of the hydrological network based on the cartographical analysis and streamflow calculations, respectively; c: Division of the study area into 7 zones; d: The final map of the hydrological network. All river networks are displayed on top of the DEM of the study area (AGIV, 2008; Werbrouck et al., 2011).

canalizing (Figure 4.3). By combining this with vectorized watercourses from the geomorphological map of the study area (De Moor and Heyse, 1994; georeferenced in a GIS) a preliminary map of the hydrological network was constructed (Figure 4.4a). The streamflow calculation was based on the method presented by Jenson and Domingue (1988) in which stream models are generated starting from topographical data as provided by a DEM (Figure 4.4b). In this case the (pre)historic DEM was used.

The map derived from the cartographical analysis (Figure 4.4a) shows a large area containing no watercourses as a result of the visual screening. Furthermore, the map conducted from the streamflow calculation (Figure 4.4b) reveals straight, unnatural watercourses due to flat surfaces in the DEM restricting the streamflow algorithm. Therefore, new maps of the drainage network were created as unique combinations of the constructed networks of the cartographical analysis and streamflow calculation. The study area was divided in 7 zones based on the geomorphology and hydrology of the region to limit the number of combinations (Figure 4.4c). Hence, instead of combining each watercourse from both analyses separately, only the watercourses per zone were combined. The combination with the highest sum of overlapping cells with the maps (upscaled to 100 m x 100 m) from the cartographical analyses and streamflow calculation, was assumed to represent the (pre)historic drainage network (Figure 4.4d; Table 4.3). River model parameters for the (pre)historic network were indirectly allocated through the classification. Rivers acquired from the cartographical analysis inherited their present-day category, but watercourses derived from the streamflow calculation were manually classified.

4.2.3.3 Recharge as a function of changing climate and vegetation type

Daily values of the recharge to the groundwater table were calculated with a modified Thornthwaite-Mather function, taking the daily precipitation (P), potential evapotranspiration (ET_0), runoff (RO), canopy interception (I), and change in soil-water content (dSW) into account (Equation 1; Steenhuis and Van Der Molen, 1986; Thornthwaite and Mather, 1955, 1957).

$$Recharge = P - ET_0 - RO - I - dSW \qquad \text{Equation 4.1}$$

Afterwards, the daily values were averaged over 30-year intervals and input into the model. The series of the daily precipitation and daily evapotranspiration were obtained following the methodology described in Finke and Hutson (2008). Annual precipitation and temperature anomalies for central western Europe and covering the entire study period in 100-year intervals, generated from quantitative palynological analysis following the methodology of Davis et al. (2003) were provided by Davis (personal communication, 2008). By adding current annual values from Merendree-Schipdonk and Uccle to the precipitation and temperature anomalies, local series were obtained. Afterwards the 100-year intervals were linearly interpolated to produce continuous series of yearly values. The daily series were calculated by rescaling a standard record of daily values from the weather station so that annual sums of daily values matched the yearly values. This daily temperature series was then used in the equation of Hargreaves and Samani (1985) to calculate daily potential evapotranspiration for 51° N. Yearly values of potential evapotranspiration measured at the weather station of Melle were used to rescale daily potential evapotranspiration values to match the yearly sum.

The temporal sequence of vegetation types in the study area was based on the work of Verbruggen et al. (1996), who defined the regional vegetation development for northern and middle Belgium, encompassing the study area. For modelling purposes, these defined vegetation types were conceptualized in 3 vegetation classes: grassland and shrubs, deciduous forest and coniferous forest (Figure 4.5; Table 4.3). The vegetation was assumed to be uniformly present over the entire study area. Only for more recent times, a heterogeneous distribution of the vegetated surface was imposed (Figure 4.6; Table

4.3): forest versus grassland and shrubs. This was based on the forest-distribution maps of De Keersmaeker et al. (2001). In general, runoff and canopy interception, needed in the recharge calculation, are described as fractions of the precipitation and are related to the vegetation type. The runoff on vegetated surfaces was assumed negligible (Batelaan, 2006) and applied likewise in the modelling. The canopy interception was set at 0%, 8% and 12% of the precipitation, for grassland and shrubs, deciduous forest and coniferous forest respectively, based on the work of Bouten (1992) and Finke (2012a).

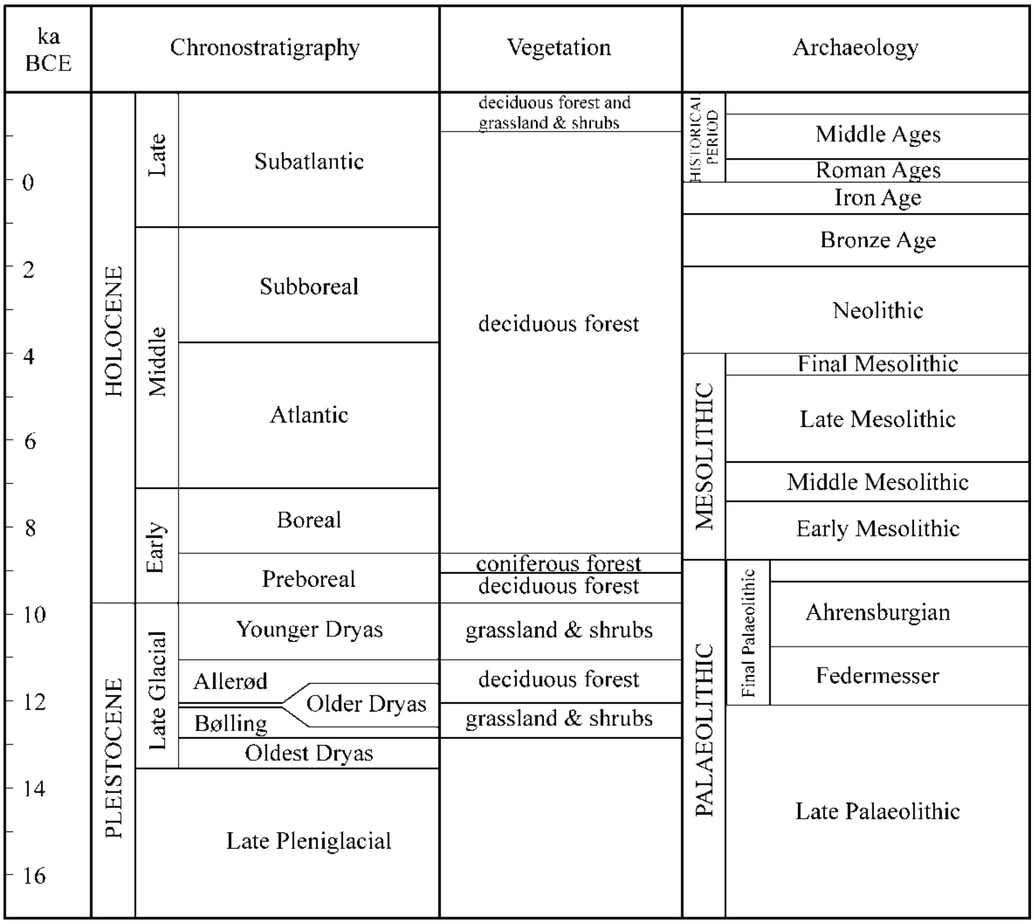

Figure 4.5 Time table listing the chronostratigraphical units and archaeological periods of the last 20 ka. Ages are expressed in ka BCE. Chronostratigraphy of the Holocene is based on Terberger et al. (2006); the subdivision of the Pleistocene is based on radiocarbon dated pollen diagrams for the Netherlands, as revised by Hoek (2001). The time frame of the archaeological periods is expressed for the situation in Sandy Flanders. Note that at present, no traces of the Late Palaeolithic and Ahrensburgian cultures have been reported in Sandy Flanders (Crombé et al., 2011; Crombé and Verbruggen, 2002). The vegetation type as applied in the model is also indicated.

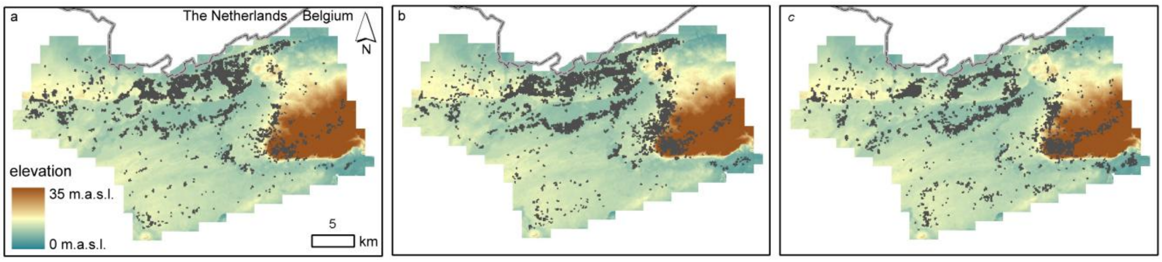

Figure 4.6 Distribution of the forested areas (in grey) in the study area for three different periods based on the research of De Keersmaeker et al. (2001). a: 1114-1803 CE; b: 1804-1923 CE; c: 1924-1983 CE.

4.2.4 Model calibration

Information on prehistoric phreatic groundwater levels is practically inexistent in literature, and whenever present, it is in most cases of indirect and dispersed nature, such as the presence of groundwater-fed peat marshes or wells found at archaeological sites. However, only few traces of peat are found the area and information on the extent, thickness and age are often lacking. Furthermore, wells only mark the presence of the water table within a certain range between the surface and the bottom of the well. Therefore, the model was calibrated in a two-step approach. Firstly, the 1924-1953 CE period was calibrated based on comparison with calculated MWT depths and secondly, a control and extra calibration on the entire period was performed by comparison with archaeological and recorded podzol evidence.

For the 1924-1953 CE period observations on the MWT depth were derived from the soil map drainage classes. At the time of mapping, drainage pipes were absent, hence this mapped state is the best recorded representation of the natural state. Each drainage class is related to a MHWT and MLWT, expressed as a range of depths below the surface (Ameryckx et al., 1995; Van Ranst and Sys, 2000; Table 4.4). For each drainage class, a mean value for the MHWT and MLWT depth was calculated, and the average of both served as the value for the MWT depth. As the augering depth during the soil survey was limited to 1.25 m below surface (Van Ranst and Sys, 2000), the lower bound of some classes was not recorded. The missing information was completed with data from a more recent soil drainage class remapping project in the study area (Zidan, 2008). The uncertainty on the calculated MWT depths was calculated based on the assumptions that the MHWT and MLWT depths were normally distributed with a cumulative probability of 70% between the upper and lower bounds. The value of 70% was derived from Dent and Young (1981) concerning the mapping quality of soil surveyors. Using the Z-score, the variance on both MHWT and MLWT depths was computed. The standard deviation on the MWT depth was taken as the square root of the average of both variances (Table 4.4). The resulting full-cover dataset of MWT depths was randomly split into a calibration and a validation set in a 70/30 ratio (Figure 4.7). However, in 19.4% of the area, the MWT depth could not be reconstructed. This is due to urban areas at the time of soil mapping, but also because of the highly industrialized region around the Canal of Ghent-Terneuzen. Furthermore, at the southern border of the Cuesta of the Waasland the MWT depths based on data from the pilot area with a recent drainage class mapping (Zidan, 2008), deviated largely from MWT depth values as calculated in time-series analyses on present-day local measurements (Finke et al., 2010).

Table 4.4 Texture and drainage classes with their MHWT and MLWT depth ranges after Ameryckx et al. (1995), as well as their computed mean MHWT depth, mean MLWT depth, MWT depth and standard deviation (σ) on the calculated MWT depth. All depths as cm below surface. ZSP: texture class of sand (Z), loamy sand (S) and light sandy loam (P); ALEU: texture classes of silt (A), silt loam (L), clay (E) and heavy clay (U); a: excessively drained; b: good drainage; c: moderate drainage; d: insufficient drainage; e: moderately poor drainage; f: poor drainage; g: very poor drainage; h: moderately poor drainage and perched water tables; i: very poor drainage and shallow perched water tables. NP: not present in the study area.

Text. class	Drain. class	MHWT depth range	mean MHWT depth	MLWT depth range	mean MLWT depth	MWT depth	σ_{MWT} *(cm)*	σ_{MWT} *(% MWT depth)*
ZSP	a	> 125	194.4	> 125	246.6	220.5	100.2	45.4
	b	90 - 120	105.0	> 125	182.2	143.6	43.6	30.4
	c	60 - 90	75.0	> 125	157.1	116.0	27.3	23.5
	d	40 - 60	50.0	> 125	140.5	95.3	15.6	16.3
	e	0 - 120	60.0	100 - 120	110.0	85.0	41.5	48.8
	f	0 - 100	50.0	50 - 100	75.0	62.5	38.1	61.0
	g	0 - 50	25.0	0 - 50	25.0	25.0	24.1	96.4
	h	20 - 40	30.0	> 125	128.7	79.3	9.0	11.4
	i	0 - 20	10.0	> 125	121.9	66.0	6.9	10.5
ALEU	a	> 125	NP	> 125	NP	NP	NP	NP
	b	> 125	NP	> 125	NP	NP	NP	NP
	c	80 - > 125	92.5	> 125	168.3	130.4	34.0	26.1
	d	50 - 80	65.0	> 125	139.2	102.1	16.6	16.3
	e	0 - 120	60.0	80 - 120	100.0	80.0	43.1	53.9
	f	0 - 80	40.0	40 - 80	60.0	50.0	30.5	61.0
	g	0 - 40	20.0	0 - 40	20.0	20.0	19.3	96.4
	h	20 - 50	35.0	> 125	125.4	80.2	10.9	13.6
	i	0 - 20	NP	> 125	NP	NP	NP	NP

The calibration of the 1924-1953 CE time period was conducted on the following model parameters: the hydraulic conductance of the riverbed, the hydraulic conductance of the upper 0.20 m of the soil surface, the transmissivity, and the vertical hydraulic conductivity divided by the thickness of the layers. Only the 5 upper computational layers (up to 25 m deep) were taken into account during the calibration, since the influence of deeper layers on the phreatic groundwater table appeared to be negligible. This was executed in a manual iterative approach in which the calibration parameters were adjusted and evaluated by comparing the MWT depths based on the drainage-class map ($MWT_{i,m}$) with the simulated MWT depths ($MWT_{i,c}$) at locations i, based on quantitative error measures (Equation 2-4): root mean square error (RMSE), mean error (ME) and mean absolute error (MAE).

$$RMSE = \sqrt{1/n\sum_{i=1}^{n}(MWT_{i,m} - MWT_{i,c})^2}$$
Equation 4.2

$$ME = 1/n\sum_{i=1}^{n}(MWT_{i,m} - MWT_{i,c})$$
Equation 4.3

$$MAE = 1/n\sum_{i=1}^{n}\left|MWT_{i,m} - MWT_{i,c}\right|$$
Equation 4.4

The final parameter values for the 1924-1953 CE calibration period, were then used in the simulations for the entire study period. However, through time, land use and land management have changed (for example the loss of forested area due to the expansion of built-on and cultivated land, or the presence of ditch networks, not existing in prehistoric times). Therefore, it was concluded that a further calibration of hydraulic conductance of the upper 0.20 m of the soil surface (C_{DRAIN}) was necessary in relation to the presence of archaeological findings (e.g. Gyucha et al., 2011). In this research we used Meso- and Neolithic find spots, Bronze Age barrows, Late Iron Age and Roman Age sites, and recorded podzol locations. All sites belonging to one archaeological period were split randomly into a calibration (70%) and validation (30%) dataset, to ensure that each of these archaeological periods was represented. Afterwards, final calibration and validation datasets (Figure 4.7) were produced by combining the separate sets. Assuming that the difference between MHWT and MWT, as recorded at the time of soil mapping, was the same in prehistoric times, the MHWT at the archaeological sites was calculated from the simulated MWT. The number of archaeological sites at which a calculated MHWT was below surface served as a criterion in this prehistoric calibration. The adjustment of C_{DRAIN} was performed with a fixed amount in a manual iterative procedure and stopped when the change in number of sites meeting the criterion was below 0.3%.

The presence of podzols served as a second control on the prehistoric simulated water tables. Point locations with well-developed podzols (marked Bh and Bhs horizons) were collected from the Aardewerk database. This dataset was randomly split into a calibration and validation part, containing 70% and 30%, respectively, of the recorded podzol profiles (Figure 4.7). These locations were then evaluated according to the following criterion: MLWT must be lower than the bottom of these B-horizons for at least 1,500 years (Jacques et al., 2010). This was based on the reasoning that clearly recognizable podzol-Bh(s) horizons will have formed in profile parts that are above the water table at least part of the year. Based on the assumption that prehistoric MLWT equally deviated from the MWT, as during the time of soil mapping, this difference was calculated and subtracted from the simulated MWT to obtain a value for the MLWT. The calibration was performed by only adjusting the parameter C_{DRAIN} with a fixed amount, in a manual iterative approach. The final value for C_{DRAIN} was chosen for which no change in number of sites with recorded podzols occurred for several iterations.

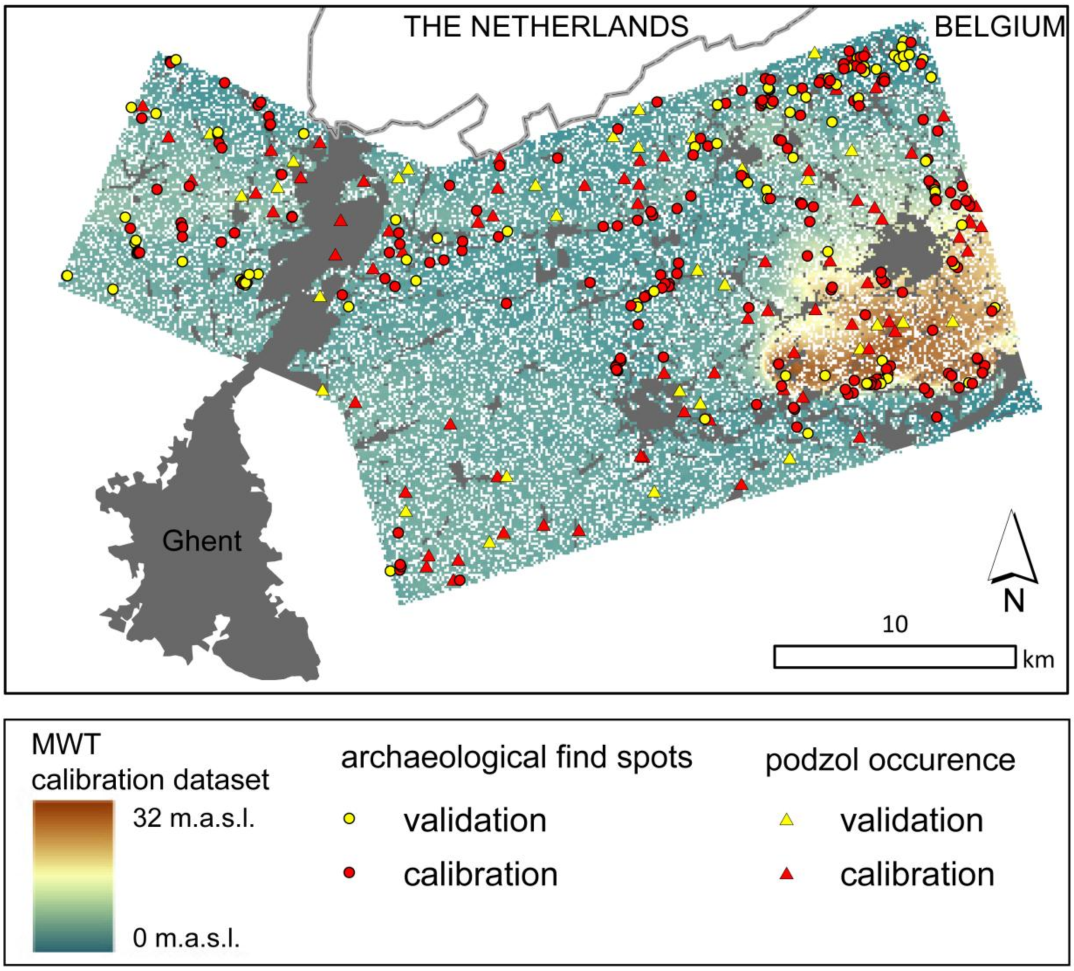

Figure 4.7 Calibration (in colour scale) and validation (in white) dataset of the MWT observations (m.a.s.l.), calculated based on the drainage class map. Calibration and validation dataset of the recorded archaeological sites and podzols.

4.3 Results and discussion

4.3.1 Uncertainties in the reconstructed boundary conditions and model limitations

Input errors affect the initial state of the model and the model boundary conditions along the time period covered with the simulations. Ideally, this uncertainty is estimated via uncertainty analysis, however when time variant boundary conditions and associated uncertainties are present, this becomes extremely complex (Finke, 2012b) and is therefore not applied in this research. An initial estimation of the model quality is therefore provided by listing the uncertainties of the various (reconstructed) model inputs (Table 4.1).

The LiDAR data have a planimetric accuracy in the order of 0.50 m and an altimetric accuracy ranging from 0.07 m on a concreted surface to 0.20 m on vegetation cover (Werbrouck et al., 2011) at point scale. The accuracy of the present DEM is better than the one from the LiDAR data as errors level each other out partly during the upscaling. This planimetric accuracy is also applicable for the post-medieval and (pre)historic DEM. Of course, due to the filtering of anthrophogenic artefacts and subsequent interpolation during the creation of the post-medieval DEM, small errors in the elevation values could have been induced. We assume these to be lower than 0.20 m. Especially embankments around rivers remain regions of higher uncertainty. Nowadays, due to silting up, the river Durme has a higher elevation than its surroundings. Areas where vectorized contours of historical maps were used in the interpolation, have a minimum accuracy of 1 m, which is the maximum equidistance between the contours. Furthermore, agricultural and construction activities in the study area, have levelled the terrain and largely removed previous micro-topography. However, the use of 100 m x 100 m grid cells largely averages out these local height differences and averaged errors are small. Plaggen depths and depths to pre-alluvial sediments were derived from the Aardewerk database and other information collected during the national soil survey campaign. We believe the recorded depths are accurate at 0.10 m. Furthermore, it was noted that the location of plaggen extraction sites is often unknown, while the extraction areas were generally much larger than the application areas (FAO, 2001). Therefore, this uncertainty is estimated at 0.05 m. Streamflow calculations on a DEM in a GIS are commonly executed in the reconstruction of hydrological networks (e.g. Colombo et al., 2007; Mandlburger et al., 2011). However, knowledge on hydrological palaeocharacteristics is scarce and there has been conducted very little research on the effect of climate change on the relationship between surface waters and aquifers that are hydraulically connected (Alley, 2001).

The most southern extension of the Holocene peat was assumed to lie to the north of the study area (Verbruggen and Semey, 1993). Therefore, it was not taken into account in the DEM and groundwater table reconstructions. De Muynck (1976) mentions the possible occurrence of small peat-filled depressions lying more to the south. Because of their limited extent, they were assumed to be of no influence on the DEM and the hydrological model. The presence of a 0.5 m thick peat deposit at one location in the eastern part of the Moervaart Depression is attested by Crombé et al. (in review). Its base is possibly dating to the transition of the Allerød to the Younger Dryas. There are indications of peat extraction in this area from the 12th century onwards (Jongepier et al., 2011). Currently more information on its extent, thickness and age are lacking. Therefore, this peat was not taken further into account. Late Glacial/Early Holocene sand drifting occurred in the study area causing the formation of dunes. These are taken into account, although they only cover 1.3% of the study area. Late-Holocene sand drifting has occurred as well. This was often a displacement of the top of a Late Glacial/Early Holocene dune towards its base (Verbruggen, 1971). Because it concerns very local displacements, these were not taken into account.

It was concluded by Davis et al. (2003) that the effect of non-climatic and local climatic factors on their methodology to reconstruct temperature anomaly series was limited. Their evaluation was based on internal consistency and agreement with other proxy records provided in literature. Concerning the precipitation anomalies, this conclusion is assumed applicable as well since the reconstruction was performed following the same method. The anomalies were adjusted to local conditions, based on present-day meteorological measurements with high accuracy. Ideally, series calculated from proxies on more local samples could lead to a refinement of the recharge data. Unfortunately, such climatic series are not yet available for the study area. The errors of the reconstructed yearly precipitation and evapotranspiration were estimated both less than 50 mm and the errors of the reconstructed January and July temperatures are less than 2 °C (Zwertvaegher et al., 2010). Canopy interception values found in literature cover a broad range depending on for example forest density, tree species, season, rainfall intensity and wind speed (Herbst et al., 2008; Hörmann et al., 1996; Price and Carlyle-Moses, 2003). This of course, also influences the recharge reconstruction. As a check, calculated recharge for the period 1954 to 1983 was compared to the present average value for Flanders (VMM, 2006): with 216.8 mm yr^{-1} and 222 mm yr^{-1}, respectively, these values are of comparable order.

The reconstructions limit the length of the study period. The Late Glacial is known as a highly dynamical period, for which intense aeolian phases with cover sand deposition and erosion (Crombé et al., in press; Derese et al., 2010; Kasse et al., 2007) and large modifications in the river systems are recorded (De Smedt et al., in press). Therefore, the study period only started at the very end of the Late Glacial, mainly focusing on the Holocene. The latter is known as a geomorphologically stable period.

4.3.2 Model quality

It must also be clear that the model, even after calibration, is not free from error. This starts with the observations compared to which the model is calibrated. Especially for drainage classes representing moderately poor to very poor drainage conditions, the standard deviation on the MWT depths, derived from the drainage classes in the soil map, is near to or more than 50% (Table 4.4). However, they only cover a small part of the study area.

Model quality for the 1924-1953 CE time period is expressed as quantitative error measures as ME, MAE and RMSE (Table 4.5). The calibration and validation results are strongly comparable. The ME is close to zero, in the order of several cm. The RMSE is in the range of several dm. Figure 4.8 graphs the MWT values based on the drainage-class map and the simulated values of the MWT for the 1924-1953 CE time period at the calibration locations (R^2=0.98). Especially for increasing values, the deviation between simulated values and values obtained from the drainage-class map, increases. This can be related to erroneous simulated MWT values in the region of the Cuesta of the Waasland (indicated as subarea 3, Figure 4.1b), or due to erroneous values in the calculated MWT observation dataset based on the mapped drainage classes, in the same region. The latter could relate to the fact that data from the recent drainage-class mapping in the pilot area, used to complete the missing information in the construction of the MWT observation dataset, would not be applicable to this cuesta area (subarea 3). Furthermore, the calibration of the prehistoric MWTs was based on adjusting the C_{DRAIN} in function of the percentage of archaeological sites and recorded podzol locations meeting a fixed criterion. The number of calibration sites meeting the criterion at the final C_{DRAIN} is above 96% (Table 4.5). The number of accepted validation sites is even slightly larger than for the calibration sites, this is true for both the archaeological sites as for the locations with recorded podzols. It is possible that non-accepted sites probably lie within a heterogeneous area (archaeological/recorded podzol site on higher grounds surrounded by lower grounds). Such detail can be lost due to the resolution (100 m x 100 m) of the modelling. Downscaling the maps of the MWT depths to a higher resolution can possibly give even better results. This is however, yet to be tested

4.3.3 Spatial and temporal variations in MWT depth

The output of the phreatic palaeogroundwater modelling consists of a series of full-cover maps of the MWT depth, encompassing the entire study period. The temporal evolution of the MWT depth (Figure 4.9a) reflects generally the calculated recharge (Figure 4.9b), and hence the climate. Towards the very end of the Younger Dryas and during the Preboreal and Boreal, mean water table levels became more shallow. The transition between the Boreal and Atlantic is characterized by an increase in the MWT depth, but from the Atlantic onwards, the MWT remains at a fairly constant level. The influence of the present-day drainage system and land use is reflected by an increase in MWT depth from 1114 CE onwards. Likely within-year fluctuations, indicated by MHWT and MLWT depths (Figure 4.9Figure 4.9a), are calculated from the simulated MWT depths. This calculation was based on the assumption that their deviation from the MWT depth in previous times equals the difference with the MWT depth, as recorded at the time of soil mapping.

Table 4.5 Model performance for the 1924-1953 CE calibration period: mean of the simulated MWT depth (mean) and standard deviation (σ). ME, MAE and RMSE based on the simulated MWT depths and the MWT depths at the calibration and validation locations (calculated based on the drainage class map). No of locations (%) of the calibration and validation datasets of archeological sites and well-drained podzols meeting the criteria after the prehistoric calibration of CDRAIN. Location of subareas 1-3 is indicated on Figure 4.1b.

				entire area	subarea 1	subarea 2	subarea 3
MWT depth	All data	mean	m	1.119	1.098	0.904	1.377
		σ	m	0.957	0.575	0.435	1.407
	Cal.	ME	m	0.012	-0.013	0.110	-0.077
		MAE	m	0.439	0.354	0.301	0.661
		RMSE	m	0.660	0.484	0.398	0.939
	Val.	ME	m	0.018	-0.006	0.117	-0.070
		MAE	m	0.437	0.350	0.302	0.656
		RMSE	m	0.656	0.488	0.397	0.931
Archaeological sites	Cal.	no of sites meeting a fixed criterion	%	92.42	-	-	-
	Val.		%	96.28	-	-	-
Recorded podzol locations	Cal.		%	90.79	-	-	-
	Val.		%	96.88	-	-	-

4.3.4 Spatial and temporal variations in MWT depth

The output of the phreatic palaeogroundwater modelling consists of a series of full-cover maps of the MWT depth, encompassing the entire study period. The temporal evolution of the MWT depth (Figure 4.9a) reflects generally the calculated recharge (Figure 4.9b), and hence the climate. At the start of the Younger Dryas, the depth of the MWT increases to reach its minimum around the middle of the Younger Dryas, climbing to higher phreatic groundwater levels throughout the Preboreal and Boreal. The transition between the Boreal and Atlantic is characterized by an increase in the MWT depth, but from the Atlantic onwards, the MWT remains at a fairly constant level. The influence of the present-day drainage system and land use is reflected by an increase in MWT depth from 1114 CE onwards. Likely within-year fluctuations, indicated by MHWT and MLWT depths (Figure 4.9a), are calculated from the simulated MWT depths. This calculation was based on the assumption that their deviation from the MWT depth in previous times equals the difference with the MWT depth, as recorded at the time of soil mapping.

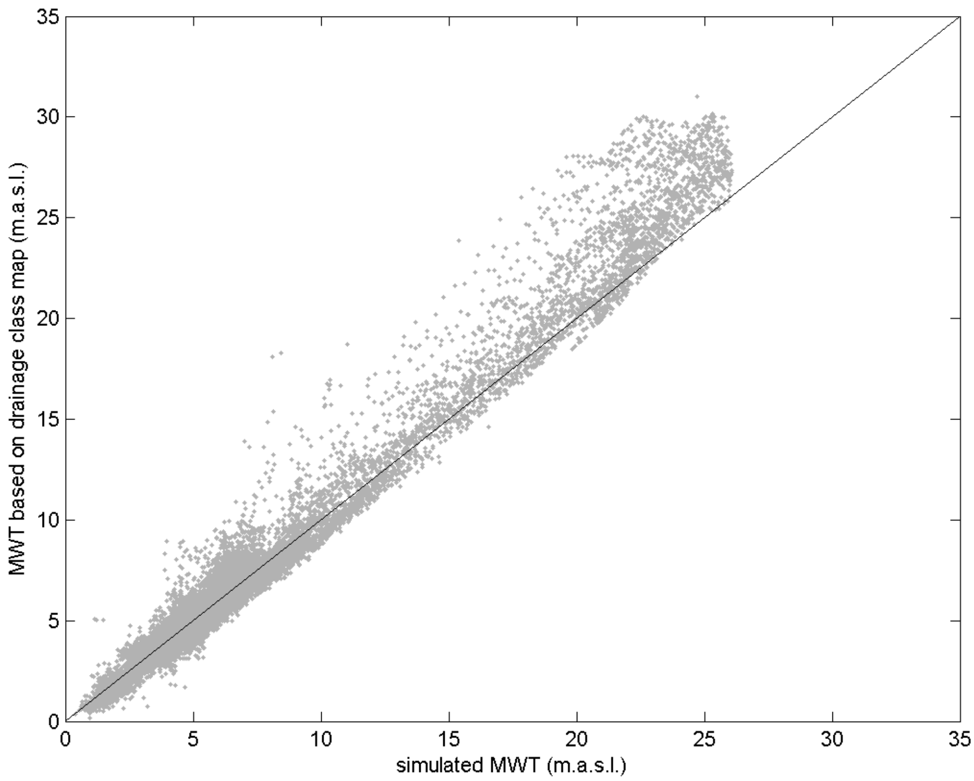

Figure 4.8 MWT values calculated based on the drainage class map (m.a.s.l.) versus simulated MWT values at the locations of the calibration dataset (grey dots). Black line: line of perfect agreement.

The full-cover maps of the MWT depth show a dry situation in practically the whole area in the Younger Dryas (Figure 4.10). The average MWT depth in the region is deeper than 1.20 m. Still, just at the southern border of the cover sand ridge, a slightly wetter area remains (average MWT depth between 0.20 and 0.60 m). From the Younger Dryas, over the Preboreal to the Boreal, a decrease of the phreatic water table depth is found. The cover sand ridge persists as a dry region in the landscape, bordered to its south by a small area with shallow groundwater tables. In the south an area occurs where, especially from the Boreal onwards, both shallow and deep groundwater tables are present within very short mutual distance. This region is characterized by small parallel ridges and depressions as the remainders of a braided river system. For the rest of the Holocene, the MWT depth is rather constant, as is the climate influencing the recharge. However, if deforestation and reforestation history between Bronze and Middle Ages would be known, this implementation in the modelling would probably have resulted in (non-forested) areas with higher water tables due to lower interception. Because of the implementation of drainage ditches, the 1950 CE situation (Figure 4.10d) is slightly drier compared to the prehistoric periods, especially in the lower lying areas.

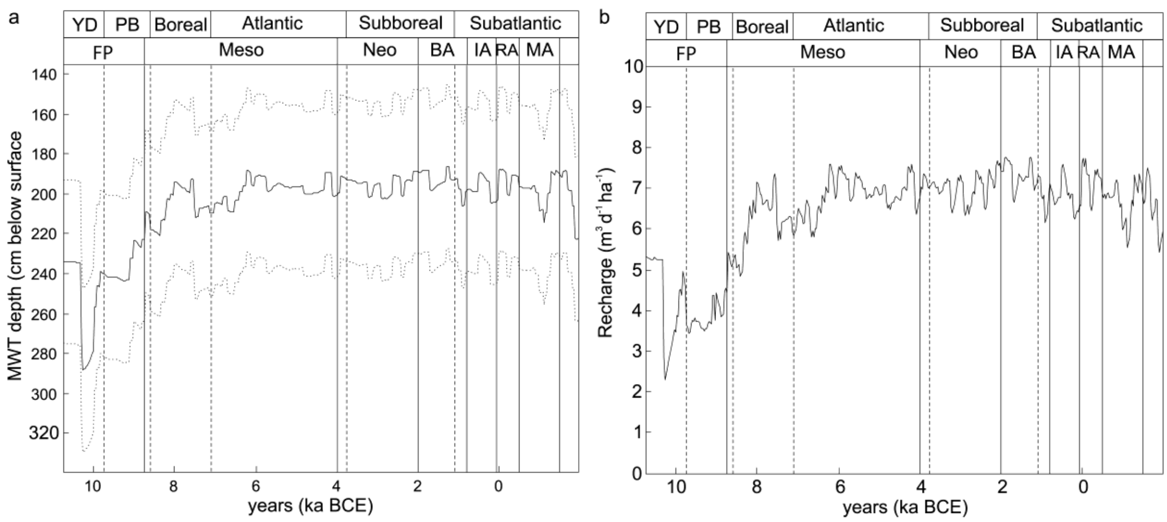

Figure 4.9 a: Time series of the simulated MWT depth (solid line) for a location on the cover sand area. Calculated MHWT and MLWT depths are also indicated as upper and lower dashed lines. b: Time series of the calculated recharge (m^3 d^{-1} ha^{-1}). Chronostratigraphical (dashed vertical lines) and archaeological periods (as defined for Sandy Flanders; solid vertical lines) are indicated on top of each graph: YD: Younger Dryas; PB: Preboreal; FP: Final Palaeolithic; Meso: Mesolithic; Neo: Neolithic; BA: Bronze Age; IA: Iron Age; RA: Roman Ages; MA: Middle Ages.

4.3.5 MWT in a geoarchaeological context

In the study area, the archaeological sites dating to the Early Mesolithic (Figure 4.10b) are mostly located on the southern border of the cover sand ridge of Maldegem-Stekene. This is an interesting location due to the gradient in MWT depths when crossing the ridge in southern direction. The archaeological sites are positioned on the drier ridge, with possible freshwater seepage in the vicinity at the southern border. Also, a number of sites is located on the drier grounds bordering the river Kale/Durme. The transition from the Boreal to the Atlantic is characterized by a slight drying and coincides with a marked decrease in sites dating to the Middle Mesolithic (Figure 4.10c; Crombé et al., 2011). This could indicate that the water level in the area, especially in the river channel, limited the availability of drinking water. For the Atlantic again slightly higher groundwater levels are found as compared to the Boreal-Atlantic transition. Simultaneously the number of sites dating to the Late Mesolithic increases albeit the density is no longer comparable to the Early Mesolithic. Although sites remain bound to drier locations in the vicinity of wetter locations, such as the southern border of the cover sand ridge and the Kale/Durme river banks, Late Mesolithic sites tend to be erected at important nodal positions, a pattern which persists during the Neolithic. According to Crombé et al. (2011) this might be linked to an increased emphasis on wetland exploitation, including fishing, which resulted in a reduction of group mobility. From the Atlantic onwards the simulated MWT depths remain quite constant. The Bronze Age barrows on the other hand, do cover this dune complex area also more further away from its southern border, while Late Iron Age and Roman find spots are practically not found here, and especially the Roman sites are mainly located in the cuesta region.

However, one region in particular remains void of archaeological evidence throughout all periods investigated: it concerns the area of parallel ridges and depressions, to the south of the Moervaart depression. The question arises in how far this is a reflection of the archaeological reality or of a biased impression due to bad preservation of the archaeological remains under the influence of natural degradation, along with the urbanization and industrialization of the region. This phenomenon was investigated for the Bronze Age barrows, but no clear answer could be given due to rather unsuccessful aerial surveys and only a limited number of sites revealed at recent excavation projects, only bordering the region under question (De Reu et al., in review). Nowadays, this area is characterized by a dense network of small brooks and ditches. In the 1960's, the poor condition of this network could lead to seasonally high groundwater tables and even flooding of the neighbouring grounds in winter (Ameryckx and Leys, 1962). In earlier times when the artificial drainage network was absent, this must have been definitely the case. Parallel higher and drier ridges separate the lower and wetter depressions.

However, they are of a rather limited extent and hence probably did not serve as good locations for settlement. In addition, the absence of major open water systems, such as lakes and large streams, might have restricted the occupation of this area.

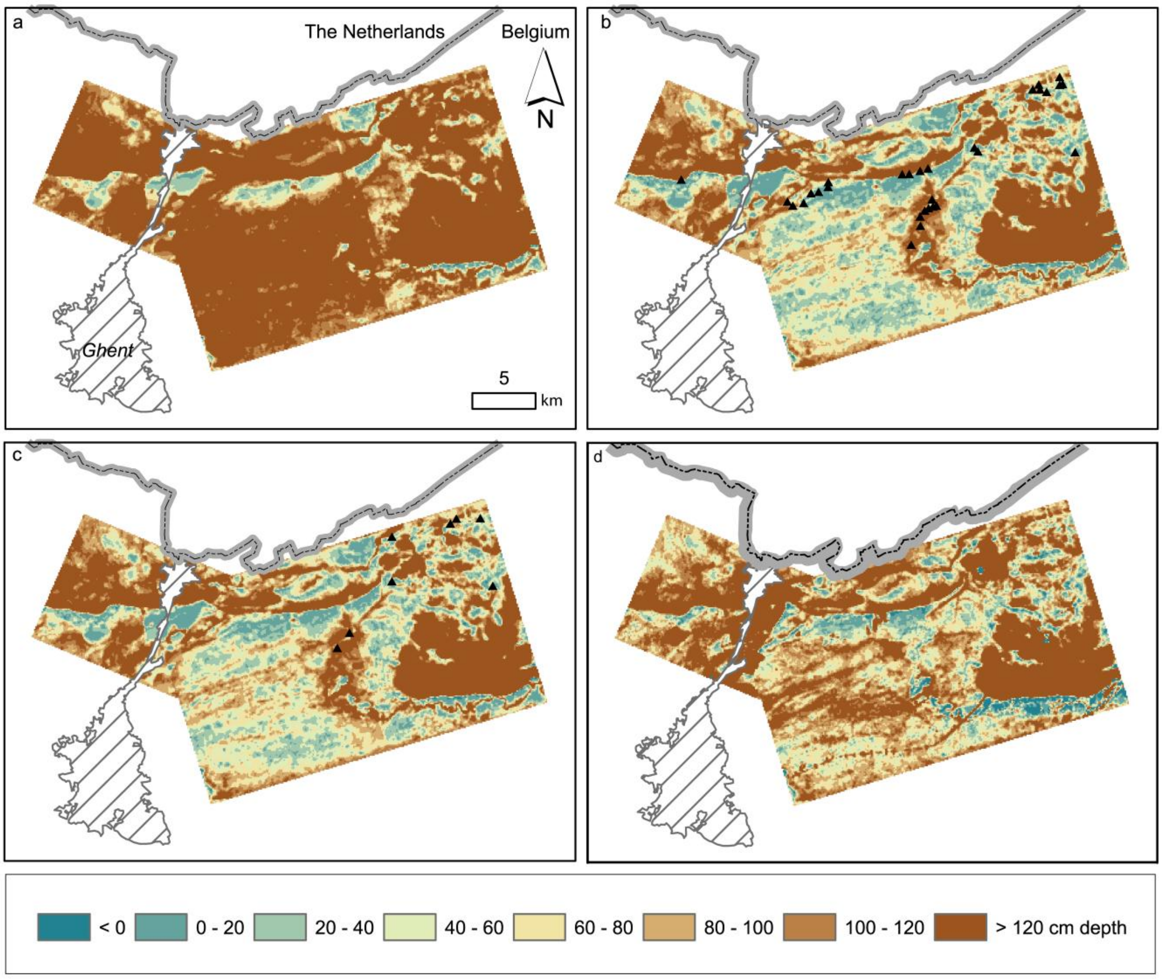

Figure 4.10 Full-cover maps of the MWT depth (expressed in cm below the surface). a: 10.15 ka BCE (Younger Dryas); b: 7.84 ka BCE (Boreal), with Early Mesolithic find spots (black triangles); c: 7.12 ka BCE (Boreal-Atlantic transition), with Middle Mesolithic find spots (black triangles); d: time of soil mapping (1950 CE).

4.4 Conclusions

A palaeogroundwater modelling was performed for Sandy Flanders resulting in a series of full-cover maps of the MWT depth enclosing a time period of 12,720 years, starting in the Younger Dryas, and covering almost the entire Holocene, till 1953 CE. Calibration for the present time (1924-1953 CE time period) was performed using drainage class information from the soil map of Flanders. The model quality for the validation dataset (ME of 0.018 m and RMSE of 0.66 m) indicates that the model predicts well the phreatic mean water tables at the time of soil mapping. Evidence on the past landscape such as archaeological sites and recorded podzol locations were used to further calibrate the model and to test model quality for prehistoric times by adjusting the hydraulic conductance of the upper 0.20 m of the soil (C_{DRAIN}): at 96.28% of the archaeological sites and at 96.88% of the podzol locations of the validation dataset the simulated water table depths were in agreement with settlement and podzolisation conditions. Difficulties reconstructing the past topographies, drainage network, vegetation type and climate, based on the current knowledge, are discussed. Application of the model provided an extensive full-cover dataset on the palaeo-MWT, showing a decrease in MWT depth from Younger Dryas to Boreal, and relatively stable MWT depths for the rest of the Holocene. A first analysis indicates that locations with strong MWT-gradients seem to be of large interest for Meso-and Neolithic man. For younger archaeological periods this situation is not as clear. The maps of the MWT can be further investigated in a geoarchaeological and land evaluation context and can be used in for example predictive modelling.

4.5 References

AGIV, 2002. Vectoriële versie van de VHA-waterlopen & -zones (versie 22/10/2002) 1/5,000. Vlaamse Milieumaatschappij - Afdeling Operationeel Waterbeheer (AGIV).

AGIV, 2008. LIDAR-hoogtepunten (versie 1.0). MOW-Afd WL, VMM-Afd OW en AGIV.

Alley, W.M., 2001. Ground water and climate. Ground Water 39, 161-161.

Ameryckx, J., Leys, R., 1962. Verklarende tekst bij het kaartblad Zeveneken 41 W, Bodemkaart van België. Instituut tot aanmoediging van het Wetenschappelijk Onderzoek in Nijverheid en Landbouw, Brussel, pp. 87.

Ameryckx, J., Verheye, W., Vermeire, B., 1995. Bodemkunde: bodemvorming, bodemeigenschappen, de bodems van België, bodembehoud en -degradatie, bodembeleid en bodempolitiek. Ameryckx, J., Gent.

Baeteman, C., 2006. De laat holocene evolutie van de Belgische kustvlakte: Sedimentatie-processen versus zeespiegelschommelingen en Duinkerke transgressies, in: de Kraker, A.M.J., Borger, G.J. (Eds.), Veen-Vis-Zout. Landschappelijke dynamiek in de zuidwestelijke delta van de Lage Landen. Geoarcheologische en Bioarcheologische Studies 8. Vrije Universiteit Amsterdam, Amsterdam, pp. 1-18.

Batelaan, O., 2006. Phreatology. Characterzing groundwater recharge and discharge using remote sensing, GIS, ecology, hydrochemistry and groundwater modelling, Vrije Universiteit Brussel, Brussels, 351 pp.

Bouten, W., 1992. Monitoring and modelling forest hydrological processes in support of acidification research. Unpublished PhD. Thesis, Universiteit van Amsterdam, Amsterdam, 218 pp.

Colombo, R., Vogt, J.V., Soille, P., Paracchini, M.L., de Jager, A., 2007. Deriving river networks and catchments at the European scale from medium resolution digital elevation data. Catena 70, 296-305.

Crombé, P., 2005. The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation Projects. Volume 1: Palaeo-environment, chronology and features. Archaeological Reports Ghent University, 3. Academia Press, Ghent.

Crombé, P., De Smedt, P., Davies, N.S., Gelorini, V., Zwertvaegher, A., Langohr, R., Van Damme, D., Van Strydonck, M., Antrop, M., Bourgeois, J., De Maeyer, P., De Reu, J., Finke, P.A., Van Meirvenne, M., Verniers, J., in review. Hunter-gatherer responses to the changing environment of the Moervaart palaeolake (NW Belgium) during the Late Glacial and Early Holocene. Quaternary International.

Crombé, P., Sergant, J., Robinson, E., De Reu, J., 2011. Hunter-gatherer responses to environmental change during the Pleistocene-Holocene transition in the southern North Sea basin: Final Palaeolithic-Final Mesolithic land use in northwest Belgium. Journal of Anthropological Archaeology 30(3), 454-471.

Crombé, P., Van Strydonck, M., Boudin, M., Van den Brande, T., Derese, C., Vandenberghe, D., Van den haute, P., Court-Picon, M., Verniers, J., Bos, J.A.A., Verbruggen, F., Antrop, M., Bats, M., Bourgeois, J., De Reu, J., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., Zwertvaegher, A., in press. Absolute dating (^{14}C and OSL) of the formation of cover sand ridges occupied by prehistoric hunter-gatherers in NW Belgium. Radiocarbon.

Crombé, P., Verbruggen, C., 2002. The Late Glacial and Early Post Glacial occupation of northern Belgium: the evidence from Sandy Flanders, in: Eriksen, B.V., Bratlund, B. (Eds.), Recent studies in the Final Palaeolithic of the European plain. Proceedings of a U.I.S.P.P. Symposium, Stockholm, 14.-17. October 1999. Jutland Archaeological Society Publications. Jutland Archaeological Society, Stockholm, pp. 165-180.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., data-contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 1701-1716.

De Clercq, W., 2009. Lokale gemeenschappen in het imperium Romanum. Transformaties in de rurale bewoningsstructuur en de materiële cultuur in de landschappen van het noordelijk deel van de civitas Menapiorum (Provincie Gallia-Belgica, ca. 100 v. Chr. - 400 n. Chr.. Unpublished PhD. Thesis, Ghent University, Ghent.

De Keersmaeker, L., Rogiers, N.L., R., De Vos, B., 2001. Ecosysteemvisie Bos Vlaanderen, Ruimtelijke uitwerking van de natuurlijke bostypes op basis van bodemgroeperingseenheden en historische boskaarten. Eindverslag van project VLINA C97/06, studie uitgevoerd voor rekening van de Vlaamse Gemeenschap binnen het kader van het Vlaams Impulsprogramma Natuurontwikkeling in opdracht van de Vlaamse minister bevoegd voor natuurbehoud.

De Moor, G., Heyse, I., 1978. De morfologische evolutie van de Vlaamse vallei. De Aardrijkskunde 4, 343-375.

De Moor, G., Heyse, I., 1994. Geomorfologische kaart, Kaartblad Lokeren. Ministerie van de Vlaamse Gemeenschap, Brussel.

De Muynck, M., 1976. Het bedolven kultuurlandschap in de polders. Een rekonstruktie uitgaande van luchtfoto's toegepast op de Oost-Vlaamse en enkele Zeeuws-Vlaamse polders, Faculty of Science, Ghent University, Ghent, p. 266.

Dent, D., Young, A., 1981. Soil survey and land evaluation. George Allen and Unwin, London.

Derese, C., Vandenberghe, D.A.G., Zwertvaegher, A., Verniers, J., Crombé, P., Van den haute, P., 2010. The timing of aeolian events near archaeological settlements around Heidebos (Moervaart area, N Belgium). Netherlands Journal of Geosciences - Geologie en Mijnbouw 89, 173-186.

De Reu, J., Bats, M., Crombé, P., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Van Meirvenne, M., Verniers, J., Werbrouck, I., Zwertvaegher, A., Bourgeois, J., 2011a. Een GIS benadering van de bronstijdgrafheuvel in Zandig-Vlaanderen: enkele voorlopige resultaten (België). Lunula, Archaeologia protohistorica 19, 3-8.

De Reu, J., Bourgeois, J., Bats, M., De Smedt, P., Gelorini, V., Zwertvaegher, A., Antrop, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Beyond the unknown. Understanding prehistoric patterns in the metropolitan landscape. Journal of Historical Geography.

De Reu, J., Deweirdt, E., Crombé, P., Bats, M., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Werbrouck, I., Zwertvaegher, A., Bourgeois, J., 2011b. Les tombelles de l'âge du bronze en Flandre sablonneuse (nord-ouest de la Belgique): un status quaestionis. Archäeologisches Korrespondenzblatt 41(4), 491-505.

De Smedt, P., Van Meirvenne, M., Davies, N.S., Bats, M., Saey, T., De Reu, J., Meerschman, J., Gelorini, V., Zwertvaegher, A., Antrop, M., Bourgeois, J., De Maeyer, P., Finke, P.A., Verniers, J., Crombé, P., in press. A multidisciplinary approach for reconstructing Late Glacial and Early Holocene landscapes. Journal of Archaeological Science.

FAO, 2001. Lecture notes on the major soils of the world. World soil resources reports 94.

Finke, P.A., 2012a. Modeling the genesis of Luvisols as a function of topographic position in loess parent material. Quaternary International 265, 3-17.

Finke, P.A., 2012b. On digital soil assessment with models and the pedometrics agenda. Geoderma 171-172, 3-15.

Finke, P.A., Brus, D.J., Bierkens, M.F.P., Hoogland, T., Knotters, M., De Vries, F., 2004. Mapping groundwater dynamics using multiple sources of exhaustive high resolution data. Geoderma 123, 23-39.

Finke, P.A., Hutson, J.L., 2008. Modelling soil genesis in calcareous loess. Geoderma 145, 462-479.

Finke, P.A., Van de Wauw, J., Baert, G., 2010. Development and testing of a method to update the drainage class map of Flanders. Final report (in Dutch). Ghent University, Ghent.

Flemish Government Report, 2001. Report WAT/L 2000 S 0002 X, Herwaardering van het grachtenstelsel. Fase 2 - Inventarisatie en opbouw van een GIS. Deel uitvoering, Department Environment and infrastructure, AMINAL - Division Water, Brussel.

Gyucha, A., Duffy, P.R., Frolking, T.A., 2011. The Körös Basin from the Neolithic to the Hapsburgs: linking settlement distributions with pre-regulation hydrology through multiple data set overlay. Geoarchaeology: An International Journal 26, 392-419.

Harbaugh, A.W., McDonald, M.G., 1996. User's documentation for the U.S. Geological Survey modular finite-difference ground-water flow model. Open-File Report 96-485. U.S. Geological Survey, Reston, Virginia.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1(2), 96-99.

Herbst, M., Rosier, P.T.W., McNeil, D.D., Harding, R.J., Gowing, D.J., 2008. Seasonal variability of interception evaporation from the canopy of a mixed deciduous forest. Agricultural and Forest Meteorology 148, 1655-1667.

Hoek, W.Z., 2001. Vegetation response to the ~14.7 and ~11.5 ka cal. BP climate transitions: is vegetation lagging climate? Global and Planetary Change 30, 103-115.

Hörmann, G., Branding, A., Clement, T., Herbst, M., Hinrichs, A., Thamm, F., 1996. Calculation and simulation of wind controlled canopy interception of a beech forest in Northern Germany. Agricultural and Forest Meteorology 79, 131-148.

Jacques, D., Leterme, B., Beerten, K., Schneider, S., Finke, P., Mallants, D., 2010. Long-term evolution of the multi-layer cover. Project near surface disposal of category A waste at Dessel. STB-NF – Version 1. NIROND-TR report 2010-03 E. Brussels: ONDRAF/NIRAS, Belgian agency for radioactive waste and enriched fissile materials.

Jenson, S.K., Domingue, J.P., 1988. Extracting topographic structure from digital elevation data for Geographic Information System analysis. Photogrammetric Engineering and Remote Sensing 54, 1593-1600.

Jongepier, I., Soens, T., Thoen, E., Van Eetvelde, V., Crombé, P., Bats, M., 2011. The brown gold: a reappraisal of medieval peat marshes in Northern Flanders (Belgium). Water History 3, 73-93.

Jordan, P., 2001. Ideology, material culture and Khanty ritual landscapes in western Siberia, in: Fewster J.J., Zvelebil, M. (Eds.), Ethnoarchaeology and hunter-gatherers: Pictures at an exhibition. BAR International Series 995. Archaeopress, Oxford.

Kamermans, H., 2006. Problems in Paleolithic land evaluation: a cautionary tale, in: Mehrer, M.W., Wescott, K.L. (Eds.), GIS and Archaeological Site Location Modeling. CRC Press Boca Raton, Florida, USA, pp. 97-122.

Kasse, C., Vandenberghe, D., De Corte, F. and Van den haute, P., 2007. Late Weichselian fluvio-aeolian sands and cover sands of the type locality Grubbenvorst (southern Netherlands): sedimentary environments, climate record and age. Journal of Quaternary Science 22(7), 695-708.

Kroon, T., Finke, P.A., Peereboom, I., Beusen, A.H.W., 2001. Redesign STONE. De nieuwe schematisatie voor STONE: de ruimtelijke indeling en de toekenning van hydrologische en bodemchemische parameters. RIZA, Alterra, RIVM, Lelystad, Nederland; 99.

Mandlburger, G., Vetter, M., Milenkovic, M., Pfeifer, N., 2011. Derivation of a countrywide river network based on Airborne Laser Scanning DEMs - results of a pilot study, 19th International Congress on Modelling and Simulation, Perth, Australia, 12-16 December 2011, pp. 2423-2429.

NGI, 2003. Gereduceerde primitief kadaster voor de stad Lokeren (originele opname: 1807-1836, reductie-actualisatie: 1845-1855, scan NGI) 1/20,000.

NGI, 2006. Navigational map of Belgium, Kaart van de Scheepvaartwegen, 1:25,000.

NGI, 2009. Topografische kaart numerieke reeks (versie 2009) 1/10,000, raster. Kaartblad 14.8-zuid. AGIV-product.

Orengo, H.A., Fiz, I., 2008. The application of 3D reconstruction techniques in the analysis of ancient Tarraco's urban topography, in: Posluchsny, A., Lambers, K., Herzog, I. (Eds.), Layers of perception. Proceedings of the 35th International Conference on Computer Applications and Quantitative Methods in Archaeology (CAA), Berlin 2007. Kolloquien zur Vor- und Frühgeschichte 10, Bonn, pp. 343-345.

Price, A.G., Carlyle-Moses, D.E., 2003. Measurement and modelling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, southern Ontario, Canada. Agricultural and Forest Meteorology 119, 69-85.

Sergant, J., Crombé, P., Perdaen, Y., 2009. Mesolithic territories and land use systems in north-west Belgium, in: McCartan, S., Schulting, R., Warren, G., Woodman, P. (Eds.), Mesolithic Horizons. papers presented at the Seventh International Conference on the Mesolithic in Europe, Belfast 2005. Oxbow Books, Oxford, pp. 277-281.

Soens, T., 2011. The genesis of the Western Scheldt: towards an anthropogenic explanation for environmental change in the medieval Flemish coastal plain (1250-1600), in: Thoen, E., Borger, G., Soens, T., De Kraker, A.M.J., Tys, D., Vervaet, L. (Eds.), Landscapes or seascapes? The history of the coastal area in the North Sea region revised. CORN Publication Series, Turnhout.

Spikins, P., 1999. Mesolithic Northern England. Environment, population and settlement. BAR British Series 283. Archeopress, Oxford.

Spikins, P., 2000. GIS Models of Past Vegetation: an example from Northern England, 10,000-5000 BP. Journal of Archaeological Science 27, 219-234.

Steenhuis, T.S., Van Der Molen, W.H., 1986. The Thornthwaite-Mather procedure as a simple engineering method to predict recharge. Journal of Hydrology 84, 221-229.

Terberger, T., Barton, N., Street, M., 2006. The Late Glacial reconsidered - recent progress and interpretations, in: Street, M., Barton, N., Terberger, T. (Eds.), Humans, environment and chronology of the Late Glacial of the North European Plain. Proceedings of Workshop 14 (Commission XXXII "The Final Palaeolithic of the Great European Plain / Le paléolithique Final de la Grande Plaine Européenne") of the 15th U.I.S.P.P. congress, Lisbon, September 2006. Verlag des Römisch-Germanischen Zentralmuseums, Mainz, pp. 189-207.

Thomas, J., 1993. The politics of vision and the archaeologies of landscapes, in: Bender, B. (Ed.), Landscape: Politics and Perspectives. Berg, Oxford, pp. 1-17.

Thornthwaite, C.W., Mather, J.R., 1955. The water balance. Publications in climatology 8/1. Drexel institute of technology, Centeron.

Thornthwaite, C.W., Mather, J.R., 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications in climatology 10/3. Drexel institute of technology, Centeron.

Tilley, C.Y., 1994. A phenomenology of landscape: places, paths, and monuments. Berg, Oxford.

van Mourik, J.M., Seijmonsbergen, A.C., Jansen, B., 2012. Geochronology of soils and landforms in cultural landscapes on aeolian sandy substrates, based on radiocarbon and optically stimulated tuminescence dating (Weert, SE-Netherlands), in: Nawrock, D.M. (Ed.), Radiometric Dating, InTech, Croatia. http://www.intechopen.com/books/radiometricdating/geochronology-of-soils-and-landforms-in-cultural-landscapes-on-aeolian-sandy-substrates-based-onrad

Van Orshoven, J., Maes, J., Vereecken, H., Feyen, J., Dudal, R., 1988. A structured database of Belgian soil profile data. Pedologie 38(2), 191-206.

Van Ranst, E., Sys, C., 2000. Eenduidige legende voor de digitale bodemkaart van Vlaanderen. Universiteit Gent, Gent.

Verbruggen, C., Denys, L., Kiden, P., 1996. Belgium, in: Berglund, B.E., Birks, H.J.B., Ralska-Jasiewiczowa, M., Wright, H.E. (Eds.), Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley and Sons, Chichester, pp. 553-574.

Verbruggen, C., Semey, J., 1993. Venen en moeren: fysisch-geografische benadering, in: De Kraker, A.M.J., Van Royen, H., De Smet, M.E.E. (Eds.), Over den Vier Ambachten: 750 jaar Keure, 500 jaar Graaf Jansdijk. Duerinck, Kloosterzande, pp. 61-65.

VMM, 2006. Grondwaterbeheer in Vlaanderen: het onzichtbare water doorgrond. Vlaamse Milieumaatschappij, Aalst.

VMM, 2008a. Grondwater in Vlaanderen: het Centraal Kempisch Systeem. Vlaamse Milieumaatschappij, Aalst.

VMM, 2008b. Grondwater in Vlaanderen: het Centraal Vlaams Systeem. Vlaamse Milieumaatschappij, Aalst.

Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital elevation model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.

Wilsnack, M.M., Welter, D.E., Montoya, A.M., Restrepo, J.I., Obeysekera, J., 2001. Simulating flow in regional wetlands with the MODFLOW wetlands package. Journal of the American Water Resources Association 37(3), 655-674.

Zhang, H., Hiscock, K.M., 2010. Modelling the impact of forest cover on groundwater resources: A case study of the Sherwood Sandstone aquifer in the East Midlands, UK. Journal of Hydrology 392, 136-149.

Zidan, Y.O.Y., 2008. Mapping phreatic water tables to update the drainage class map 1:20,000 in the Scheldt Valley near Ghent. Unpublished thesis, Department of Geology and Soil Science. Ghent University, Ghent, pp. 89.

Zume, J.T., Tarhule, A.A., 2011. Modelling the response of an alluvial aquifer to anthropogenic and recharge stresses in the United States Southern Great Plains. Journal of Earths System Science 120(4), 557-572.

Zvelebil, M., 2003. Enculturation of Mesolithic landscapes, in: Larsson, L., Kindgren, H., Knutsson, K., Leoffler, D., Åkerlund, A. (Eds.), Mesolithic on the Move. Papers presented at the Sixth International Conference on the Mesolithic in Europe, Stockholm 2000. Oxbow Books Ltd., Oxford, pp. 65-73.

Zwertvaegher, A., Werbrouck, I., Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, P., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the Use of Integrated Process Models to Reconstruct Prehistoric Occupation, with Examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal 25(6), 784-814.

Chapter 5
Spatio-temporal modelling of soil characteristics

Abstract

Full-cover maps for several specific soil characteristics were produced at particular time-intervals over a time span of 12,716 years for a 584 km^2 large study area located in Belgium. The pedogenetic process model SoilGen2 was used to reconstruct the evolution of several soil variables at specific depths in the soil profile at various point locations (96 in total). The time span covered by the simulations encompassed the final part of the Younger Dryas and the Holocene up till present. Time series on climate, organisms and groundwater table were reconstructed and supplied to the model as boundary conditions. Model quality optimization was performed by calibrating the solubility constant of calcite by comparison of the simulated time necessary for decalcification with literature values and evaluating the calibrated value over a wide range of precipitation surpluses representative for the regarded time period. The simulated final state was evaluated against measurements collected in a database representing the historic state of the soil at approximately 1950. The simulated specific soil characteristics at the point locations were then used to produce full-cover maps at the particular time-intervals by regression kriging. Such maps are believed to provide useful information for geoarchaeological studies and archaeological land evaluations.

This chapter is based on Zwertvaegher, A., Finke, P.A., De Smedt, P., Gelorini, V., Van Meirvenne, M., Bats, M., De Reu, J., Antrop, M., Bourgeois, J., De Maeyer, P., Verniers, J., Crombé, P., in review. Spatio-temporal modelling for soilscape reconstruction. Geoderma.

5.1 Introduction

Since prehistoric times man has lived in close interaction with the land, which aspects are believed to have influenced decision making on occupation and utilization of a region. For example, analyses of the spatial distribution of archaeological finds and their possible correlation with physical/environmental variables was the subject of investigations since the 1970s (e.g. De Reu et al., 2011; Niknami et al., 2009). Anthropogenic activity, on the other hand, influences the environment as well (Knight and Howard, 2004; Oetelaar and Oetelaar, 2007). Use of the land in prehistoric times encompassed settlement, but also the provisioning in livelihood for example through hunting and/or fishing and gathering. The latter was the main way of subsistence until the Mesolithic inclusive. Agriculture was practiced from the Neolithic onwards, its starting point, degree of continuity and intensity varying spatially (Crombé and Vanmontfort, 2007). Various types of pre- and protohistoric land use serving as biophysical attractors for occupation were listed by Zwertvaegher et al. (2010), together with their associated land qualities and characteristics. For example, the land utilization type rain-fed agriculture is among other things influenced by land qualities such as moisture, oxygen and nutrient availability in the soil.

The component soil is an important factor in establishing the suitability of the land for several types of land use. Natural soil fertility is determined by the physical and chemical soil properties that are the product of several soil forming processes and are therefore variable through time. Mostly, only the present-day state of the soil is known, together with the condition of the parent material. Unless soil chronosequences are at hand, no information on past soil conditions is available (Finke, 2012). Therefore, process models using the knowledge on physical and chemical processes, are interesting tools in the reconstruction of the palaeocharacteristics of the land (Zwertvaegher et al., 2010). Here, the pedogenetic process model SoilGen (Finke, 2012; Finke and Hutson, 2008) was used to provide the necessary variables for a specific time and depth of the soil profile at several point locations (Zwertvaegher et al., 2010).

The main objective of this work was to produce full-cover maps of the study area of soil characteristics relevant for past human occupation at certain points in time. To attain this, the model boundary conditions and initial conditions were reconstructed for the time period at hand. Additionally, the model reliability was maximized by calibration of the model processes and evaluation of the simulated final state by comparison with the measured final state. Finally, the model outputs at several point locations were used in the reconstruction of full-cover maps of specific soil characteristics.

5.2 The SoilGen model

The SoilGen model (Finke, 2012; Finke and Hutson, 2008) was developed to simulate soil formation in unconsolidated sediments. A soil profile at a certain point location is represented in the model by a number of compartments (here, taken as 0.05 m thickness). The physical and chemical soil properties are updated at varying time steps. Their temporal resolution depends on the specific parameter and process dynamics. This mostly concerns the subday time scale (Finke and Hutson, 2008). The factors of soil formation as defined by Jenny (1941), are taken into account as boundary and initial conditions, as well as by several simulated processes (for an overview, see Sauer et al., 2012). Below, a general overview of the model is given. For a more detailed model descriptions we refer to Finke and Hutson (2008) and Finke (2012).

The SoilGen2 model core is based on the LEACHC model (Hutson and Wagenet, 1992) that is calculating water, solute and heat flow. These flows are governed by finite difference approximations of the Richard's equation for the unsaturated zone, the convection-dispersion equation and the heat flow equation respectively. Information on the parent material is introduced to the model as initial conditions. Physical weathering and weathering of the primary minerals is handled, as well as clay migration, which is induced by rain splash detachment at the surface bringing part of the clay particles in the dispersed state (Finke, 2012). Precipitation, potential evapotranspiration, air temperature and rainfall composition are applied to the model as boundary conditions. The influence of topography is parameterized by the slope aspect and gradient and the wind bearing (Finke, 2012). This enables the model to modify precipitation and potential evapotranspiration to local exposition properties. Furthermore, erosion and sedimentation events are also managed as input (Finke, 2012). Hydrological conditions are set using a default free drainage lower boundary, except in the occurrence of a precipitation deficit, in which case a zero flux condition is applied. Shallow water tables occurring inside the modelled soil profile are to be supplied by the user as an extra boundary condition. When seasonal dynamics are absent in the input (for example mean water tables delivered at yearly time scale), seasonal water table fluctuations are simulated by imposing a reduced permeability at the height of the mean water table, which causes a perched water table to be simulated around the mean water table depth that is responding to variations in precipitation surplus. The vegetation is conceptualized by 4 vegetation types (grass/shrubs, conifers, deciduous wood and agriculture). Each type has a specific root distribution pattern, ion and water uptake and release, and C-cycling (Finke, 2012; Finke and Hutson, 2008). Decomposition and mineralization of the organic matter (OM) is calculated within a C-cycling submodel of SoilGen, based on RothC 26.3 (Coleman and Jenkinson, 2005). The produced CO_2 is handled by the gas regime equation and the calculated partial pressure in its turn influences the chemical equilibria between the solution phase, the precipitated, the exchange and the unweathered phase. Human influence is modelled by fertilization and tillage. Redistribution of the several soil phases (minerals, OM, soil water and dissolved elements) by bioturbation and tillage, is mimicked by the model as an incomplete mixing process (Finke and Hutson, 2008).

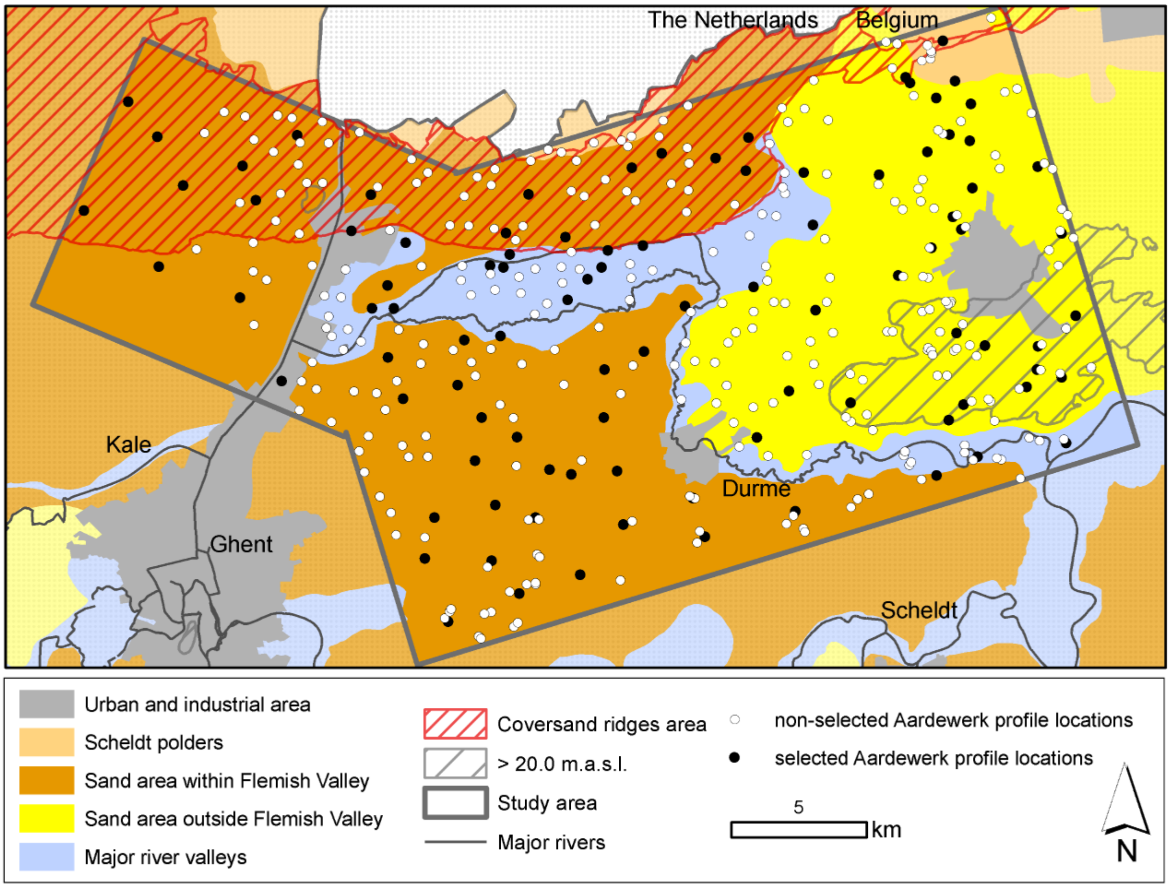

Figure 5.1 Geographical regions in the northern part of Flanders (AGIV, 2001; Antrop et al., 2002) with indication of the selected (white dots) and non-selected (black dots) profile locations from the Aardewerk database (Van Orshoven et al., 1988).

The various parts of the SoilGen model have been tested: water and solute transport (Addiscott and Wagenet, 1985; Dann et al., 2006; Jabro et al., 2006), soil chemistry (Jalali and Rowell, 2003) and carbon dynamics (Smith et al., 1997). Furthermore, the model was tested and evaluated for a wide range of parameters (Finke, 2012; Finke and Hutson, 2008; Sauer et al., 2012).

5.3 Reconstructing model boundary conditions at the point location

5.3.1 Available data

The Belgian soil was systematically mapped (1/20,000 based on 2 samples per ha) during the national soil survey campaign, initiated in 1947. During the campaign additional soil profile descriptions, horizon sampling and analyses were performed. The major part of these data (13,000 profiles) were stored in the Aardewerk database (Van Orshoven et al., 1993; Van Orshoven et al., 1988), containing a total of 53 variables (Van Orshoven et al., 1988). These concern the identification and characterization of the profiles and their associated horizons, for instance granulometry, organic carbon (OC), pH(H_2O), pH(KCl), cation exchange capacity (CEC), exchangeable cations, free iron and mineralogy of the sand fraction (Dudal et al., 2005). The information from this database was used to assess the initial soil state. Furthermore, it represents the final state of the soil that is necessary for model evaluation.

A total of 390 profiles from the Aardewerk database are situated inside the study area (Figure 5.1). From these, a number of 96 locations were selected to perform the soil development reconstruction. The selection is distributed over the entire study area and covers the regional ranges in texture and drainage class. The sampling design is representative of the geographical space, which was confirmed by a visual comparison of the actual distribution with the envelopes of a CSR (Complete Spatial Randomness) function. However, certain inconsistencies were found in the original Aardewerk database, which were firstly removed. Profile layers with total fine earth not equal to 100% were assigned the fine earth fractions of the adjoining layer with the highest similarity in OC and calcite content. Furthermore, OC contents of 0.0% for recorded peat layers were adjusted to a fixed value of 70.0%

5.3.2 Parent material

Information on the initial soil conditions was estimated from the Aardewerk profile descriptions. The initial elevation of the soil profiles was corrected for material deposited on top of the soil in more recent times, such as plaggen and marine sediments. Their average thicknesses were deduced from the database and set at 0.40 m (no of locations=15) and 0.50 m (no of locations = 1) for plaggen soils and locations subjected to marine influence and associated storm surges occurring in the 11th and 13th centuries (Soens, 2011), respectively. By removing these upper layers of the profile and reducing the height with this fixed value the initial profile height was reconstructed.

Furthermore, the OC content was adjusted for increasing values gained during soil formation and set at a predefined value of 0.1% in all layers. Only soil profiles with recorded peat presence and soil layers below 1.0 m with OC content not equal to 0.0% retained their original recorded OC content. The OC content of B and BC horizons, independent of their depth, was also set at 0.1% to erase the influence of podzolisation.

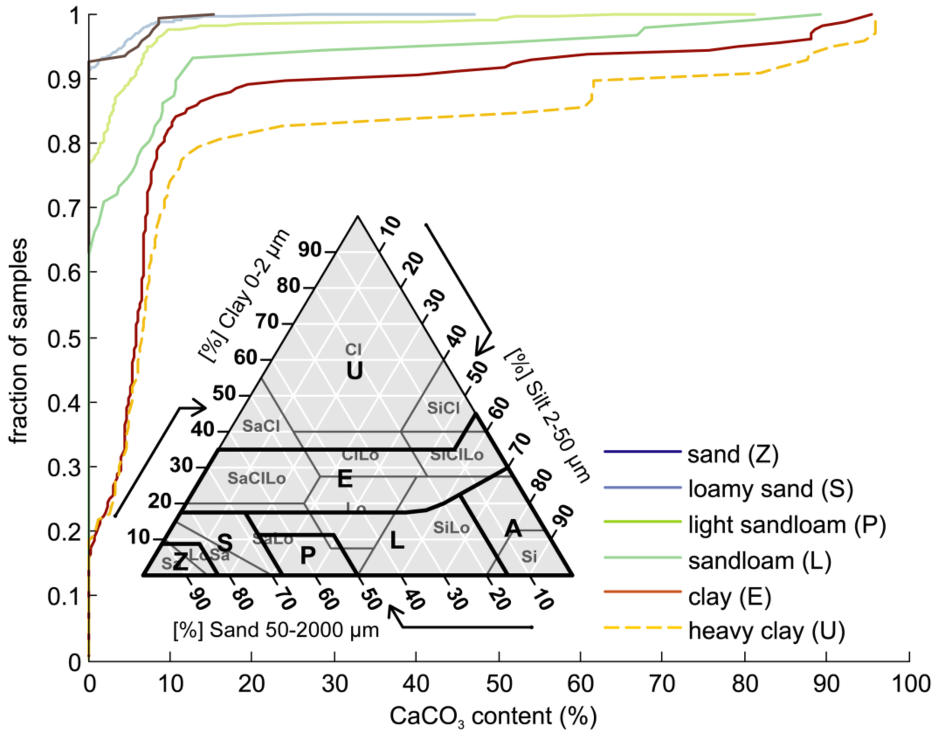

Figure 5.2 Cumulative distribution function of the $CaCO_3$ content (%) as recorded for the 390 Aardewerk soil profiles located in the study area. A division is made per texture class (Belgian system) in order to assess the initial $CaCO_3$ content of the different parent materials. Texture triangle with Belgian classification system (black) and USDA classification system (grey) is inserted. For the explanation of the USDA abbreviations is referred to Figure 5.10.

Initial $CaCO_3$ content was estimated from the cumulative distribution of the measured calcite content per (Belgian) texture class for the 390 Aardewerk profiles in the study area (Figure 5.2). For all texture classes a large amount of samples with low calcite content was found, which was assumed to correspond with decalcified samples. Samples with high calcite content (>40.0%), especially in the sandloam, clay and heavy clay texture classes, reflect the presence of calcareous marls (located in the Moervaart Depression, Figure 5.1) or calcium-rich alluvial deposits. The plateau of the cumulative distribution is not entirely flat and displays the natural variation occurring at deposition and probably also the effect of calcite accumulation within the marls. The values at the beginning of each plateau were assumed to represent the initial calcite content, resulting in 8.5% for the Belgian texture classes sand, loamy sand and light sandloam, and 13.0% for the texture classes loam, clay and heavy clay.

Initial CEC was calculated using a regression equation of Foth and Ellis (1996), who calculated CEC from OC and clay content (in %; Equation 1) based on 200,000 soil samples. A constant (f) was introduced to optimize and calibrate the equation for the local conditions of the study area. The value corresponding with the lowest RMSE between the estimated and measured (from Aardewerk database, no of locations = 390) CEC was chosen as the final scaling-factor (f=1.16) to calculate the initial CEC.

$$CEC = f \times (3.20 + 3.67 \times OC + 0.146 \times Clay) \qquad \text{Equation 5.1}$$

The initial bulk density was calculated with the pedotransfer functions described by Wösten et al. (2001) based on a total of 863 measured soil characteristics in Dutch soils, using the reconstructed silt, clay and OC contents, and the median of the sand fraction (M50). The latter was based on the median measurements of sandy layers recorded in the Aardewerk database (M50 = 145 μm). Finally, Gapon exchange constants (elements Al, Ca, K, Mg, Na and H) provided by de De Vries and Posch (2003) for peat, clay, silt and sand and depths between 0.6 to 1.0 m were assigned to each layer based on the reconstructed fractions of OC and fine earth.

5.3.3 Climate

The SoilGen model requires yearly average January and July air temperatures and annual precipitation and potential evapotranspiration data as input (Figure 5.3) These time series were calculated following the methods described in Finke and Hutson (2008). Present-day climate data used in these calculations were measured in the year 2005 at the weather station of Uccle in Belgium (50.8° N, 4.35° E). Temperature information on the entire simulation period was derived from area-averaged January and July air temperature anomalies, supplied by Davis et al. (2003). These anomaly series were produced for the most recent 12,000 years, in 100-year intervals, for 6 different regions encompassing Europe, based on quantitative pollen analyses (Davis et al., 2003). The

January and July air temperature anomalies for central western Europe were converted towards local time series by adding actual measurements from the weather station. This discontinuous series was transformed by SoilGen into a continuous yearly values ($T_{Jan,y}$ and $T_{Jul,y}$) by linear interpolation between the 100-year intervals. Subsequently, a time series of weekly temperature data was calculated inside the model, using the continuous yearly time series and a standard time record of weekly temperature values from the weather station. The week values at this weather station for the months January and July were averaged ($T_{Jan,ws}$ and $T_{Jul,ws}$). For each year, the difference between $T_{Jan/Jul,y}$ and $T_{Jan/Jul,ws}$ was calculated, interpolated for the other months of the year and added to the weekly values of the standard record.

Annual precipitation anomalies for a time series covering the most recent 12,000 years in 100-year intervals were also provided by Davis (unpublished data), generated by the same method as described in Davis et al. (2003). By adding the current annual values from the weather station , the anomalies were converted to actual precipitation data. Equal to the temperature series, the SoilGen model linearly interpolated between the 100-year intervals, producing a yearly time series of annual precipitation. This yearly series was then used to scale a standard record of daily precipitation data from the weather station, using a multiplier P_y/P_{ws}, in which P_y is the annual precipitation for the corresponding year in the precipitation time series and P_{ws} is the yearly precipitation measured at the weather station.

The equation of (Hargreaves and Samani, 1985) was used to calculate the daily potential evapotranspiration (ET_0) for 51° N, based on the average daily temperature and the temperature ranges from the weather station. A correction factor was obtained to calibrate the model, by comparing the yearly ET_0 measured at the weather station, with the yearly sum of calculated daily ET_0 values. Testing this calibrated model in a range of annual average temperatures, a linear regression function between ET_0 and the average yearly temperature was produced and used, together with the reconstructed temperature series, to construct a yearly ET_0 time series. The series was downscaled to a daily temporal resolution, by correcting the calculated daily ET_0 values for the weather station with a factor $ET_{0,y}/ET_{0,ws}$, where $ET_{0,y}$ is the yearly ET_0 at the corresponding year in the ET_0 time series and $ET_{0,ws}$ is the yearly ET_0 at the weather station.

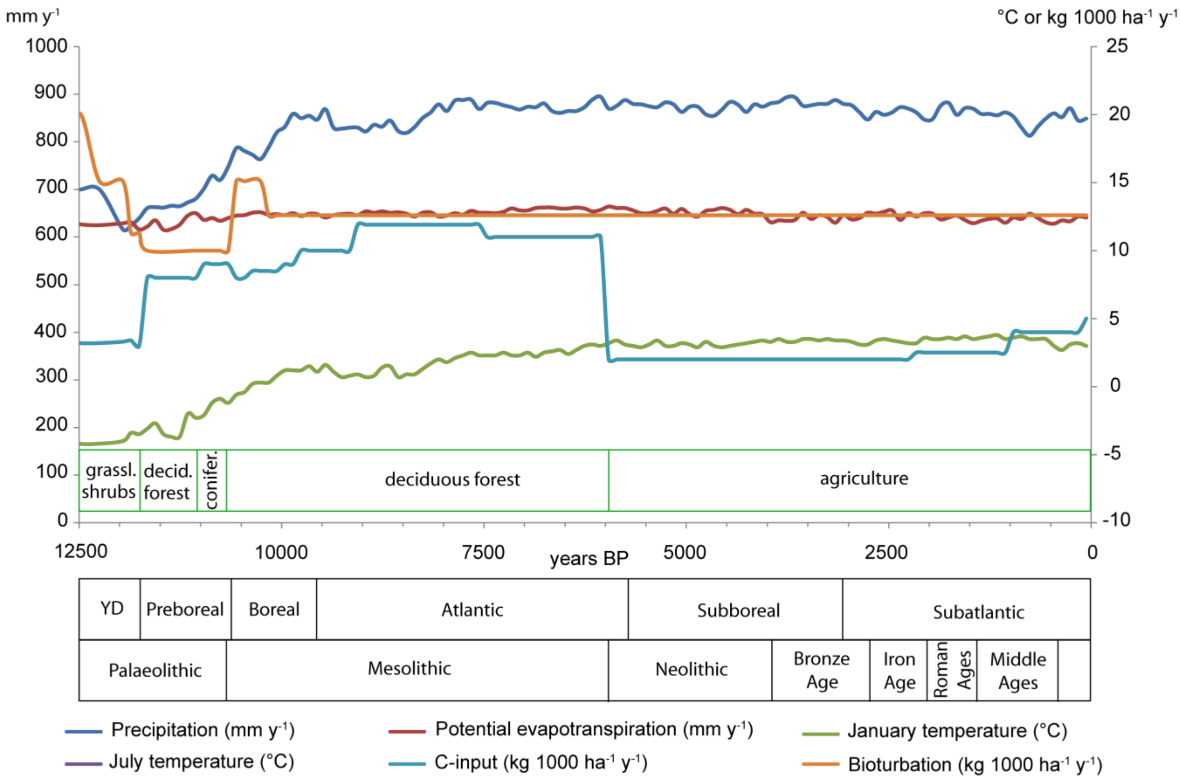

Figure 5.3 The reconstructed boundary conditions related to climate, bioturbation and vegetation in function of the simulated time period. Vegetation types are: grassland (grassl.) and shrubs, deciduous forest (decid.), coniferous forest (conifer.) and agriculture. Chronostratigraphy and archaeological periods are also indicated.

5.3.4 Organisms

The vegetation history of the region was conceptualized by the 4 vegetation types present in the model (Figure 5.3). Each type influences the interception evapotranspiration in varying order (0% of the precipitation for grassland and shrubs and agriculture, 8% for deciduous forest and 12% for coniferous forest). Furthermore, the yearly leaf and root litter input were based on the dominant vegetation and reconstructed average July air temperatures and are provided to the model as a yearly time series of (Figure 5.3). The time series of the bioturbation (Figure 5.3) is also directly related to the variations in vegetation type. Values concerning the minimum and maximum bioturbation depth and depth of the maximum bioturbation, together with the mass fractions of the solid phase mixed at the corresponding depths, were derived from vegetation related indicative values provided by Gobat et al. (1998) in the same manner as proposed by Finke and Hutson (2008).

Human influence by the means of agriculture was imposed in the model through the vegetation type agriculture and fertilization. From the Neolithic onward agriculture in the region became established, although most probably not in a continuous manner. Agriculture was applied in the model from 5960 BP onwards, although fertilization was only applied from 2560 BP (Iron Ages), similar to Finke and Hutson (2008; Belgian scenario). As from that year, the method of liming described by Plinius the Younger was used (application of ~1 ton marl ac^{-1} per every 10 year, equal to 1.88 mol $CaCO_3$ m^{-2} per every 10 year; Finke and Hutson, 2008). From 60 BP onwards current liming management (0.276 mol $CaCO_3$ m^{-2} y^{-1}; Finke and Hutson, 2008) was assumed. The C-input to the soil by agricultural practice was implemented in the model by the introduction of the two-field crop rotation (from 2160 BP), three-field crop rotation (from 1060 BP), and modern agriculture (from 60 BP). C-inputs were obtained by estimating residues of barley in cropped years and biomass produced by weeds in set-aside years and taking a weighted average according to the rotation system.

5.3.5 Groundwater

The position of the groundwater table affects the drainage of the soil and its characteristics. For example, poorly drained soils often have less profile differentiation, a higher OC and nitrogen content, a lower pH and higher Si to Al ratio than well-drained soil series under otherwise similar conditions (Jenny, 1941). The evolution of the mean water table for 30 year intervals was provided by Zwertvaegher et al. (in review), generated by a steady state groundwater modelling using 30-year averaged recharge data and adjusted topography and drainage network. The climate and vegetation data determining the recharge were calculated in a similar manner as mentioned above. A continuous yearly series was obtained by a linear interpolation between the values. The mean water table was converted to the depth of a stagnating layer for SoilGen model calculations.

5.4 Model calibration

The decalcification rate, which influences a.o. pH, porosity and cation content, was calibrated by adjusting the solubility constant of calcium carbonate (K_{SO}). Normalized carbonate leaching rates (1.7 – 2.0 mol m^{-2} y^{-1} for coarse parent materials) for fixed soil water fluxes (1000 mm y^{-1}) where reported by Egli and Fitze (2001) based on various soils in central Europe. The number of simulated years necessary to decalcify 1100 mm of a sandy parent material with a given $CaCO_3$ content under a leaching flux of 247 mm y^{-1} (high percolation value for the Holocene in the study area), was adapted by adjusting the K_{SO} to reproduce the necessary time for decalcification defined by the metamodel of Egli and Fitze (2001). The K_{SO} with the highest comparison in decalcification times between both models was chosen and afterwards used to evaluate model performance against the Egli and Fitze (2001) metamodel within a wider range of soil water fluxes.

5.5 Model performance evaluation

Model performance was evaluated by comparison of the simulated values and the observed values as collected in the Aardewerk database. This was done for the following variables: sand, silt and clay fractions (in mass % of fine earth), OC fraction (mass % of the solid fraction) and calcite mass fractions, pH and CEC ($mmol_c$ kg^{-1} soil). Measurements were only available for the final state. The final simulation year (1950) largely corresponds with the measurement years. These cover the years 1950-1953 (n=8, 29, 41, 11, respectively), however a minor few are dating to 1962 (n=5). Weighted averages for 4 zones of different depths were calculated: 0-0.4 m, 0.4-0.8 m, 0.8-1.2 m and 1.2 till the depth of the profile, which varied between the several locations. For the variable pH, the averages were calculated on the back-transformed concentrations and afterwards recalculated towards the pH. The CEC in the Aardewerk database was however not measured consistently for each layer and/or profile. This resulted in a comparison at only 88 locations compared to 96 locations for the other variables. The model performance was evaluated using three statistical deviance measures: the root mean square error (RMSE), which represents the model's ability to accurately represent the observations, the mean error (ME) and the modelling efficiency (EF). The latter indicates the efficiency of the model in representing the measurements in accordance to their average value and gives an overall assessment of the goodness of fit (Mayer and Butler, 1993). In general, values of RMSE and ME should be close to 0 and close to 1 for the EF (Loague and Green, 1991).

5.6 From point scale to full coverage

The simulated values at the different point locations were used to produce full-cover maps of the target variables for the entire study period for a given year and depth range. The maps should reflect the condition of the topsoil because they will be used for land evaluation purposes. Therefore, the simulated values for the upper 0.4 m were combined and subsequently mapped. This mapping was achieved by performing a block (40 m x 40 m) regression kriging in R (R Development Core Team, 2011) using several predictors (auxiliary maps) and based on the generic framework for spatial prediction as proposed by Hengl et al. (2004). Target variables were chosen based on their relevance for past human occupation: sand, silt and clay fractions (%), OC content (%),calcite fraction (mass fraction), pH, base saturation (%) and bulk density (kg dm^{-3}). Following Hengl et al. (2004), the soil variables were standardized to a 0 – 1 scale and logit transformed to improve the normality of the target variable. Further advantage of the standardization is that the predictions are bound to the physical range (Hengl, 2007; Hengl et al., 2004).

The used predictors are the elevation, the mean water table and the texture class. These represent two continuous and one categorical variable, respectively. All maps were used on the spatial grain of 40 m by 40 m. This resolution was chosen in the light of future work, such as a land evaluation in which agricultural fields on the above mentioned grain are assumed reasonable (Zwertvaegher et al., 2010). Information on the elevation was present as a digital elevation model (DEM) of the study area. Depending on the chosen simulation year, a different DEM was used as predictor. A present DEM, which is representative of the actual topography was originally produced by Werbrouck et al. (2011) on a 2 m x 2 m resolution and applied as predictor map for years between 1804 CE (Common Era) till present. A pre-medieval DEM in which anthropogenic artefacts were removed, was delivered by Werbrouck et al. (2011) and used for the years between 1114 CE - 1803 CE. For the years before 1114 CE, a (pre)historic DEM was used in which plaggen layers and also marine sediments deposited during medieval storm surges and floodings were removed (Zwertvaegher et al., in review).

In the same manner, the mean water table map of the specific year was also used as a predictor. These maps were produced by Zwertvaegher et al. (in review)on a 100 m x 100 m resolution and were afterwards downscaled to a 10 m x 10 m resolution following the method proposed by Sivapalan (1993) and Bierkens et al. (2000). Firstly, a regression relation was calculated based on the presently measured mean water table (Equation 2; mwt_i in cm below surface) at 69 point locations in a pilot area of approximately 34 km^2

inside the current study area (Zidan, 2008) and on the present-day elevation (y_i in m, derived from the present DEM on 10 m x 10 m resolution).

$$mwt_i = b_0 + b_1 \times y_i \qquad \text{Equation 5.2}$$

This regression relation was assumed to be applicable to the entire study area and period. Based on this relation, combined with the weighted average mean water table (Equation 3; *MWT* in cm below surface, per 100 m x 100 m), the weighted average elevation (*Y* in m, per 100 m x 100 m) and the elevation (y_i in m, per 10 m x 10 m cell), the mean water table for the 10 m x 10 m resolution (mwt_i in cm below surface) was calculated. Weighted averages were computed using a moving window surrounding the location *i*.

$$mwt_i = MWT - (b_1 \times Y) + b_1 \times y_i \qquad \text{Equation 5.3}$$

The predictor map on the texture classes was derived from the present-day soil map of Flanders (AGIV, the Flemish Geographical Information Agency). Following Hengl et al. (2004), this categorical layer was converted to binary (0 – 1) indicator maps. Due to the low amount of observations per separate texture class unit (minimum 5 observations per mapping unit; Hengl, 2009) and due to their limited presence in the study region, several classes were merged based on their affinity: the units heavy clay, clay, peat and marl, on the one hand and sandy loam and light sandy loam, on the other hand. Sand and loamy sand classes were taken as two separate categories. This resulted in 4 indicator maps. Together with the two earlier mentioned auxiliary maps, this led to a total of 6 predictor maps. A principal component analysis was performed on the predictors to account for mutual independence between the auxiliary maps (Hengl et al., 2004). The resulting PCA maps were used in a step-wise multiple linear regression analysis (ordinary least squares method). Due to lack of an independent validation dataset, the results were evaluated by a leave-one-out cross-validation (R gstat package; Pebesma, 2004). This was also performed for an oridinary kriging.

Based on the regression kriging maps of the sand, silt and clay fractions, and using the classification method as provided by the R soiltexture package from Moeys (2012) a texture class map (USDA classification) of the topsoil was produced.

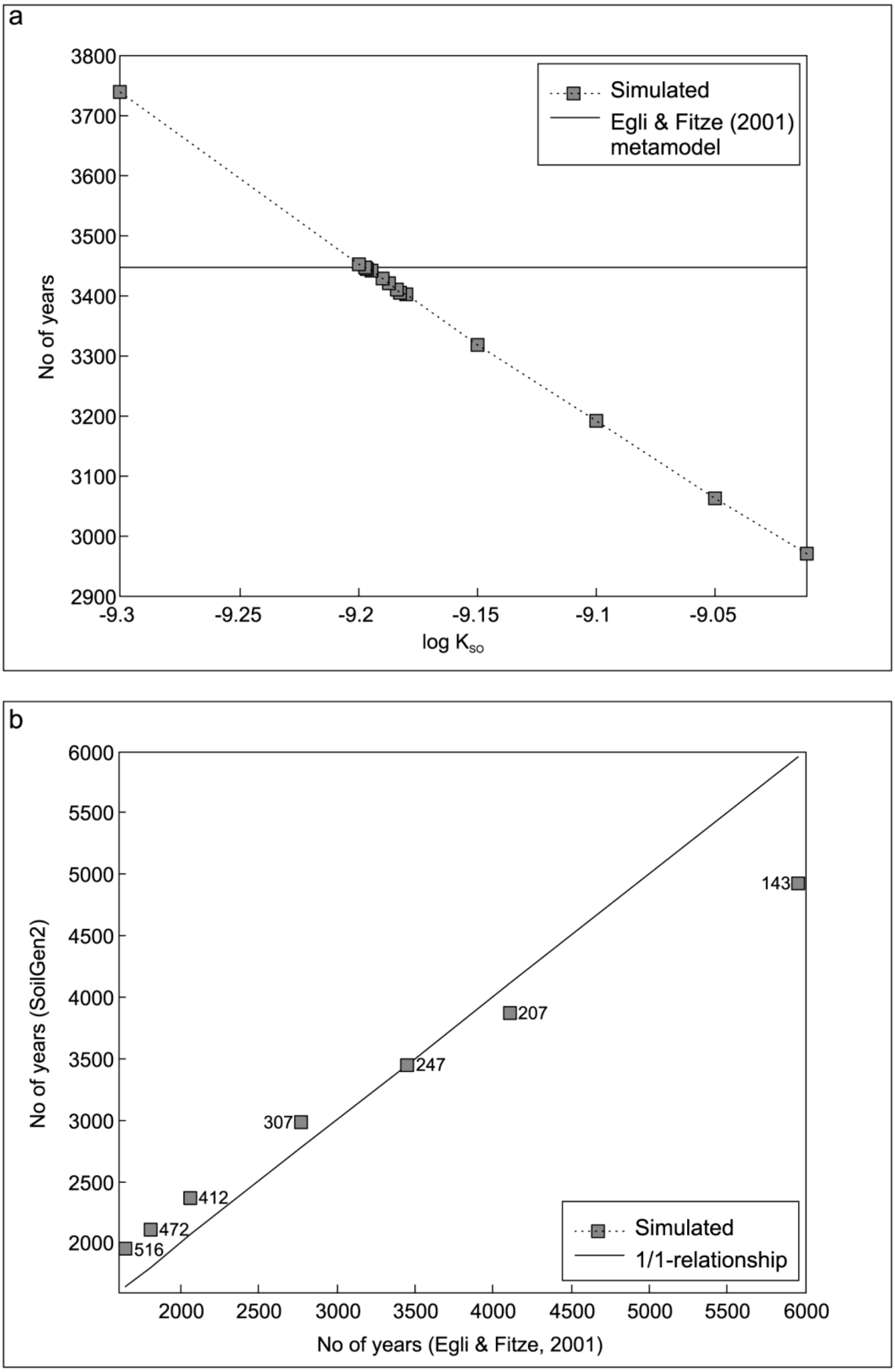

Figure 5.4 a. Calibration of the solubility constant of calcite (log K_{SO}) under leaching conditions of 247 mm y^{-1}; b. Comparison of the simulated number of years needed for decalcification against the calculated values with the Egli & Fitze (2001) metamodel, under a range of varying leaching conditions: precipitation surplus of 143, 207, 247, 307, 412, 472 and 516 mm y^{-1}.

5.7 Results and discussion

5.7.1 Calibration results

According to the Egli and Fitze (2001) metamodel, a total of 3,446 years is necessary to decalcify (leaching rate set at 1.95 mol m^{-2} y^{-1}) 1100 mm of a sandy profile with given carbonate content under leaching conditions of 247 mm y^{-1}. This time period was matched by the SoilGen model at a log(K_{SO}) of 9.20 (Figure 5.4a). Testing this value within a broader range of annual precipitation surpluses against the Egli and Fitze (2001) metamodel values (Figure 5.4b) indicates that the SoilGen model simulates the decalcification rather well at high and extremely high precipitation surpluses, but overestimates the carbonate decalcification rate at very low surpluses. This resulted in a RMSE (root mean square error) of 452 years. Such very low values only occur at the beginning of the study period: from the Younger Dryas till the beginning of the Boreal.

5.7.2 Predicted versus measured soil characteristics

The simulation results for the fine earth fractions display an almost perfect fit with the measurements (EF close to 1; low RMSE and ME; Table 1; Figure 5.5a-c). Only in the upper 0.4 m the model efficiency achieves worse than the global average for the clay fractions (Figure 5.5c) and only slightly better for the silt fractions (Figure 5.5b; Table 5.1). Measured clay contents in the upper 0.4 m average around 4.0% (Table 5.2) in the texture group with coarser textured soils (Belgian texture classes Z, S and P grouped), and around 21.6% (Table 5.2) for the group with finer textures (Belgian texture classes L, E, U grouped). However, the simulated clay fractions for this upper zone, with averages at 0.8% (coarser texture classes) and 4.7% (finer texture classes), are much lower than these measured values (Figure 5.6c; Table 5.2). Furthermore, they are lower than the initial (estimated) values. Around a depth of 0.4 m the simulated clay fraction reflects the measured one. This would suggest that the clay migration in the upper parts of the profile is overestimated by the model and exceeds the clay formation, which might be also underestimated. The clay illuviation depth on the other hand is well predicted. Similar model trends on the prediction of the clay contents were also observed by Finke (2012) and (Sauer et al., 2012).

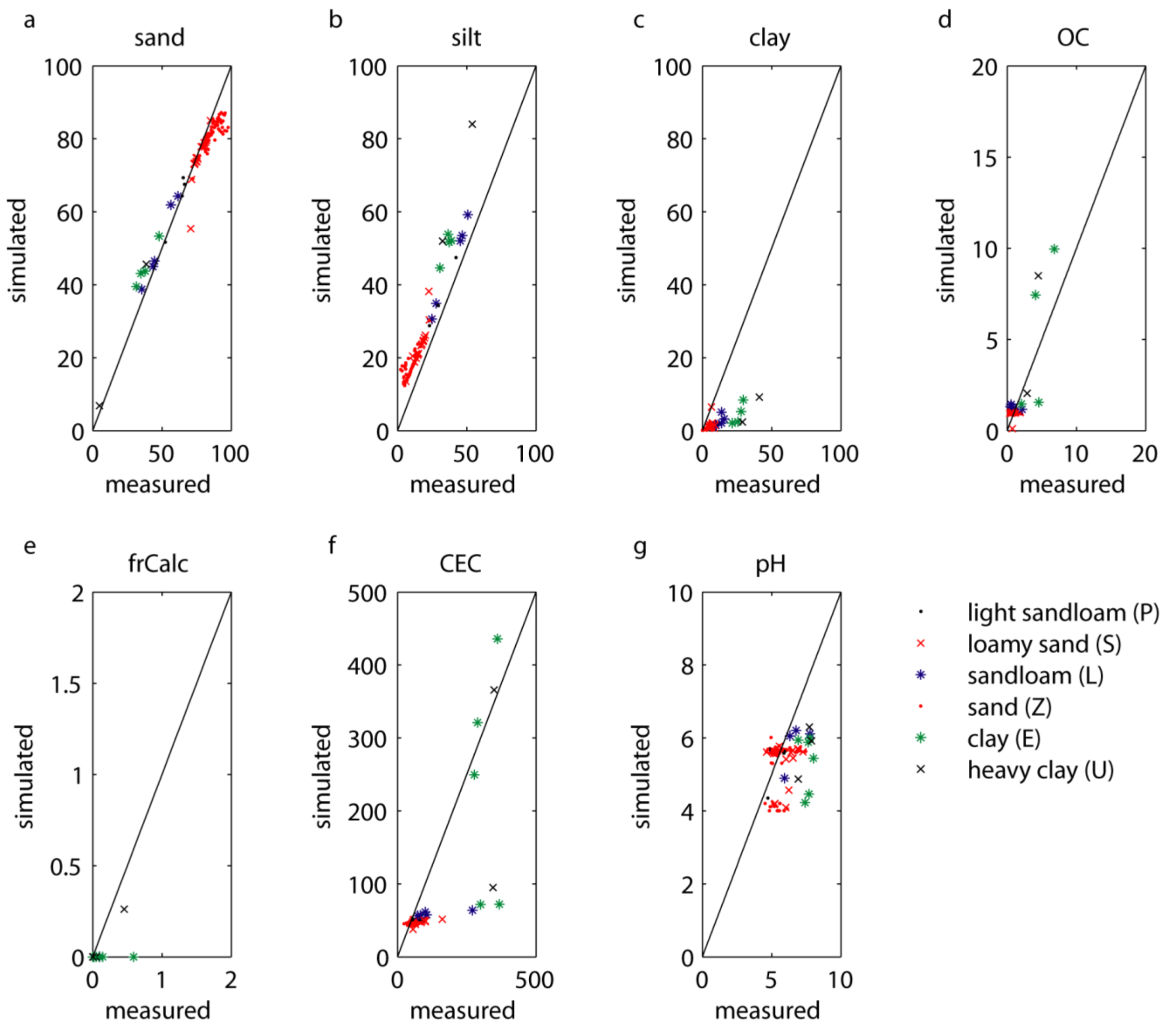

Figure 5.5 Model performance evaluation for the upper 0.4 m of the profile. Weighted averages of the measured Aardewerk values are compared to the weighted averages of the simulated values for several soil variables: sand, silt and clay fractions in mass % of the fine earth fraction (a-b-c); OC in mass % of the solid fraction (d); calcite in mass fraction (e); CEC in mmol$_c$ kg^{-1} soil (f) and pH (g).

The silt fraction in the 0.4 m of the profiles appears to be generally overestimated for all texture classes (Figure 5.5b). The sand fraction is slightly underestimated in the coarser and overestimated in the finer textured soil classes (Figure 5.5a). Especially for the coarser textured soils this indicates that the weathering in the topsoil of the sand particles towards the silt fraction is overestimated by the model. Furthermore, the underestimation of the clay fraction affects the predicted sand and silt fractions in the opposite way.

Concerning the OC content, the EF indicates that the model performs rather well at all depth zones, except between 0.4-0.8 m. However, no clear trend is found: the deviation of the predicted values from the measurements can be positive or negative. The general trend with depth is as expected: predicted OC content in the topsoil at the final state is higher than the initial values, and decreases with increasing depth (Figure 5.6d). However, several profiles are Podzols and characterized by elevated OC contents in the B horizon, generally appearing in the second depth zone (0.4-0.8 m). The podzolisation process is however not yet included in the SoilGen model. This explains the underestimated OC contents and the worse model efficiency between 0.4-0.8 m depth. The organic material applied to the topsoil is defined by the type of vegetation and in the final phase by the type of agriculture. Vegetation and agriculture type were administered uniform to all simulation locations, although this is not the case for the actual state. This might explain the non-consistent trend in OC deviation between predictions and measurements in the upper parts of the soil.

Regarding the CEC, the model performs at all depth zones better than the overall average of the measurements (positive EF; Table 5.1). The average measured CEC in the top 0.4 m of the profiles is 61.8 $mmol_c\ kg^{-1}$ in the coarser textured soils and 243.2 $mmol_c\ kg^{-1}$ for the finer textured soils (Table 5.2). Generally, these measurements are underestimated by the model (Figure 5.5f). Furthermore, at a 0.25-0.30 m depth, the model induces artefacts in the CEC depth profile at all locations (Figure 5.6f). This is related to a drop in simulated OC at equal depth. Because the CEC is strongly related to the clay and OC content, an underestimation of the CEC is to be expected whenever clay and/or OC content are also underestimated. As mentioned above, this is especially true for the clay fraction in the 0.4 m of the profile.

Table 5.1 Root mean square error (RMSE), mean absolute error (ME) and modelling efficiency (EF) for sand, silt, clay (mass % of fine earth) and OC (mass % of the solid fraction), calcite (mass fraction) and pH (all with n=96), and CEC ($mmol_c\ kg^{-1}$ soil; n=88) for zones of different depth beneath the surface (m). The total depth varies per profile location.

	Depth beneath the surface (m)											
	0-0.4			**0.4-0.8**			**0.8-1.2**			**1.2-end**		
	RMSE	ME	EF	RMSE	ME	EF	RMSE	ME	EF	RMSE	ME	EF
Sand	5.85	3.40	0.89	1.84	1.06	0.99	0.98	0.66	1.00	3.09	-0.36	0.98
Silt	9.17	-8.39	0.35	2.25	-0.93	0.97	0.73	-0.24	1.00	1.78	-0.10	0.98
Clay	7.72	4.99	-0.17	1.41	-0.13	0.96	0.90	-0.42	0.98	2.55	0.47	0.90
OC	0.85	-0.21	0.28	0.35	0.14	-0.13	0.11	-0.04	0.48	0.08	-0.06	0.07
Calcite	0.07	0.01	0.25	0.09	0.02	-0.03	0.06	0.01	0.58	0.12	-0.08	-19.15
CEC	67.58	27.93	0.41	44.93	14.55	0.40	46.20	16.05	0.45	34.15	12.18	0.44
pH	1.09	0.49	-0.52	1.15	0.29	-0.43	1.19	0.44	-0.31	1.33	0.56	-0.32

Table 5.2 Minimum, maximum and mean measured and predicted values of several soil variables up till 0.8 m depth. ZSP: Belgian texture classes sand (Z), sandloam (S) and light sandloam (P) grouped; LEU: Belgian texture classes loam (L), clay (E) and heavy clay (U) grouped. Units: sand, silt, clay in mass % of fine earth; OC in mass % of the solid fraction; calcite expressed as mass fraction; CEC in $mmol_c$ kg^{-1} soil.

ZSP	Depth beneath the surface (m)											
	0-0.4						0.4-0.8					
	minimum		maximum		mean		minimum		maximum		mean	
	Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim
Sand	52.38	51.66	97.75	89.06	84.22	79.79	54.38	54.71	99.00	97.74	86.64	86.06
Silt	2.25	10.75	42.25	47.42	11.76	19.37	0.55	1.61	39.75	40.49	9.72	10.40
Clay	0.00	0.12	11.58	6.47	4.02	0.84	0.00	0.54	12.25	11.93	3.64	3.54
OC	0.17	0.11	2.13	1.13	0.80	0.94	0.00	0.13	1.23	1.06	0.30	0.17
Calcite	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.01	0.00
CEC	23.38	37.82	161.75	51.69	61.84	46.53	25.13	36.23	105.50	59.59	54.41	46.87
pH	4.53	4.00	7.46	6.01	5.60	5.31	4.30	4.00	8.10	6.22	5.86	5.82

LEU	Depth beneath the surface (m)											
	0-0.4						0.4-0.8					
	minimum		maximum		mean		minimum		maximum		mean	
	Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim	Meas	Sim
Sand	4.88	6.81	61.50	70.71	39.74	45.25	1.75	1.32	93.88	92.20	53.11	57.76
Silt	24.75	27.72	54.00	83.99	38.65	50.02	3.25	3.69	56.63	57.41	32.52	28.05
Clay	9.63	1.47	41.13	17.05	21.61	4.74	1.00	2.27	52.13	55.58	14.37	14.18
OC	0.48	1.17	6.80	12.94	2.69	4.91	0.06	0.14	1.29	7.28	0.40	0.83
Calcite	0.00	0.00	0.59	0.26	0.11	0.02	0.00	0.00	0.59	0.41	0.11	0.03
CEC	72.88	56.49	367.88	558.45	243.20	215.13	35.13	42.52	341.25	377.77	138.29	91.30
pH	5.21	4.23	8.02	6.30	7.14	5.57	5.81	4.00	8.38	6.33	7.41	5.61

The errors with respect to the calcite contents are low, but so is the actual calcite fraction (Table 5.2). The EF indicates a slightly better efficiency than the average of the measurements. The calcite accumulates at a certain depth, but the predicted accumulated fractions are often larger than the measured ones (Figure 5.6e). In general, at present most profiles are decalcified. This trend is also predicted by the model. However, a few locations still contain $CaCO_3$ (for example, a maximum of 60% in the upper 0.4 m of certain profiles) over their entire measured depth. These concern mostly marl deposits dating to the Late Glacial (Bats et al., 2011; Crombé, 2005) and even these modelled profiles are practically entirely decalcified. However, the solubility constant of calcite was calibrated (see section 8.1.) and concluded to be adequate. This might suggest that during the simulation, although the calcite dissolution rate is estimated well, the dissolved calcite is too rapidly removed towards larger depths of the profile. This is most probably due to the enforced water table dynamics in the profiles, which appear to be overestimated. Underestimated calcite contents influence for example the pH and the base saturation. Considering the pH, the model performs generally worse than the global average of the measurements (negative EF). Measured pH in the study area ranges between 4.5 and 8.0 (Table 5.2) in the upper 0.4 m. This is however not matched by the simulations where the profiles are on average too acid. This is especially true for the finer textured soil classes (Figure 5.6g).

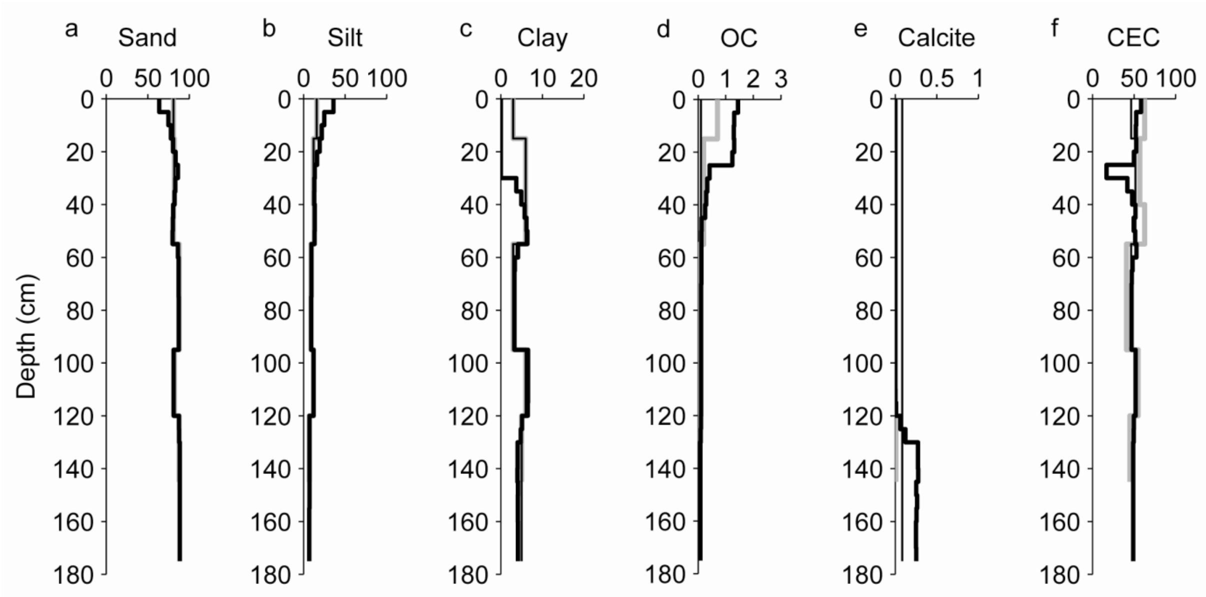

Figure 5.6 Evolution of the initial (thin black line), measured (grey line) and simulated (bold black line) soil variables with depth: sand, silt and clay fractions in mass % of the fine earth fraction (a-b-c); OC in mass % of the solid fraction (d); calcite in mass fraction (e); CEC in $mmol_c\ kg^{-1}$ soil (f) and pH (g).

5.7.3 Full-cover maps of soil variables at different points in time

The results of the regression kriging were compared with those of an ordinary kriging by performing a leave-one-out cross-validation, since no independent validation dataset was at hand (Table 5.3). It must be mentioned however, that the cross-validation is in fact performed on point kriging and not on block kriging. Although the validation results are not in absolute terms applicable to the resulting maps, we believed the observed relative trends to be applicable to the performed block kriging. The amount of variation explained was for all target variables the highest with the regression kriging. This appeared to be a better predictor than the ordinary kriging. Consistently, the RMSE on the regression kriging maps was also lower than for ordinary kriging. Furthermore, equal trends were found for other simulation years as well. However, the explained variation for pH, base saturation, OC and calcite content can vary largely between

Table 5.3 Evaluation of the cross-validation on the ordinary (OK) and regression (RK) kriging performed on several logit transformed target soil variables for the year 12716 BP. Sand, silt and clay fractions expressed in mass % of the fine earth fraction; OC in mass % of the solid fraction; calcite as mass fraction; base saturation in %; bulk density expressed as kg dm^{-3}.

Variable	Explained variation (%)		RMSE	
	OK	RK	OK	RK
Sand	34.54	63.81	0.88	0.65
Silt	45.09	63.45	0.64	0.52
Clay	23.72	69.47	0.93	0.59
OC	9.01	44.80	0.65	0.50
Calcite	62.03	66.70	0.22	0.21
pH	-2.06	16.89	0.04	0.04
Base saturation	6.49	40.88	2.17	1.72
Bulk density	25.40	67.76	0.18	0.12

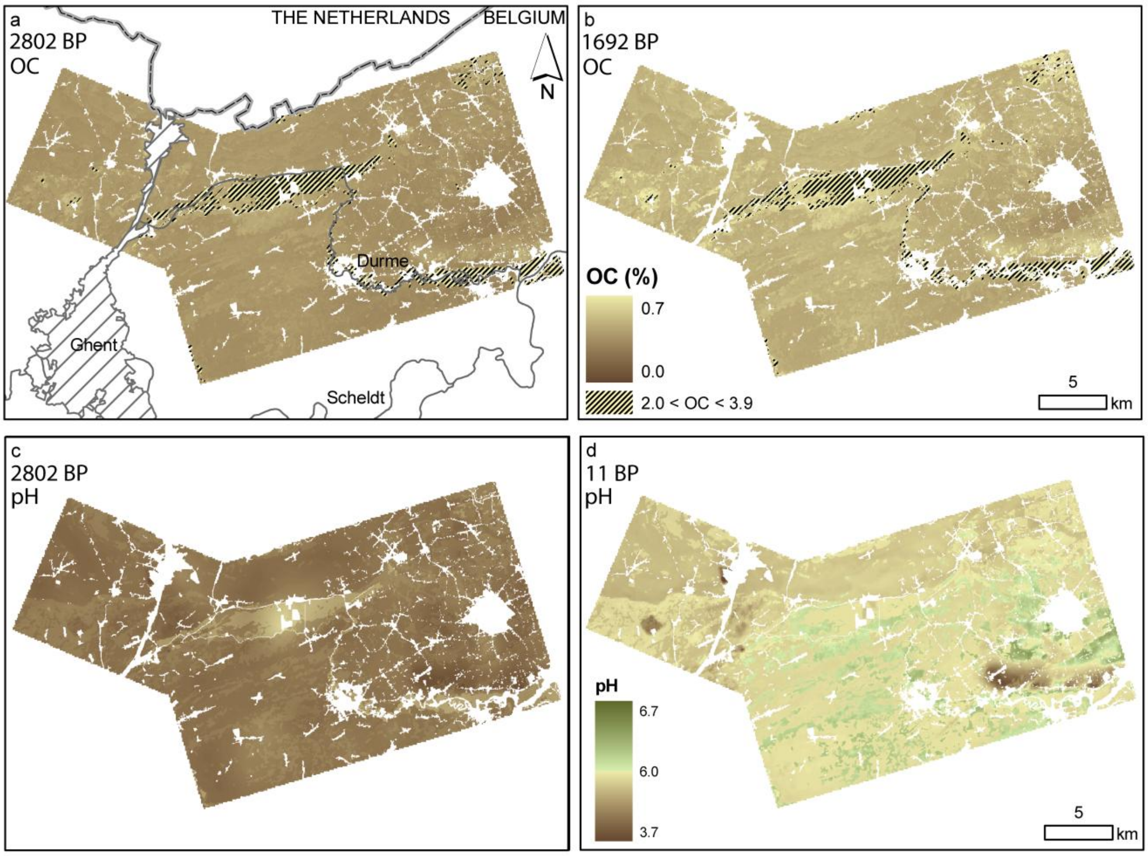

Figure 5.7 Regression kriging maps of the OC content and the pH in the topsoil (0-0.4 m) for two different times. a. OC content at 2802 BP: prehistoric agriculture; b. OC content at 1692 BP: two-field crop rotation; c. pH at 2802 BP: prehistoric agriculture without liming; d. pH at 11 BP: modern agriculture and modern liming system. (Other maps used: AGIV, 2002).

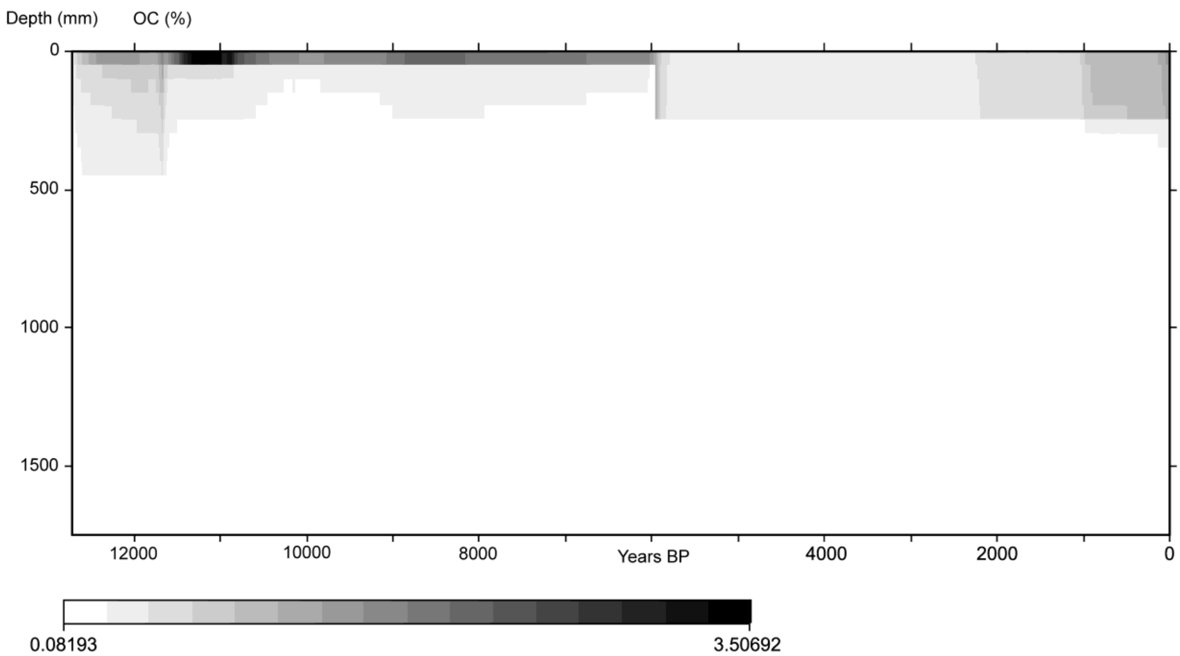

Figure 5.8 Simulated evolution of the OC content (% of the solid fraction) at one location over the entire simulation period.

simulation years and even be rather low. We believe this is most probably related to the data set: the simulation values as well as the profile location design. More accurate model predictions of the soil variables will most likely increase the accuracy of the kriging predictions. Furthermore, according to Hengl et al. (2004), a more even distribution of the point data is more appropriate for regression kriging.

An additional advantage of regression kriging over ordinary kriging is that, due to the use of auxiliary maps, regional trends are displayed on the kriging maps. For example, the OC content predicted on the regression kriging maps of the upper 0.4 m of the soil (Figure 5.7) is the highest in the areas bordering the rivers, while lower OC contents are predicted in the parts of the study area where sandy textured soils are dominant. The Moervaart Depression exhibits large OC contents as well. This area is characterized by clayey and loamy sediments, as well as peaty infillings and marls that representing alluvial and even former lacustrine environments. Therefore, the higher OC contents spatially predicted here, are also in line with the expectations.

Furthermore, similar trends are also displayed on the regression kriging maps considering more previous time periods (Figure 5.7). They reflect the time evolution simulated at the separate point locations (Figure 5.8). For example, high OC values of the upper 0.4 m such as the ones predicted for the Preboreal under natural vegetation conditions (Figure 5.8) were strongly lowered due to the effect of prehistoric agriculture (Figure 5.7a). The establishment of the two-field crop rotation system, applied in the

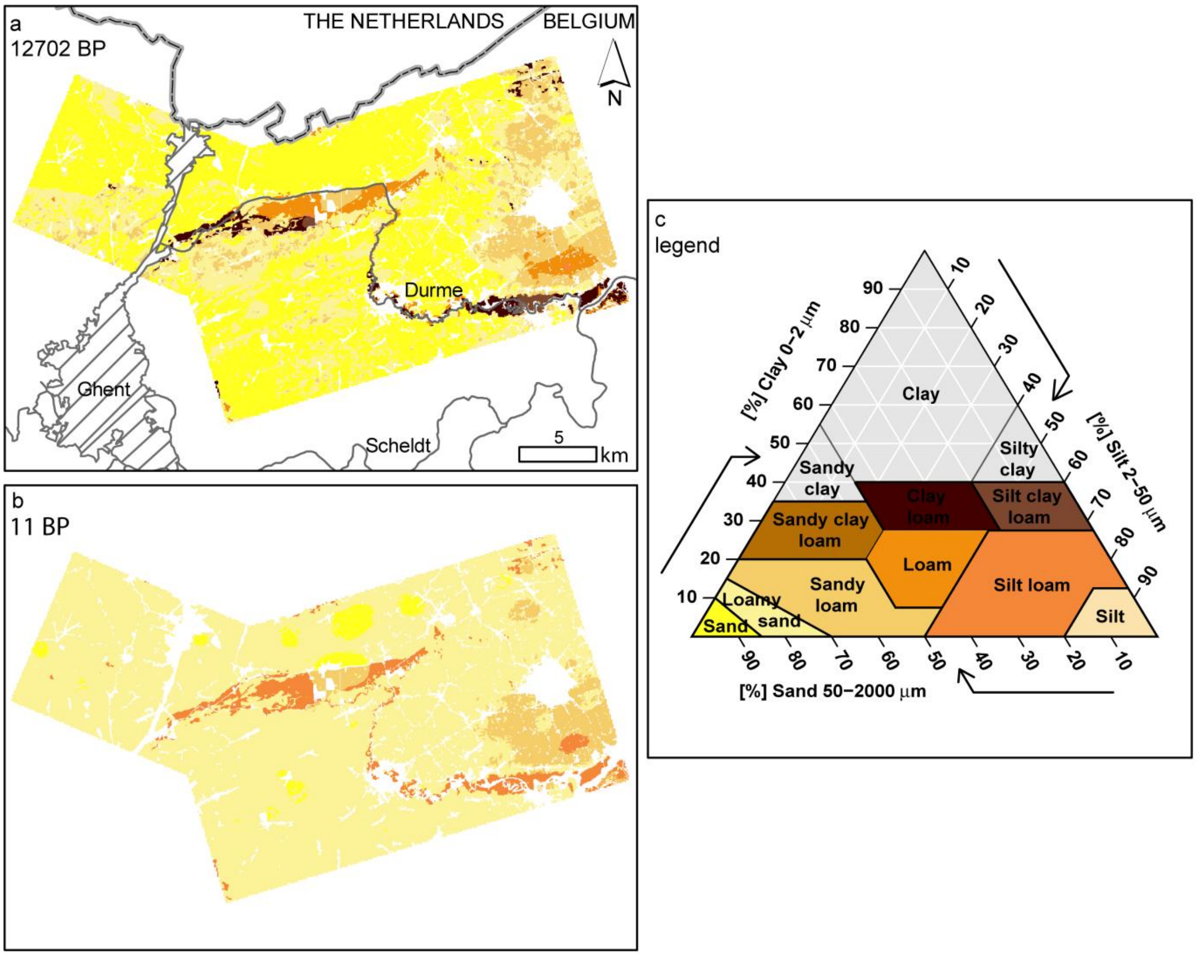

Figure 5.9 Texture class maps of the topsoil (0-0.4 m) according to the USDA classification system based on the regression simulation results for the sand, silt and clay fractions at two different times. a. 12702 BP ; b. 11 BP; c. USDA texture triangle explaining the used colour codes. (Other maps uses: AGIV, 2002).

model from 2160 BP (Late Iron Age) onwards, positively influenced the OC contents (Figure 5.7b). A trend that was continued by the introduction of three-field crop rotation and modern type agriculture, because of its higher biomass production. Similarly, the effect of liming, introduced in the model from 2560 BP onwards, is expressed for example in the increase in pH (Figure 5.7d). Again, regional trends are as expected: the highest values are found in the alluvial plains of the rivers and in the Moervaart Depression, characterized by its marl infillings; the more acid values occur in the surrounding sandy sediments. The southern edge of the sand ridge of Maldegem – Stekene has the highest leaching and reveals the lowest pH values. Very low pH values in the southeastern part of the study area are caused by overestimated groundwater depths (Zwertvaegher et al., in review). However, as already said, the pH is underestimated by the model and this results in too acid predictions at the profile locations. This is reflected in the full-cover kriging maps. Furthermore, certain local hot spots (Figure 5.7c) are found on the regression kriging map. Because regression kriging predicts the value of the target variable at the input location, this is related with inconsistencies in the target data due to underestimated pH simulations. Better model predictions of the soil variables will most likely result in better kriging predictions.

The predictions on the fine earth fractions were used to create topsoil texture class maps according to the USDA soil texture classification system (Figure 5.9). Again, regional patterns are observed: finer textured soils in the alluvial valleys, while the rest of the study area is largely characterized by coarser material. However, for the most recent period (Figure 5.9b) textures are not entirely consistent with what can be found on the present day soil map. This is related to overestimation of weathering and clay migration in the simulations, which resulted in an underestimation of the sand and clay fractions and an overestimation of the silt fraction.

5.8 Conclusions

The SoilGen2 model was used to predict the evolution of several soil variables at various depths at 96 profile locations in a 584 km^2 study area in Sandy Flanders (Belgium). A time period of 12,716 years was covered, starting in the Younger Dryas and spanning the entire Holocene. The model quality was optimized by calibration of the calcite solubility constant and testing the calibrated value under a wide range of representative precipitation surpluses. The model performance evaluation indicated that the fine earth fractions were reasonably well predicted. However, clay fractions in the upper part of the soil were strongly underestimated due to overestimation of the clay migration, while clay formation might be underestimated. On the other hand, the illuviation depth was estimated well. Sand and silt fractions were respectively under- and overestimated, as the result of an overestimation of the weathering. CEC, calcite content and pH were underestimated. The model quality can therefore be optimized by focussing on these processes. Additionally, errors may have been introduced by poor estimates of initial soil properties in the Younger Dryas. Adding the podzolization process will enhance the OC estimations at higher depths in these coarser textured soils. Furthermore, the mimicked dynamics of shallow water tables falling within the profile need to be re-examined. Of course, one must keep in mind that a better reconstruction of the boundary conditions can also improve model quality. However, the necessary data are not always available. For example, pollen and archaeological evidence are often badly preserved in sandy soils.

The use of a regression kriging framework (Hengl et al., 2004) on the simulated point locations enabled the creation of full-cover maps of several soil characteristics at certain points in time. The regional variation on the regression kriging maps reflected well the expected trend. The results can be optimized by using a more equally distributed point dataset (Hengl et al., 2004). Furthermore, increased model quality will most probably also affect the regression kriging. Hengl et al. (2004) point out that the methodology on the spatial prediction of soil variables can be extended by including temporal variability of soil variables, as well as their variability with depth. We believe the SoilGen model combined with the regression kriging framework is a step in answering this question. Future research for other appropriate and/or improved auxiliary maps seems at hand, especially for internal (in depth) kriging predictions.

5.9 References

Addiscott, T.M., Wagenet, R.J., 1985. Concepts of solute leaching in soils - A review of modeling approaches. Journal of Soil Science 36(3), 411-424.

AGIV, 2001. Vectoriële versie van de Traditionele Landschappen (versie 1.0) 1/50,000. MVG-LIN-AROHM-Monumenten en Landschappen (GIS-Vlaanderen).

AGIV, 2002. Vectoriële versie van de VHA-waterlopen & -zones (versie 22/10/2002) 1/5,000. Vlaamse Milieumaatschappij - Afdeling Operationeel Waterbeheer (AGIV).

Ameryckx, J., 1960. La pédogenèse en Flandre sablonneuse. Pédologie 10, 124-190.

Antrop, M., Van Eetvelde, V., Janssens, J., Martens, I., Van Damme, S., 2002. Traditionele Landschappen van Vlaanderen. Universiteit Gent, Vakgroep Geografie. http://www.geoweb.ugent.be/landschapskunde/projecten/traditionele-landschappen-vlaanderen (Geraadpleegd op 14 augustus 2012).

Bats, M., De Smedt, P., De Reu, J., Gelorini, V., Zwertvaegher, A., Antrop, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2011. Continued geoarchaeological research at the Moervaart palaeolake area (East Flaners, B): field campaign 2011. Notae Praehistoricae 31, 201-211.

Bierkens, M.F.P., Finke, P.A., de Willigen, P., 2000. Upscaling and downscaling methods for environmental research. Kluwer Academic Publishers, Dordrecht.

Blume, H.-P., Leinweber, P., 2004. Plaggen soils: landscape history, properties, and classification. Journal of Plant Nutrition and Soil Science 167, 319-327.

Coleman, K., Jenkinson, D.S., 2005. ROTHC-26.3. A model for the turnover of carbon in soil. Model description and windows users guide. November 1999 issue (modified April 2005), Harpenden, UK.

Crombé, P., 2005. The last hunter-gatherer-fishermen in Sandy Flanders (NW Belgium). The Verrebroek and Doel excavation Projects. Vol.1. Archaeological Reports Ghent University, 3. Ghent University, Gent.

Crombé, P., Vanmontfort, B., 2007. The neolithisation of the Scheldt and Basin in western Belgium. Proceedings of the British Academy 144, 261-283.

Crombé, P., Van Strydonck, M., Boudin, M., Van den Brande, T., Derese, C., Vandenberghe, D., Van den haute, P., Court-Picon, M., Verniers, J., Gelorini, V., Bos, J.A.A., Verbruggen, F., Antrop, M., Bats, M., Bourgeois, J., De Reu, J., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., Zwertvaegher, A., 2012, in press. Absolute dating (14C and OSL) of the formation of cover sand ridges occupied by prehistoric hunter-gatherers in NW Belgium. Radiocarbon.

Dann, R.L., Close, M.E., Lee, R., Pang, L., 2006. Impact of data quality and model complexity on prediction of pesticide leaching. Journal of Environmental Quality 35(2), 628-640.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., Contributors, D., 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 1701-1716.

De Moor, G., Heyse, I., 1974. Lithostratigrafie van de Kwartaire afzettingen in de overgangszone tussen de kustvlakte en de Vlaamse Vallei in Noordwest België. Natuurwetenschappelijk Tijdschrift 56, 85-109.

De Moor, G., van de Velde, D., 1995. Toelichting bij de Quartairgeologische Kaart. Kaartblad 14: Lokeren, Universiteit Gent, Ministerie van de Vlaamse Gemeenschap - Afdeling Natuurlijke Rijkdommen en Energie, Brussel.

De Reu, J., Bourgeois, J., De Smedt, P., Zwertvaegher, A., Antrop, M., Bats, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2011. Measuring the relative topographic position of archaeological sites in the landscape, a case study on the Bronze Age barrows in northwest Belgium. Journal of Archaeological Science 38, 3435-3446.

De Vries, W., Posch, M., 2003. Derivation of cation exchange constants for sand, loess, clay and peat soils on the basis of field measurements in the Netherlands. Alterra-report 701, Alterra Green World research, Wageningen.

Dudal, R., Deckers, J., Van Orshoven, J., Van Ranst, E., 2005. Soil Survey in Belgium and its Applications.

Egli, M., Fitze, P., 2001. Quantitative aspects of carbonate leaching of soils with differing ages and climates. Catena 46, 35-62.

FAO, 1976. A framework for land evaluation. Soils Bulletin 32. FAO, Food and Agriculture Organization of the United Nations, Rome.

FAO, 2001. Lecture notes on the major soils of the world. World Soil Resources Report No. 94, Wageningen, International Institute of Aerospace Survay and Earth Sciences, Catholic University of Leuven, International Soil Reference and Information Centre, FAO, Rome.

Finke, P.A., 2012. Modeling the genesis of luvisols as a function of topographic position in loess parent material. Quaternary International 266, 3-17.

Finke, P.A., Hutson, J.L., 2008. Modelling soil genesis in calcareous loess. Geoderma 145, 462-479.

Foth, H.D., Ellis, B.G., 1996. Soil Fertility (2nd ed). CRC press, Lewis, pp. 304.

Gobat, J.-M., Aragno, M., Matthey, W., 1998. Le sol vivant. Press polytechniques et universitaires romandes, Lausanne.

Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. . Applied Engineering in Agriculture 1, 96-99.

Hengl, T., 2007. A practical guide to geostatistical mapping of environmental variables. EUR 22904. Scientific and Technical Research series. Luxemburg.

Hengl, T., 2009. A practical guide to geostatistical mapping. www.lulu.com, Amsterdam.

Hengl, T., Heuvelink, G.B.M., Stein, A., 2004. A generic framework for spatial prediction of soil variables based on regression kriging. Geoderma 120, 75-93.

Heyse, I., 1979. Bijdrage tot de geomorfologische kennis van het Noordwesten van Oost-Vlaanderen. verhandelingen van de koninklijke Academie voor Wetenschappen, letteren en schone kunsten van België, Klasse der wetenschappen. Paleis der Academiën, Brussel.

Hutson, J.L., Wagenet, R.J., 1992. LEACHM: Leaching Estimation And Chemistry Model: A process based model of water and solute movement transformations, plant uptake and chemical reactions in the unsaturated zone. Vol. 2, Version 3, Water Resources Inst., Cornell University, Ithaca, NY.

IUSS Working Group WRB, 2006. World reference base for soil resources 2006. A framework for international classification, correlation and communication. World Soil Resources Report No. 103, FAO, Rome.

Jabro, J.D., Jabro, A.D., Fox, R.H., 2006. Accuracy and performance of three water quality models for simulating nitrate nitrogen losses under corn. Journal of Environmental Quality 36(4), 1227-1236.

Jalali, M., Rowell, D.M., 2003. The role of calcite and gypsum in the leaching of potassium in a sandy soil. Experimental Agriculture 39, 379-394.

Jenny, H., 1941. Factors of Soil Formation. A System of Quantitative Pedology. McGraw-Hill Book Company, Inc., New York, pp. 281.

Knight, D., Howard, A.J., 2004. Trent Valley Landscapes. The archaeology of 500,000 years of change. Heritage Marketing and Publications Ltd, King's Lynn.

Loague, K., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport models: Overview and application. Journal of Contaminant Hydrology 7, 51-73.

Mayer, D.G., Butler, D.G., 1993. Statistical validation. Ecological Modelling 68, 21-32.

Moeys, J., 2012. The soil texture wizard: R functions for plotting, classifying, transforming and exploring soil texture data.

Niknami, K.A., Amirkhiz, A.C., Jalali, F.F., 2009. Spatial pattern of archaeological site distribution on the eastern shores of Lake Urmia, northwestern Iran. Archaeologia a Calcolatori 20, 261-276.

Oetelaar, G.A., Oetelaar, J., 2007. The new ecology and landscape archaeology: incorporating the anthropogenic factor in models of settlement systems in the Canadian prairie ecozone. Canadian Journal of Archaeology 31, 65-92.

R Development Core Team, 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Sanders, J., Sys, C., Vandenhout, H., 1989. Bodemkaart van België - Verklarende tekst bij het kaartblad Stekene 26E, Centrum voor de afwerking van de Bodemkaart in het Noorden van het land.

Sauer, D., Finke, P.A., Sørensen, R., Sperstad, R., Schülli-Maurer, I., Høeg, H., Stahr, K., 2012. Testing a soil development model against southern Norway soil chronosequences. Quaternary International.

Sivapalan, M., 1993. Linking hydrologic parameterizations across a range of scales: hill slope to catchment to region. In: Exchange processes at the land surface for a range of space and time scales. Proceedings of the Yokohama symposium. IAHS Publ., pp. 115-123.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertob, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81(1-2), 153-225.

Soens, T., 2011. The genesis of the Western Scheldt: towards an anthropogenic explanation for environmental change in the medieval Flemish coastal plain (1250-1600). In: E. Thoen, G. Borger, T. Soens, A.M.J. De Kraker, D. Tys, L. Vervaet (Eds.), Landscapes or seascapes? The history of the coastal area in the North Sea region revised. CORN Publication Series, Turnhout.

Tavernier, R., Maréchal, R., Ameryckx, J., 1960. Bodemkartering en bodemklassifikatie in België, Ministerie van Landbouw, Nationaal Comité van FAO.

Van Orshoven, J., Deckers, J.A., Vandenbroucke, D., Feyen, J., 1993. The completed database of Belgian soil profile data and its applicability in planning and management of rural land. Bulletin des Recherches Agronomiques de Gembloux 28, 197-222.

Van Orshoven, J., Maes, J., Vereecken, H., Feyen, J., Dudal, R., 1988. A structured database of Belgian soil profile data. Pedologie 38(2), 191-206.

Van Ranst, E., Sys, C., 2000. Eenduidige legende voor de digitale bodemkaart van Vlaanderen. Universiteit Gent, Gent.

Verbruggen, C., 1971. Postglaciale landschapsgeschiedenis van zandig Vlaanderen. Botanische, ecologische en morfologische aspekten op bais van palynologisch onderzoek, Rijksuniversiteit Gent.

Verbruggen, C., Denys, L., Kiden, P., 1996. Belgium. . In: B.E. Berglund, H.J.B. Birks, M. Ralska-Jasiewiczowa, H.E. Wright (Eds.), Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley & sons, Chichester, pp. 553-574.

Verbruggen, C., Denys, L. & Kiden, P., 1996. Belgium. In: B.E. Berglund, H.J.B. Girks, M. Ralska-Jasiewiczowa, H.E. Wright (Eds.), Palaeoecological events during the last 15000 years: Regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley & Sons Ltd., Chichester.

Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital elevation model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.

Wösten, J.H.M., Veerman, G.J., De Groot, W.J.M., Stolte, J., 2001. Waterretentie- en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: de Staringreeks, Alterra, Wageningen.

Zidan, Y.O.Y., 2008. Mapping phreatic water tables to update the drainage class map 1:20,000 in the Scheldt Valley near Ghent. Unpublished thesis. Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Physical Land Resources Thesis, Ghent University, Ghent, 89 pp.

Zwertvaegher, A., Finke, P.A., De Reu, J., Vandenbohede, A., Lebbe, L., Bats, M., De Clercq, W., De Smedt, P., Gelorini, V., Sergant, J., Antrop, M., Bourgeois, J., De Maeyer, P., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Reconstructing phreatic palaeogroundwater levels in a geoarchaeological context, a case study in Flanders (Belgium). Geoarchaeology: An International Journal.

Zwertvaegher, A., Werbrouck, I., Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, P., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the Use of Integrated Process Models to Reconstruct Prehistoric Occupation, with Examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal 25(6), 784-814.

Chapter 6
Land evaluation

Abstract

An archaeological land evaluation considering the Neolithic, Bronze and Iron Age, was performed for a study area in Sandy Flanders. The land characteristics were delivered by a framework of integrated process models. Based on the performed land evaluation, preliminary conclusions on the suitability and the carrying capacity of the land were made. The largest part of the study area was concluded to be dominantly marginally suitable (68.6-78.3%) for all evaluated land utilization types and time periods. A large part of the area was classified as not suitable (21.6-31.2%) and a very small part of the total area was classified as moderately suitable (0.01-0.38%). Based on estimated crop yields and livestock composition, a maximum of 9,490 persons could be supported by the 50,592 ha large study area (i.e. 5.3 ha per) in the Middle Bronze Age. This is achieved when 12% of the area is under crop cultivation. For arable areas below 12% of the study area, carbohydrate production from grains appeared to limit the population number; for larger areas the number of people is limited by the animal protein production. The use of process models gives promising results because they provide a fully quantitative input of the land characteristic to the land evaluation and it makes the methodology entirely reproducible. However, this framework should preferably be expanded with a dynamic crop growth simulation model to also quantify land evaluation outputs and enhance carrying capacity assessment.

6.1 Introduction

In 1992, in Malta, the European Convention on the Protection of the Archaeological Heritage was held (Council of Europe, 1992). Since then, several countries have subscribed and ratified this Malta Convention, also called the Valetta Treaty. As a result, more focus is placed on the proper disclosure of the archaeological heritage and its management, but also on non-destructive inventorying techniques and methodologies considering the spatial analysis of the archaeological site locations. Spatial analysis in archaeology has a long history, starting already at the end of the 19th century, having its roots in the discipline of economic geography (Rood, 1982). However, it soon became clear that for the explanation of the spatial distribution of archaeological find spots not only economic factors, but also cultural and political agents, as well as geofactors (constituents of the landscape) needed to be taken into account (Rood, 1982). The relation between these human factors on the one hand and the landscape on the other hand, and therefore also the spatial patterning of the remains of these anthropologic activities, can be tackled by the performance of an archaeological land evaluation modelling.

Land evaluation is *'the process of assessment of land performance when used for specified purposes involving the execution and interpretation of surveys and studies of landforms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation'* (FAO, 1976). At present, land evaluation serves as a valuable support in many fields, for example, in land use planning, land management or land-degradation control (FAO, 2007), and it is especially useful in long-term food security assessments and carrying capacity studies in (developing) countries under growing population pressure (e.g. Wright, 1987; Ye et al., 2009). The methodology was first implemented in archaeology by Kamermans et al. (1985) as a form of deductive predictive modelling. Other known studies on archaeological land evaluation are, for example, by Finke et al. (1994), Finke and Sewuster (1987), Kamermans (1993) and Van Joolen (2003). Mostly, agrarian land use is evaluated, although it is also possible to look at a broad interpretation of the land use and exploitation. For example, Kamermans (1993) investigated the land evaluation predictive potential for generalist and specialist hunter-gatherers and sedentary fisher communities in Palaeolithic and Mesolithic Central Italy (Agro Pontino, Lazio region).

In contrast to present-day land evaluation, where present and future land and land uses are considered, the basic characteristic of archaeological land evaluation is that it tries to establish the suitability of past landscapes for past uses of land. Therefore, past land use and technologies, as well as past landscapes and land characteristics, need to be reconstructed (Van Joolen, 2003). However, the characterization of the past land in archaeological land evaluation is often directly based on present-day surveyed properties. Therefore, we have proposed (Zwertvaegher et al., 2010; Chapter 3) the use of process models in order to reconstruct properties of the land, required to perform the land evaluation. It is our aim to test the land evaluation methodology with the reconstructed land characteristics for the study area, with a focus on agrarian communities, as well as to test the assessment of a population carrying capacity based on the suitability maps resulting from the land evaluation. To achieve this, several specific research questions need to be answered. These objectives are:

- To define the past land uses in the study area and period;
- To define the requirements of the considered land use;
- To define and quantify the land characteristics necessary to assess the defined requirements and land qualities;
- To define the suitability ranges per land characteristic/land quality;
- To define how the land qualities need to be evaluated and to practically implement this to perform the land evaluation and produce land suitability maps;
- To test the land suitability classification with the known archaeological sites;
- To perform and evaluate a carrying capacity assessment based on the land suitability classification.

6.2 Pre- and protohistoric agriculture in the sandy lowlands: a literature review

Archaeological evidence on the agrarian production and food procurement system in the study region and by extension Sandy Flanders, is rather limited. Therefore, to obtain an overall view on the land use, information needs to be combined from different regions covering similar environmental and archaeological contexts, preferably all within the sandy lowlands of the Northern European Plain. However, scholars often point to the poor preservation conditions of organic remains in these sandy soils under the prevailing climatic conditions, which largely limit the evidence (e.g. Bakels, 2005; Baxter, 2004). This forms a discrepancy with the wetland environments, which are generally revealing more information. It must also be taken into consideration that not all archaeological remains have the same probability of preservation. For example, the finds of peas (*Pisum sativum*) are rather limited, which might be related to their processing. This all contributes to the fact that various hypotheses on pre- and protohistoric land use and agriculture are found in archaeological literature. These are often based on sometimes restricted, dispersed and indirect evidence, where equal finds sometimes have led to contradicting ideas.

6.2.1 Final Mesolithic and Neolithic

The Mesolithic-Neolithic transition in the sandy regions of the Northern European Plain, is generally seen as a process of acculturation, in contrast to the loess area where agriculture apparently arrived as a full package. In this process, the adoption of animal husbandry in the Mesolithic broad-spectrum economy, is after some centuries followed by the incorporation of crop cultivation. This is evidenced for example, by findings at the Dutch wetland site at Swifterbant, where a sequence of small-scale incorporations of first pottery (ca. 5000 BCE), then domesticated animals (ca. 4700 BCE) and finally cereal cultivation (4100 BCE), were recorded (Cappers and Raemaekers, 2008). Emmer wheat (*Triticum dicoccon*) and barley (*Hordeum vulgare*) were the dominant cereals, although einkorn wheat (*Triticum monococcum*) and possibly bread wheat (*Triticum aestivum/durum*) were also found. Furthermore, at the Swifterbant site S4 (the Netherlands) a possible agricultural field of 100 m^2 was found (Raemaekers, 2007). Micromorphological analyses suggested thorough soil mixing, most probably as the result of tillage (Huisman et al., 2009), possibly with a hoe (Raemaekers, 2007). Here, a cultivation regime of spring cropping of emmer and barley in a small-scale strip intercropping system on the sandy levees was proposed. It was assumed that nutrients were sporadically replenished by the seasonal flooding of the levees (Cappers and Raemaekers, 2008). The amount of evidence for local agriculture at various Dutch wetland sites, suggests that crop cultivation was incorporated in the subsistence economy from 4300 BCE onwards, and that the remains were not just the result of exchange of surplus yields from agrarian societies in the interior (Out, 2008). However, the question remains in how far evidence from these wetland sites is applicable to the cover sand area. For this region, the neolithization debate is still ongoing.

Kirleis et al. (2012) evaluated the archaeobotanical data from Neolithic sites of several northwestern European countries. For the entire region, comparable trends were found: a dominance of emmer wheat and barley, mainly naked. Depending on the time and region, both cereal taxa occurred in changing ratios: while in southern Scandinavia, hulled wheat was prominent, naked barley seemed to be more dominant in northern Germany and the Netherlands. Einkorn, spelt (*Triticum spelta*) and naked wheat (bread wheat or macaroni wheat) also appeared, although not everywhere (Kirleis et al., 2012). Opium poppy (*Papaver somniferum* ssp. *setigerum*) and flax (*Linum usitatissiumum*) were rare, but present. According to Bakels (2005), flax was grown from the Middle Neolithic onward, even in the more sandy areas. Out (2009) states that the very few remains of opium poppy suggest that it was an unusual crop plant. Remains of pea are very rarely found in the Netherlands, and in northern Germany (Kirleis et al., 2012; Out, 2009). The economic importance of pea, however, is difficult to reconstruct because of the limited possibility of carbonisation during crop processing and food preparation and bad preservation in the waterlogged state (Out, 2009). Based on the remains of gathered plants found at the several sites, the diet also consisted of gathered fruits and nuts. Considering the faunal remains, Bogucki (1988) states that in contrast to the loess belt, the proportion of wild species in the faunal assemblages of the Northern European Plain is much higher, although their percentage can vary considerably between different sites and site types. Hunting and fishing appeared to be a very important part of the subsistence. The list of domesticated animals contains dog, cattle, sheep/goat and pig (Lauwerier et al., 2005). Although for the latter, the difference between wild and domesticated pig is not easy from an osteological point of view (Bogucki, 1988).

It is generally assumed that shifting cultivation (also called slash-and-burn, long fallow or forest fallow) was practiced in the sandy areas. This type of cultivation requires the clearance of primary or secondary forest, often by burning, after which the newly cleared soil is cultivated for one to five years (Bogaard, 2004). Often, arguments for shifting cultivation are based on indirect evidence. For the *Linearbandkeramik* in the loess belt, this was contradicted by Bogaard (2004). Based on the study of weed assemblages, the most dominant crop-husbandry technique was concluded to be intensive garden cultivation with long-established autumn-sown cereal plots (Bogaard, 2004). Unfortunately, studies based on this more direct evidence provided by weed and grain assemblages, are not yet available for the Neolithic in the more sandy areas. In the Netherlands, the oldest ard marks date from the Middle Neolithic (Bakels and Zeiler, 2005; Fokkens, 2005a). However, evidence from for example Germany, Great Britain and Denmark, suggest that the ard was already in use in the Early Neolithic (Milisauskas and Kruk, 2011; Wilkinson and Straker, 2008). Milisauskas and Kruk (2011), in an overview on European prehistory, mention figurines that might represent oxen as a possible indication for the use of the ox-drawn ard. The ard itself did not turn the soil and was therefore most probably used to create furrows to germinate the seeds (Fokkens, 2005a; Van Joolen, 2003), after the soil was already broken by other means and tools. The practice of manuring is still largely debated. According to Bakels (1997), domestic waste was used as a fertilizer in western Europe already from the Late Neolithic onwards. For Neolithic to Iron Age Scotland, it was demonstrated that midden heaps (compost piles) were sometimes in situ ploughed and cultivated (Guttmann, 2005).

6.2.2 Bronze and Iron Age

Based on direct botanical evidence from weeds, crops and gathered fruits and nuts, de Hingh (2000) evaluates the agrarian production and food procurement for the Meuse-Demer-Scheldt region. This region corresponds to the cover sand areas of the southern Netherlands and northeastern Belgium (Roymans and Gerritsen, 2002). She characterizes the agricultural regime during the Middle Bronze Age as a cereal-based intensive agriculture. The cultivated cereals were naked and hulled barley, millet (*Panicum miliaceum*), emmer wheat, spelt wheat, possibly completed with einkorn and bread wheat (de Hingh, 2000). The dominance of emmer wheat and naked barley, was previously mentioned by Theunissen (1999) for the Middle Bronze Age Hilversum culture in the southern Netherlands. It is remarkable that extensive or shifting cultivation could not be demonstrated based on the archaeobotanical evidence. The agricultural regime was characterized by manuring, intensive soil working, hoeing, weeding, probably ploughing with the ard, and no fallow periods. Fokkens (1986) mentioned that fallow periods should have been short (only few years), since re-growth of trees and deep root systems would have otherwise seriously hampered the ploughing.

Furthermore, the Middle Bronze Age is characterized by the introduction of the wooden longhouse. In certain sites (for example the site of Loon op Zand in the Netherlands), a part of the floor plan exhibited the remains of stable boxes, leading to the interpretation of the houses as byre-houses: farmhouses containing living quarters, as well as a part for stabling the animals. Although most house plans do not reveal evidence of stable boxes, the longhouses are generally assumed to be byre-houses. Several explanations on the introduction of the separate stable part are suggested, such as the protection against raids or the enhanced collection of animal dung for manuring (Louwe Kooijmans, 1993). These reasons are not exclusive and can be cumulative. It is generally believed that the byre-house plays a central role in the integrated mixed crop-livestock farming, which is considered to be fully established in the Middle Bronze Age (Fokkens, 2005c). In this type of farming, crop cultivation and livestock farming are combined with the advantage of reusing resources: crop residues as animal fodder and the animal excreta as manure and crop nutrients (FAO, 2001). Based on archaeozoological remains, it is concluded that the animal husbandry was dominated by cattle, although pigs, sheep and/or goats were also kept (Fokkens, 2005a; Theunissen, 1999). Sometimes, evidence for stabling of 30 to 40 cattle was found (Fokkens, 2005b). The average herd of cattle is estimated at a number of 20 animals per farm (Theunissen, 1999). Hunting and fishing, as well as the collection of wild fruits and nuts, still played a role in the food subsistence, most probably being part of an economic strategy of risk reduction (de Hingh, 2000).

It is assumed that the settlements were organised in 2 to 3 clustered farmsteads, at some hundred meters distance from each other. Each farm was inhabited by a large household, in which 3 to 4 generations (grandparents, parents and children) lived together. This extended family was comprised of approximately 8 to 12 persons. Most probably, the entire settlement, formed by ca 16 to 36 people, exploited an area of around 100 ha or more (Theunissen, 1999). Within this area, the farms were rebuild at regular times. Hence, the principle of ‘wandering farms’ (Fokkens, 2005a). Several reasons for this wandering are postulated: the depletion of the soil, the maximum lifespan of the post-built houses, which was estimated at ca 30 year, and cultural terms and traditions (de Hingh, 2000; Roymans and Gerritsen, 2002).

From the Late Bronze Age onwards, pulses are found in the botanical record: lentil (*Lens culinaris*), pea, and possibly horse bean (*Vicia faba*), together with the oil-containing gold-of-pleasure (*Camelina sativa*) and probably flax, next to the cereals already known from the Middle Bronze Age (except naked barley; de Hingh, 2000). Based on evidence from collected weed assemblages, this large variety of crop species is concluded to be linked with a highly differentiated agricultural regime in which soil working and manuring were important factors (de Hingh, 2000). This correlates most probably with an infield-outfield type of agriculture, or a co-occurrence of different scales and intensities of cultivation. Several of the attested crop species, such as lentil, pea, horse bean, millet, gold-of-pleasure and flax, require a small-scale intensive cultivation and a horticulture-like care (de Hingh, 2000). The arable plots were part of systematically organized Celtic field systems, with a typical layout of small parcels, surrounded by wide banks (Kooistra and Maas, 2008). It is suggested that the size of the plots (on average 30 m x 30 m) is the amount of land one farmer could plough, sow and harvest in a time frame of one day (van Wijngaarden-Bakker and Brinkkemper, 2005). However, it is uncertain how much of these plots were simultaneously in use. Speculations are often based on expected yields to feed a specified amount of people in a defined time period and providing enough sowing seed for the following season. Of course, yield estimations in their turn are based on assumptions about the agricultural regime (for example, manuring or not, type of sowing, etc.). According to Fokkens (1991), each household yearly cultivated 1 to 5 ha of arable land, or between 11 and 55 fields, based on an average surface of 0.1 ha per field. On the other hand, de Hingh (2000) concludes that the total of cultivated plots per household was quite low, the use of small and scattered plots being a way to reduce risk and uncertainty, meanwhile encouraging the cultivation of various crops on a mixture of land with a range of soil types and other conditions. Several hypothesis on cultivation regime, such as single or mixed cropping, maslin cultivation, type of crop rotation, do exist in archaeological literature, although the rationale behind these hypotheses is not always tenable (de Hingh, 2000). Finds of single crop assemblages do not automatically prove single cropping, since several crops can be cultivated on the same field and be harvested separately. Mixed assemblages on the other hand are not always a direct indication of mixed cropping, for example mixing smaller millet grains with larger grains of barley/wheat to reduce intergranular voids in the storage and prevent the disturbance by weevils, as practiced in 17th century France (de Hingh, 2000). However, mixed cropping (several crops simultaneously cultivated at the same field) and/or multiple cropping (successive cultivation of several crops at the same field) is assumed by de Hingh (2000) for Late Bronze Age and Early Iron Age agriculture.

During the Middle and Late Iron Age, farms are still frequently moved and rebuild, although the distance between the previous and the new location appears to be shorter. Sometimes overlapping floor plans are found. This is generally assumed to be linked with a higher permanency of the settlements, leading to more nucleated hamlets and small villages with fixed farmsteads in the Roman period (Roymans and Gerritsen, 2002; Schinkel, 2005). More solid houses are also present, which might also indicate an objective of longer residency (de Hingh, 2000). Sites with a very systematic organization in which the farmyards are surrounded by ditches are often found. These are called 'fermes indigènes' and are specifically well known from Late Iron Age northern France (Annaert and Creemers, 2012). The Celtic field systems are believed to decline. In this late phase, intensive cultivation and manuring was practiced more and more on the banks between the fields, than on the intermediate fields (Roymans and Gerritsen, 2002). Pliny the Elder mentions the use of marl for liming to enhance soil fertility during Roman times in Britannia and Gallia (Kuhlmann, 2001). The cultivated crops are the same as the ones found during the Early Iron Age, except for lentil that disappears (de Hingh, 2000). From the Iron Age onward, the ard was already an established tool, however with the production of iron, the wooden ardshare was sometimes protected with an iron sheath (Bakels, 2009; van den Broeke, 2005). In the Netherlands, evidence of this iron sheath was found dating to the 3rd century BCE (van den Broeke, 2005).

6.3 Methodology

6.3.1 Description of the potential land utilization types

Potential land utilization types (LUT) are used in archaeological land evaluation, to describe, in detail, potential ways in which people used the land in the past (Van Joolen, 2003). The temporal resolution of the data limited the number of time periods for which LUTs could be reconstructed. We have focussed this study on agrarian (crop cultivation) land use. Furthermore, only those periods were considered for which available evidence indicated a land use that differed from the one prevailing in the previous period. Following Kamermans (1993), the economic system was assumed to be largely constant during the entire time frame of the distinguished periods. Weed assemblages distinguished by de Hingh (2000) provided the most direct evidence on pre- and protohistoric land use and therefore the same time differentiation was used, resulting in 4 periods: Neolithic and Early Bronze Age (i), Middle Bronze Age (ii), Late Bronze Age and Early Iron Age (iii) and Midde and Late Iron Age (iv). The attributes relevant to the description of the potential LUTs were collected from literature. Based on this information, several potential LUTs were defined (Table 6.1). LUTs in which manuring was applied were also tested without manuring to evaluate its effects.

For the Neolithic and Early Bronze Age:

i. Subsistence rainfed cereal farming with prolonged fallowing (shifting cultivation), in which barley was permanently cultivated during the arable period. Ox-drawn ards were used to make furrows for the seeds (restricted input). No manuring was assumed.

ii. The same LUT as in (i), but with emmer wheat instead of barley.

For the Middle Bronze Age:

iii. Subsistence rainfed cereal farming with no fallow, in a two year rotation of barley (no difference made between naked and hulled barley) and emmer wheat. Ox-drawn ards were used to make furrows for the seeds. (a) Manuring with animal dung collected from stables; (b) No manuring.

iv. Subsistence rainfed cereal farming with no fallow, in a mixed cropping of emmer wheat and spelt wheat. Ox-drawn ards were used to make furrows for the seeds. (a) Manuring with animal dung collected from stables; (b) No manuring.

For the Late Bronze Age and Early Iron Age:

v. Subsistence rainfed cereal farming, in yearly rotation of emmer wheat and barley. Ox-drawn ards were used to make furrows for the seeds. (a) Manuring with animal dung collected from stables; (b) No manuring.

vi. The same LUT as in (vii), but with spelt wheat in rotation instead of barley. (a) Manuring with animal dung collected from stables; (b) No manuring.

vii. Subsistence rainfed farming with intensive (horticulture-like care) permanent cultivation of pea. Ox-drawn ards were used to make furrows for the seeds. There is intensive manual labour, such as frequent weeding. (a) Manuring with animal dung collected from stables; (b) No manuring.

viii. The same LUT as in (viii), but with lentil. (a) Manuring with animal dung collected from stables; (b) No manuring.

For the Middle and Late Iron Age:

ix. Subsistence rainfed cereal farming, in yearly rotation of emmer wheat and barley. Ox-drawn ards with iron ardshare were used. Liming was performed. (a) Manuring with animal dung collected from stables; (b) No manuring.

x. The same LUT as in (xi), but with spelt wheat in rotation instead of barley. (a) Manuring with animal dung collected from stables; (b) No manuring.

xi. Subsistence rainfed farming with intensive (horticulture-like care) permanent cultivation of pea. Ox-drawn ards with iron ardshare were used. There is intensive manual labour, such as frequent weeding. Liming was performed. (a) Manuring with animal dung collected from stables; (b) No manuring.

xii. Subsistence rainfed farming with intensive (horticulture-like care) permanent cultivation of pea. Wooden ox-drawn ards with no protective iron sheat were used. There is intensive manual labour, such as frequent weeding. Liming was performed. (a) Manuring with animal dung collected from stables; (b) No manuring.

Table 6.1 Evaluated land-utlization types. NEO: Neolithic; EBA: Early Bronze Age; MBA: Middle Bronze Age; LBA: Late Bronze Age; EIA: Early Iron Age; MIA: Middle Iron Age; LIA: Late Iron Age.

Code	Period	Yr BCE	Crops	Cropping system	Cattle manure	Liming	Mechanization
i	Neo-EBA	3971	emmer	single crop	no	no	wooden ard
ii	Neo-EBA	3971	barley	single crop	no	no	wooden ard
iii: a & b	MBA	1331	emmer & barley	rotation	a: yes; b: no	no	wooden ard
iv: a & b	MBA	1331	emmer & spelt	mixed	a: yes; b: no	no	wooden ard
v: a & b	LBA-EIA	941	emmer & barley	rotation	a: yes; b: no	no	wooden ard
vi: a & b	LBA-EIA	941	emmer & spelt	mixed	a: yes; b: no	no	wooden ard
vii: a & b	LBA-EIA	941	pea	single crop	a: yes; b: no	no	wooden ard
viii: a & b	LBA-EIA	941	lentil	single crop	a: yes; b: no	no	wooden ard
ix: a & b	MIA-LIA	252	emmer & barley	rotation	a: yes; b: no	yes	iron ard
x: a & b	MIA-LIA	253	emmer & spelt	mixed	a: yes; b: no	yes	iron ard
xi: a & b	MIA-LIA	253	pea	single crop	a: yes; b: no	yes	iron ard
xii: a & b	MIA-LIA	253	pea	single crop	a: yes; b: no	yes	wooden ard

6.3.2 Description of the land use requirements

As a second step of the land evaluation, the defined land utilization types were translated into land use requirements or limitations, in order to match these with the prevailing land properties at the considered time. For arable farming, requirements are related to physiological requirements of the cultivated crops, to management specifications and conservation conditions (Table 6.2). In function of these requirements, the relevant land qualities for the specific land use in the study area and study period were determined. A land quality is described by the FAO (1976) as 'a complex attribute of land, which acts in a manner distinct from the actions of other land qualities in its influence on the suitability of land for a specific kind of use'. These qualities are not directly measurable, but can be derived from land attributes, called land characteristics, that can be measured or estimated. Per land quality, boundaries of the individual suitability classes, necessary to produce rated land quality maps were

Table 6.2 Land use requirements in terms of land qualities (based on crop, management and conservation requirements) and their related land characteristics.

Land use requirements in terms of land qualities	Related land characteristics
Crop requirements	
Oxygen availability	Mean water table depth
Moisture availability	Mean water table depth, texture
Nutrient availability	CEC, OC, base saturation
Soil toxicity	pH
Rooting conditions/Rootability	Bulk density, texture
Germination conditions	Texture
Management requirements	
Soil workability	Texture
Conservation requirements	
Erosion hazard	Texture, slope
Soil degradation hazard	Texture

defined (Tables 6.3-6.7). Each class was assigned the suitability 'highly suitable', 'moderately suitable', 'marginally suitable', or 'not suitable'.

The aeration of the soil determines the amount of oxygen available to plant-root respiration, as well as root and foot rots caused by fungal or bacterial pathogens under poor aeration conditions (FAO, 1985). The depth to the seasonal water table was used to assess the oxygen availability. The effect of average seasonal water table on crop yield of summer wheat was shown by Visser (1958). These data were used to determine the suitability class boundaries for emmer, spelt and barley (Table 6.3), which are all denoted as preferring well-drained soils in both optimal and absolute growth conditions (FAO Ecocrop, 2012). Less than 40% relative yield was observed for water tables at less than 0.15 m below surface. The highest yields were obtained for groundwater tables deeper than 0.80 m (the measurement range was 1.00 m). The classification of oxygen availability for pea (Table 6.3) was based on Belford et al. (1980), who investigated the effect of water table depth and waterlogging on the yield of peas. A water table depth of 0.50 m below the surface during 5 days, had no effect on the seed yield (Belford et al., 1980). Lentil, a pulse just as pea, was considered more susceptible to water logging than pea (Department of food and agriculture, government of Western Australia, 2012). Therefore, the crop was given more strict boundaries in the suitability classification for oxygen availability (Table 6.3).

Table 6.3 Suitability classes for nutrient and oxygen availability and toxicity for five different crops. S1: highly suitable; S2: moderately suitable; S3: marginally suitable; NS: not suitable.

Nutrient availability						
		emmer wheat[1]	spelt wheat[1]	barley[2]	pea[2]	lentil[2]
CEC ($cmol_c$ kg^{-1} soil)	≤5[1] / ≤3[2]	S3	S3	S3	S3	S3
	5-20[1] / 3-20[2]	S2	S2	S2	S2	S2
	>20	S1	S1	S1	S1	S1
Base saturation (%)	≤25	S3	S3	S3	S3	S3
	25-50	S2	S2	S2	S2	S2
	>50	S1	S1	S1	S1	S1
OC (%)	≤0.5[1] / ≤0.4[2]	S3	S3	S3	S3	S3
	0.5-1[1] / 0.4-0.8[2]	S2	S2	S2	S2	S2
	>1[1] / >0.8[2]	S1	S1	S1	S1	S1
Oxygen availability						
		emmer wheat	spelt wheat	barley	pea	lentil
MWT depth (m)	≤0.05	NS	NS	NS	NS	NS
	0.05-0.15	S3	S3	S3	S3	NS
	0.15-0.20	S3	S3	S3	S3	NS
	0.20-0.40	S3	S3	S3	S2	S3
	0.40-0.50	S2	S2	S2	S2	S2
	0.50-0.80	S2	S2	S2	S1	S1
	>0.80	S1	S1	S1	S1	S1
Toxicity						
		emmer wheat	spelt wheat	barley	pea	lentil
pH	≤3	NS	NS	NS	NS	NS
	3-5	S3	S3	S3	S3	S3
	5-5.5	S2	S2	S2	S2	S2
	5.5-7.3	S1	S1	S1	S1	S1
	7.3-8.5	S2	S2	S2	S2	S2
	>8.5	NS	NS	NS	NS	NS

The moisture availability for crop growth was assessed as a function of the water table depth at the time of growing and the texture class (Table 6.4). The water need for the five crops is the highest during the mid-season stage, followed by the development stage (FAO, 1986). Considering a growing season between April and October, the water level was assumed to be the mean water table depth. All five crops prefer well-drained soils, although spelt and lentil appear to be less susceptible to excessively drained conditions (FAO Ecocrop, 2012). Nutrient availability (Table 6.3) was assessed based on the cation exchange capacity (CEC), the organic carbon content (OC) and the base saturation of the soil. Optimal soil-fertility conditions for all five crops are defined as moderate, although barley, pea and lentil apparently perform better under low soil

Table 6.4 Suitability classes for the moisture availability for five different crops, as a function of texture class and mean water table (MWT) depth. S1: highly suitable; S2: moderately suitable; S3: marginally suitable; NS: not suitable.

Moisture availability							
Texture class	MWT depth (m)						
	≤0.20	0.20-0.40	0.40-0.60	0.60-0.80	0.80-1.00	1.00-1.20	>1.20
spelt wheat, lentil							
clay	S1	S1	S1	S1	S1	S2	S3
silty clay	S1	S1	S1	S1	S1	S2	S3
silty clay loam	S1	S1	S1	S1	S1	S1	S2
clay loam	S1	S1	S1	S1	S1	S2	S3
sandy clay	S1	S1	S1	S1	S1	S2	S3
sandy clay loam	S1	S1	S1	S1	S1	S1	S2
loam	S1	S1	S1	S1	S1	S1	S2
silt loam	S1	S1	S1	S1	S1	S1	S2
silt	S1	S1	S1	S1	S1	S1	S2
sandy loam	S1	S1	S1	S2	S2	S3	NS
loamy sand	S1	S1	S1	S2	S2	S3	NS
sand	S1	S1	S1	S2	S2	S3	NS
emmer wheat, barley, pea							
clay	S1	S1	S1	S1	S2	S3	NS
silty clay	S1	S1	S1	S1	S2	S3	NS
silty clay loam	S1	S1	S1	S1	S1	S2	S3
clay loam	S1	S1	S1	S1	S1	S3	S3
sandy clay	S1	S1	S1	S1	S2	S3	NS
sandy clay loam	S1	S1	S1	S1	S1	S2	S2
loam	S1	S1	S1	S1	S1	S2	S2
silt loam	S1	S1	S1	S1	S1	S2	S2
silt	S1	S1	S1	S1	S1	S2	S2
sandy loam	S1	S1	S1	S2	S3	NS	NS
loamy sand	S1	S1	S1	S2	S3	NS	NS
sand	S1	S1	S1	S2	S3	NS	NS

fertility levels than emmer and spelt (FAO Ecocrop, 2012). Therefore, a distinction was made between both groups. The boundaries for the CEC classes and for base saturation and OC classes were based on Hodges (1995). The overall suitability classes for the nutrient availability were taken as the rounded up averages of the classes for CEC, OC and base saturation. Soil toxicity can be caused by, for example, salinity, Al and Mn contents in the soil solution, amongst other things. Under the temperate climate prevailing in the study area throughout the entire Holocene, soil salinity was assumed not to be relevant.

Under waterlogging conditions or in acid soils, Mn toxicity can occur as a result of elevated Mn(II) contents in the soil solution. Ranges of background values of Mn in different soil types in Flanders, provided by De Temmerman et al. (1984), range from 10-300 mg/kg DM (dry matter) in sandy soils to 200-600 mg/kg DM in clay soils. These concern the natural values not elevated by industrial activities. Total soil Mn contents affecting the crop yield for barley range from 555-2200 mg/kg (Hernandez-Soriano et al., 2011). Taken into consideration that the natural background values in the Flemish soils are practically entirely below the minimum limit as opposed for barley, possible toxicity by Mn was not considered in the evaluation. At low pH values an increased mobility of potentially toxic metals can occur, therefore the pH was used as an indicator for possible toxicity. The pH values determining the boundaries of the suitability classes for the soil toxicity (Table 6.3) were based on Landon (1991) and Batjes (1995).

Table 6.5 Suitability classes for the rooting and germination conditions. S1: highly suitable; S2: moderately suitable; S3: marginally suitable; NS: not suitable.

Rooting conditions				
Texture class	Bulk density (10^3 kg m^{-3})			
clay	≤1.30	1.30-1.39	1.39-1.47	>1.47
silty clay	≤1.30	1.30-1.39	1.39-1.47	>1.47
silty clay loam	≤1.40	1.40-1.49	1.49-1.58	>1.58
clay loam	≤1.40	1.40-1.49	1.49-1.58	>1.58
sandy clay	≤1.40	1.40-1.49	1.49-1.58	>1.58
sandy clay loam	≤1.46	1.46-1.67	1.67-1.78	>1.78
loam	≤1.46	1.46-1.67	1.67-1.78	>1.78
silt loam	≤1.43	1.43-1.67	1.67-1.79	>1.79
silt	≤1.34	1.34-1.54	1.54-1.65	>1.65
sandy loam	≤1.50	1.50-1.63	1.63-1.80	>1.80
loamy sand	≤1.60	1.60-1.69	1.69-1.85	>1.85
sand	≤1.60	1.60-1.69	1.69-1.85	>1.85
Germination condition				
Texture class	Rooting conditions			
	S1	S2	S3	NS
clay	S1	S2	S3	NS
silty clay	S1	S2	S3	NS
silty clay loam	S2	S3	NS	NS
clay loam	S1	S2	S3	NS
sandy clay	S1	S2	S3	NS
sandy clay loam	S1	S2	S3	NS
loam	S2	S2	S3	NS
silt loam	S2	S3	NS	NS
silt	S1	S3	NS	NS
sandy loam	S1	S2	S3	NS
loamy sand	S1	S2	S3	NS
sand	S1	S2	S3	NS

Rooting conditions are affected by stoniness, soil depth and bulk density, amongst other things. As mentioned above, stoniness in the study area was low and not limiting. The same holds true for the soil depth. The rootability was therefore assessed as a function of only the bulk density (Table 6.5). Critical and limiting values for root growth per texture class were taken from Pearson et al. (1995). Just after germination, the presence of crusts can impede the root growth of the seedlings (Gardner et al., 1999). Especially soils with high silt content are prone to crusting (Pearson et al., 1995). Therefore, texture class was considered in assessing the germination (Table 6.5). The workability of the soil determines to which degree the management of a specific area under a particular regime is feasible. It is a function of the topsoil texture and structure.

Table 6.6 Suitability classes of the workability of the soil as a function of texture and slope. S1: highly suitable; S2: moderately suitable; S3: marginally suitable; NS: not suitable.

Workability				
Texture class	Slope (%)			
	≤8	8-16	16-24	>24
manual labour or use of ox-drawn wooden ard				
clay	NS	NS	NS	NS
silty clay	NS	NS	NS	NS
silty clay loam	S3	NS	NS	NS
clay loam	S3	NS	NS	NS
sandy clay	S3	NS	NS	NS
sandy clay loam	S2	S3	NS	NS
loam	S2	S3	NS	NS
silt loam	S2	S3	NS	NS
silt	S2	S3	NS	NS
sandy loam	S1	S2	S3	NS
loamy sand	S1	S2	S3	NS
sand	S1	S2	S3	NS
use of ox-drawn wooden ard with iron ardshare				
clay	S3	NS	NS	NS
silty clay	S3	NS	NS	NS
silty clay loam	S2	S3	NS	NS
clay loam	S2	S3	NS	NS
sandy clay	S2	S3	NS	NS
sandy clay loam	S2	S3	NS	NS
loam	S2	S3	NS	NS
silt loam	S2	S3	NS	NS
silt	S1	S2	S3	NS
sandy loam	S1	S2	S3	NS
loamy sand	S1	S2	S3	NS
sand	S1	S2	S3	NS

Stoniness in the area was low and therefore not restricting the management system. The workability was therefore assessed as a function of the slope (slope classes following Sys et al., 1991) and USDA texture classes (Table 6.6). The range of workable soils was assumed to have broadened with the iron sheathing, protecting the fragile tip of the wooden ard, from the Middle Iron Age onward. The effects of texture and slope on manual labour and on the use of the wooden ard without iron ardshare were assumed to be equal. The soil erosion hazard by water erosion, was assessed as a function of the slope angle in relation to specified soil texture groups. Slope classes were based on Le Bissonais et al. (2001). The erodibility of the soil (Table 6.7), differentiated between the texture classes, was based on the average erodibility values calculated by Guimiere et al. (2009). Arbitrary erodibility values of 1 and 2.5 10^6 kg m^{-4} s were chosen as the boundaries between slightly erodible, moderately erodible and very erodible. The erodibility of the soil was combined with slope-percentage classes to achieve the land suitability classes for the erosion hazard. Furthermore, the physical degradation of the soil (Table 6.7), for example due to animal traction, is also taken into account. The susceptibility of the soil to crust formation (high silt content) was used to assess the degradation hazard.

Table 6.7 Suitability classes of the erosion and degradation hazard. S1: highly suitable; S2: moderately suitable; S3: marginally suitable; NS: not suitable.

Erosion hazard						Degradation hazard
Texture	Slope %					
	≤2	2-5	5-10	10-15	>15	
clay	S1	S2	S2	S3	NS	S2
clay loam	S1	S3	S3	NS	NS	S2
loam	S1	S2	S2	S3	NS	S3
loamy sand	S1	S2	S2	S3	NS	S3
sand	S1	S1	S1	S2	S3	S2
sandy clay	S1	S1	S1	S2	S3	S3
sandy clay loam	S1	S2	S2	S3	NS	S3
sandy loam	S1	S2	S2	S3	NS	S3
silt	S1	S2	S2	S3	NS	S3
silty loam	S1	S3	S3	NS	NS	S2
silty clay	S1	S2	S2	S3	NS	S1
silty clay loam	S1	S2	S2	S3	NS	S1

6.3.3 Description of the land

The requirements for a given type of land use need to be compared with the land properties. In present-day land evaluation studies, land characteristics can often be directly measured or estimated from other known and measured variables. However, when working in a geoarchaeological context, the characteristics for the pre- and protohistoric land need to be assessed, which deviate from the present-day ones and cannot be measured directly. Therefore, process models were used to acquire these values (Table 6.8). For the methodology on the reconstruction of the MWT depth and the soil variables we refer to Zwertvaegher et al. (in review$_{a,b}$), as well as Chapters 4 and 5. if necessary, maps were down- or upscaled to the resolution of the land evaluation. For example, maps of the MWT depth, originally constructed at a 100 m x 100 m spatial grain, were downscaled based on a regression relation between presently measured mean water tables (Zidan, 2008) and the present DEM, following the method of Sivapalan (1993) and Bierkens et al. (2000). The slope was derived from the reconstructed (pre)historic DEM, after upscaling to 40 m x 40 m, using the nearest-neighbour slope algorithm (Burrough and McDonell, 1998). The spatial resolution of the land evaluation was set at 40 m x 40 m. We believe this to be representative of the average size of agricultural fields during the study period. For example, Celtic field systems, known from the late Bronze Age and Iron Age, consist of several quasi rectangular arable plots, measuring between 25 and 45 m in length (Kooistra and Maas, 2008).

The simulations with SoilGen2 used for the soil formation calculations and the reconstruction of the different soil variable maps, did take fertilization into account from 2560 BP onwards, starting in the Early Iron Ages (Zwertvaegher et al., in review$_b$): 1.88 mol $CaCO_3$ m^{-2} every 10 year, following the 10-year interval lime application as described by Plinius the Younger (Finke and Hutson, 2008). However, to evaluate the effect of possible manuring with cattle dung, which was not taken into account in the simulations, an extra processing of the OC, CEC, pH and base saturation maps was performed. Nyakatawa et al. (2001) state that the addition of organic manure can increase the soil OC with 30-80%. Furthermore, the increase in OC content results in a higher CEC (Risse et al., 2001). To account for the influence of organic manuring, a topsoil (first 0.15 m of the soil) increase in OC of 55% was assumed when manuring was applied. This increase was rescaled for the total depth of the soil compartment (0.0-0.4 m depth) and added up with the original, simulated value for the OC. To calculate the influence of the OC increase on the CEC, the equation of Foth and Ellis (1996) was used (for the equation, see Chapter 5), in which CEC is expressed as a function of OC and clay percentage. This resulted in a CEC increase that was added to the original, simulated CEC value.

Risse et al. (2001) state that manure not only enhances the plant nutritional status of the soil and its structure, but can also be used to neutralize soil acidity. For example, at the Magruder Plots (long-term soil fertility wheat research plots) in Oklahoma, soil pH of manured plots (pH of 6.32) is higher than that of the control plots (pH of 5.83) and plots receiving inorganic fertilizer and lime (pH of 5.51; Boman et al., 1996). However, the values of pH rise due to manuring, as found in literature, vary largely due to the different application rates and times, the initial chemical compositions of the used soils and manures, and the reported depths. Furthermore, the pH rise in manured soils is probably a complex result of the buffering capacity of carbonates, bicarbonates as well as organic acids with carboxyl and phenolic hydroxyl groups, present in the manure (Whalen et al., 2000). Because the original composition of the protohistoric manure is not known, as well as the delivering animals (most likely cattle, but maybe also sheep/goat), it is hard to quantify the exact pH rise of the soil as a result of the manuring. Therefore, following Adeniyan et al. (2011), a value of $79\ 10^{-7}$ M H^+ was subtracted from the originally simulated H^+ concentration for the bulk of the 0.40 m topsoil at locations where the pH was below 5.1, when manuring was applied.

The effect of manuring on the base saturation by addition to the soil of basic cations, was estimated based on the work of Adeleye et al. (2010) who attested a rise in basic cations in the range of 14.0-20.8% in the upper 0.15 m of the soil, due to the application of poultry manure. Taken into consideration that cattle manure contains ca. 1.75 times less basic cations than poultry litter (Adeniyan et al., 2011), an average of 10% rise in base saturation (expressed as $cmol_c\ kg^{-1}$ soil) was added to the upper 0.15 m of the soil, when manure was applied. After rescaling to the total thickness of the soil compartment (0.4 m), the resulting base saturation was defined as a percentage of the adjusted CEC.

Table 6.8 The used land characteristics, their source (model) and model output resolution, as well as the resolution in the land evaluation. For each land characteristic map, reference is made to the chapter where its reconstruction is explained. MWT: mean water table; RK: regression kriging.

Land characteristic maps	**Model**	**Model-output resolution**	**Land evaluation resolution**	**Chapter**
MWT depth map (after downscaling and upscaling)	MODFLOW	100 m x 100 m	40 m x 40 m	4
Slope map (derived from (pre)historic DEM; after upscaling)	DEM	2 m x 2 m	40 m x 40 m	4
Texture map (derived from sand, silt and clay maps)	SoilGen2 & RK	40 m x 40 m	40 m x 40 m	5
pH map	SoilGen2 & RK	40 m x 40 m	40 m x 40 m	5
Bulk density map	SoilGen2 & RK	40 m x 40 m	40 m x 40 m	5
CEC map (extra conversion for manuring with cattle dung)	SoilGen2 & RK	40 m x 40 m	40 m x 40 m	5
OC map (extra conversion for manuring with cattle dung)	SoilGen2 & RK	40 m x 40 m	40 m x 40 m	5
Base saturation map	SoilGen2 & RK	40 m x 40 m	40 m x 40 m	5

6.3.4 The land evaluation procedure

The land evaluation procedure was executed according to the flowchart given in Figure 6.1. The following steps were performed:

- Maps of the different land characteristics were delivered by the groundwater and pedogenetic models (Chapters 4 and 5);
- When manure was applied, maps of OC, CEC, pH and base saturation were recalculated;
- Rated land quality maps were made based on the combination of the necessary land characteristics maps and the corresponding individual suitability classifications (Tables 6.3 to 6.7). As can be seen from these tables, most land qualities were based on combinations of two land characteristics. Only for the land quality ‘nutrient availability’, a combination of three land characteristic OC, CEC and base saturation

was used. In this case, the land characteristics maps were classified according to Table 6.3, converted (S_1, S_2, S_3 and NS equalled the values 1, 2, 3 and 4, respectively) and combined in a three-dimensional matrix. The rounded down average of their combination was converted into the ultimate individual suitability class (1, 2, 3, and ≥ 4 equalled S_1, S_2, S_3 and NS) for the land quality 'nutrient availability';

- When mixed cropping was performed, the rated land quality maps related with the requirements of the specific crops were compared. Mixed cropping is often used as a strategy to reduce risk, since it helps to avoid crop failure due to bad weather conditions. Normally, crops are mixed that can complement each other. When the environmental conditions for the one crop are limited, the other crop performs better. Therefore, per land quality, the class of the most suitable crop was taken as the ultimate suitability class. For rotation of crops, the same method was applied, only then the class of the least suitable crop was taken as the final suitability class;

- In the last step of the procedure, all rated land quality maps were compared following the procedure of the limiting conditions (Dent and Young, 1976): per land unit (here, this is one raster cell) the lowest individual rating of the land quality maps was taken as the final suitability at that specific location.

6.3.5 The carrying capacity assessment

A carrying capacity assessment was performed based on the potential production of the region and the human dietary requirements, both expressed in kcal. This assessment was limited to the Middle Bronze Age because of the sufficient data availability, especially on household and livestock composition. This assessment should be seen as a first, land evaluation based attempt to quantitatively assess the carrying capacity for prehistoric cultures in Flanders. The following steps were involved:

- Selection of the LUT: A LUT was assumed in which a mixed emmer-spelt cropping system was practiced as part of a mixed farming system with crop cultivation and livestock herding.

- Estimation of the crop yield: Crop reference yield for a mixed emmer-spelt cropping system with manuring was set at 1,570 kg ha^{-1}. This was based on Reynolds (1992), who reported average yields on the experimental Iron Age Butser Ancient Farm (England) of 1,650 kg ha^{-1} and 1,490 kg ha^{-1} for autumn-sown emmer and spelt in separate cultivation without manure input. Yields, expressed as a percentage of this optimum yield, were assigned to each land suitability classification (Table 6.9), based on FAO formulated percentages (FAO, 1983)

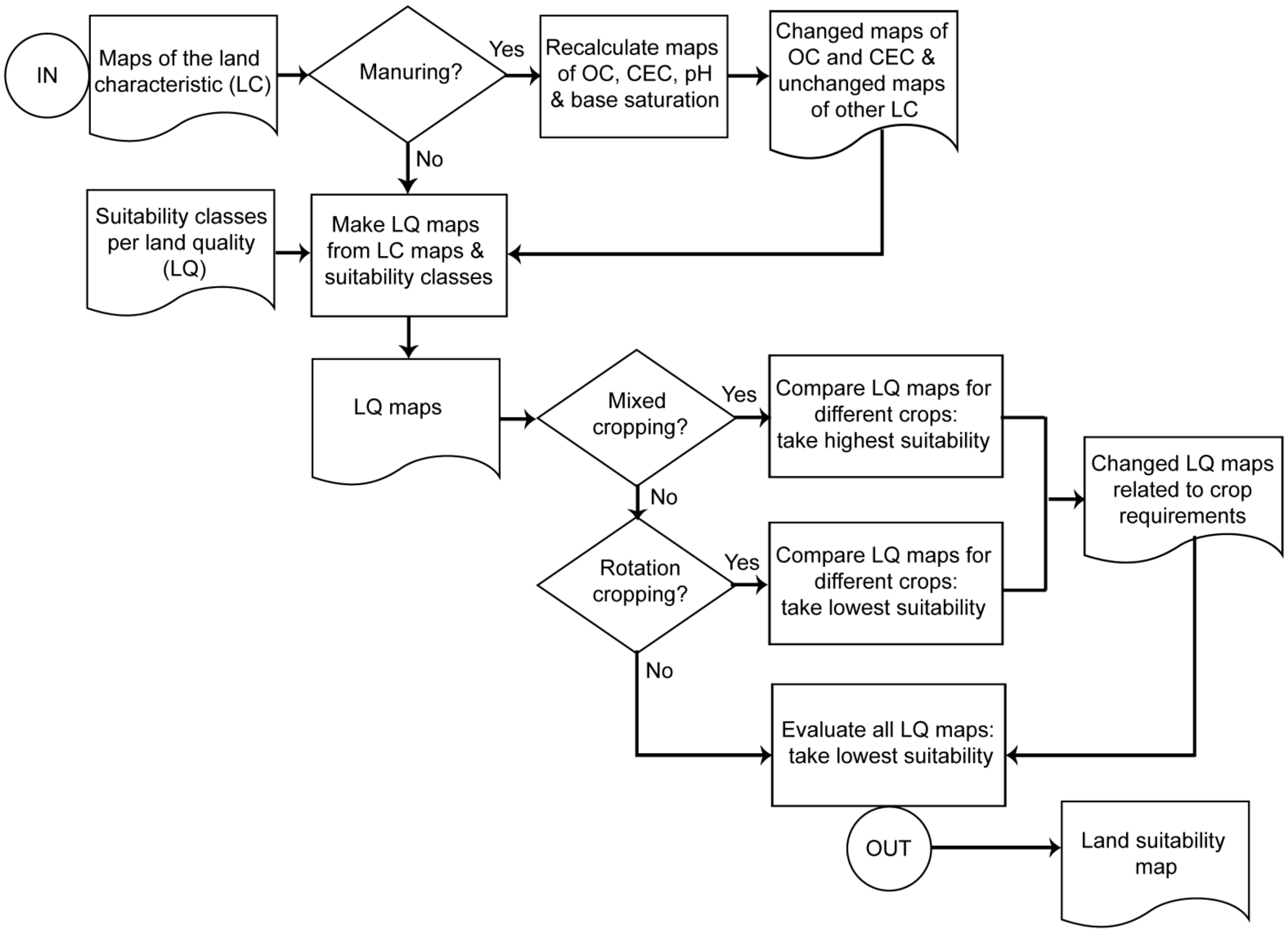

Figure 6.1 Flowchart of the land evaluation procedure.

Land units classified as NS were assumed to be only suited for extensive grazing, therefore crop yield was set at 0% of the reference yield. A production loss of 200 and 63 kg ha^{-1} were chosen for loss by storage (Gregg, 1987) and the following year's sowing seed (Reynolds, 1992; for sowing in furrows), respectively. The total crop yield for the entire area (Y_T) was calculated was calculated according to the following formulas:

$$Y_{c,i} = Y_{t,i} - L_{st} - L_{sd} \quad \text{Equation 6.1}$$

$$Y_T = \sum_{i=1}^{4} (A_{u,i} \times Y_{c,i}) \quad \text{Equation 6.2}$$

where

min: the minimum of the values between brackets;

i: the suitability classification, with S_1, S_2, S_3 and NS corresponding with i = 1 to 4;

$Y_{c,i}$: the consumable crop yield (kg ha^{-1}) of the suitability class i;

$Y_{t,i}$: the total crop yield (kg ha^{-1}) of the suitability class i (based on the reference crop yield and Table 6.9);

L_{st}: the production loss by storage (kg ha^{-1});

L_{sd}: the production loss for next years' sowing seed (kg ha^{-1});

Y_t: the total crop yield (kg) produced in the entire area;

$A_{u,i}$: the area (ha) represented by the suitability class i that is used for crop cultivation. The total area for crop cultivation ranges from 0 to 100% of the study area, and is assigned to the areas classified as suitable (S_1, S_2 and S_3). starting with the areas with the highest suitability.

Table 6.9 Land suitability classification and corresponding crop yield.

Land suitability classification		Crop yield (% of reference yield)	FAO (1983)
S1	Highly suitable	90	80-100
S2	Moderately suitable	60	40-80
S3	Marginally suitable	30	20-40
NS	Not suitable	0	0-20

- Estimation of the livestock meat and milk production: The livestock compostion of an average Middle Bronze Age farm was chosen at 20 cattle (Theunissen, 1999; assumed 2 oxen, 1 bull, 9 calve, 8 cows), 3 sheep (1 ram, 1 ewe, 1 lamb) and 1 pig. Sheep and pig numbers were based on average stock animal percentages found at Bronze Age sites (85% cattle, 10% sheep, 5% pig; van Wijngaarden-Bakker and Brinkkemper, 2005). The grazing area for a Middle Bronze Age farm with above mentioned animal composition was set at 20.77 ha, based on the assumption of extensive grazing with 1 ha of grassland per livestock unit (LU; cow: 1 LU; sheep: 0.17 LU; pig: 0.26 LU; OTerm, 2003). This is comparable to the value of 19.0 ha as proposed by Fokkens (1998) for a herd size of 20 cattle in an area with forest:marshland:stubble field in a 65:35:5 ratio. The total amount of animals in the study region was based on the area available for grazing (A_g) and the estimated grazing area per farm.

It was assumed that only 20% of the livestock was yearly slaughtered for meat. Sheep and pig live weight was based on average values for present-day animals (Table 6.9). However, cow live weight varies largely between cows and bulls, as well as between dairy and beef cows. Keeping in mind that cattle, through time, has been selected for its ability to gain weight, a much lower live weight of 200 kg per cow was assumed. A 50% yield of the live weight was taken for all animals (based on present-day average values for cows: dead weight is 60% of the live weight, yield is 80% of the dead weight). It was assumed that milk was produced by all cows and ewes, set at 550 L y^{-1} for Neolithic cows (Milisauskas, 2011) and 80 L y^{-1} following Berger (2004). Only half of the produced milk was assumed available for human consumption.

Table 6.10 Animal weight, milk production and composition of meat and milk as taken in the carrying capacity assessment. NR: not relevant.

	Cow	**Sheep**	**Pig**
Live weight (kg)	200	50	80
Meat production (kg)	100	25	40
Milk production (L y^{-1})	550	80	NR
Composition of primary product: meat			
Proteins (%)	27	26	32
Fat (%)	10	11	21
Composition of secondary product: milk			
Proteins (%)	3.4	4.4	NR
Fat (%)	4.6	7.6	NR

- Conversion of the total crop yield and the total meat and milk production into total macronutrient production (kg): The produced grain was assumed to consist of carbohydrates (80%) and proteins (10%). The percentages of proteins and fats in the meat and milk products are given in Table 6.10. Based on the yearly produced amounts of grain, meat and milk, the total yearly macronutrient production was calculated.

- Calculation of the average macronutrient requirement: The calculation of the average daily energy requirement was based on the composition of a Middle Bronze Age farm family consisting of 3 to 4 generations of approximately 8 to 12 persons (Theunissen, 1999). A family of 2 grandparents (age category: 31-50 years), 2 parents (age category: 19-30 years) and 4 children (age categories: 4-5 and 10-11 years) was assumed, with an equal male-female ratio and living on an active level (Table 6.11). This resulted in an average daily energy requirement of 2,250 kcal per person.

  According to the Institute of Medicine (2002), 45-65% of the daily energy requirement for adults should be delivered by carbohydrates, 20-35% by fat and 10-35% by proteins. Based on the fact that carbohydrates and proteins correspond to 4 kcal g^{-1} and fat for 9 kcal g^{-1}, and assuming an average daily energy requirement of 2,250 kcal per person, an average yearly requirement for each of these macronutrients was calculated.

- Calculation of the population density of the region: The area under crop cultivation is varied from 0% of the total study area to the maximum area (expressed as % of the total study area) that is suitable for crop cultivation (sum of areas with S1, S2 and S3 classification) and carbohydrate and plant protein production. Each time, the most suitable areas for crop cultivation are used first. The remaining part of the study area (NS classified areas as well as areas classified as suitable but not used for crop cultivation) is available for extensive grazing and fat and animal protein production. For the different areal percentages and for each macronutrient, the production (kg) is compared with the required amounts (kg $person^{-1}$) to calculate the number of persons that can be supported by the specific macronutrient production (Figure 6.3). The most limiting macronutrient was assumed to define the total number of people supported by the study area and used to calculate the potential population density of the region. Because plant proteins from grains do not contain all essential amino-acids, animal proteins were assumed to be an essential part of the prehistoric diet.

Table 6.111 Daily energy requirement for an active level (Health Canada Federal department, 2012).

age category (years)	daily energy requirement (kcal)	
	female	male
31-50	2250	2900
19-30	2350	3000
10-11	2050	2300
4-5	1500	1650

6.4 Results

6.4.1 The suitability maps

For the Neolithic - Early Bronze Age, two land utilization types were tested: the permanent cultivation of emmer and of barley, respectively. All other conditions were taken similar: no manuring and the use of manual labour or the wooden ard, which were both set at equal limitations. Considering the cultivation of emmer, the largest part of the area was classified as marginally suitable (68.8% of the mapped area) and not suitable (31.2%). Less than 0.1% was classified as moderately suitable (0.01%) and highly suitable areas were absent. The most limiting land quality in areas with marginal suitability appeared to be the nutrient state (especially CEC and base saturation), followed by the acidity of the soils. In areas classified as not suitable, the moisture availability was the most limiting factor. In the Moervaart Depression limitations on the land use were posed by the oxygen availability to the roots, as a result of very shallow water tables. Alongside certain river reaches, the physical degradation of the soil was set as the most limiting factor. Exactly the same results were found for the cultivation of barley. This was due to the fact that for the land qualities that defined the limitations in the Neolithic, emmer and barley had equal suitability ranges.

For the Middle Bronze Age two cropping systems were tested: the cultivation of emmer and barley under rotation, and of emmer and spelt in a mixed cropping system (Figure 6.2). In both types, the wooden ard was used. Each system was evaluated with and without cattle manure application. Less than 0.001% of the area was classified with a higher suitability (only 1 class higher) as a result of the manuring. However, for the mixture of emmer and spelt, a lower percentage of the area was classified as not suitable (21.6%), in comparison to the rotation of emmer and barley (29.7%). This was due to the higher tolerance of spelt for excessively dry soils, in comparison with to emmer and barley. Due to the mixed cropping system, the suitability class of the most tolerant crop was taken as the overall class for the specific crop requirement. Again, the same trend as for the Neolithic was observed: overall limitations on the land use were due to moisture availability (higher areas, generally classified as not suitable), nutrient availability (CEC, base saturation and OC; generally classified as marginally suitable) and acidity of the soil (generally classified as marginally suitable). Again, the physical degradation of the soil is limiting around rivers and also in the western part of the Moervaart Depression. In the latter region, oxygen availability is a limiting factor as well.

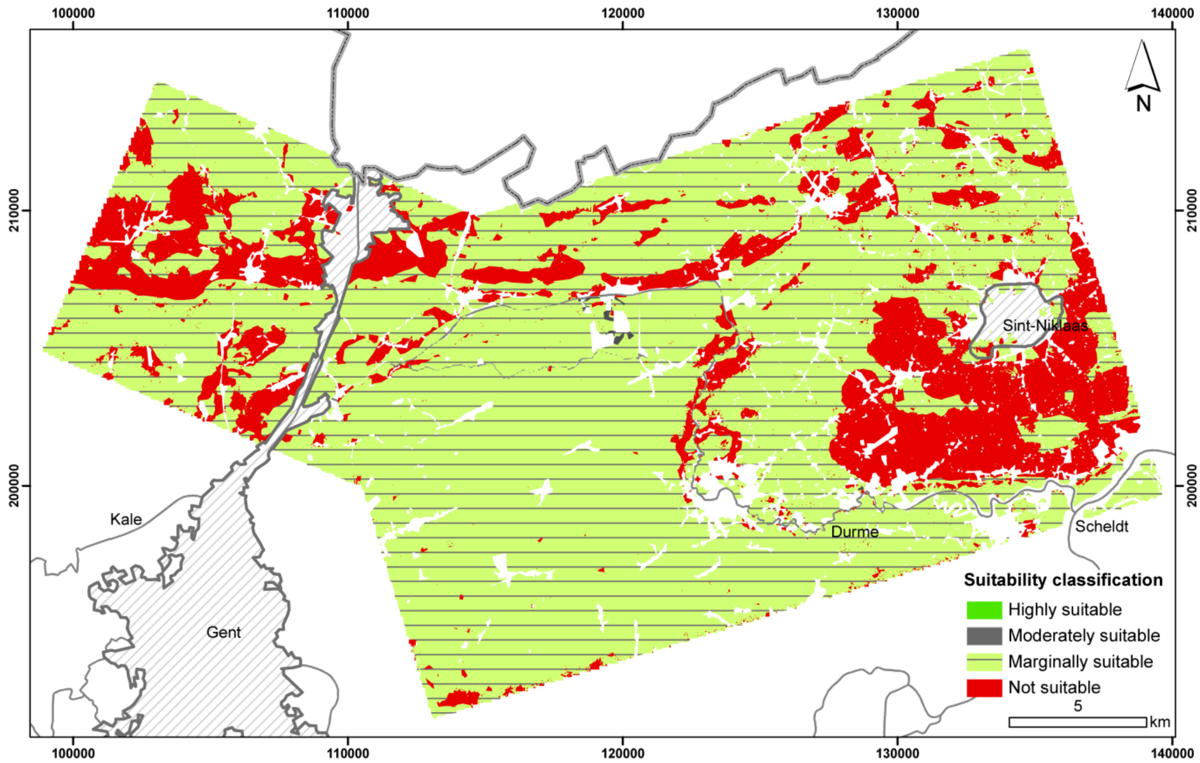

Figure 6.2 Suitability map of the Middle Bronze Age LUT of mixed emmer and spelt cultivation with manuring (the map is also representative for the LUT without manuring, since the difference is less than 0.001% of the total area). White areas: no data; Shaded areas: the cities of Ghent and Sint-Niklaas. (Other maps used: AGIV, 2002).

For the Late Bronze Age – Early Iron Age, the overall view, independent of the land utilization type, was comparable to previous periods: the largest part of the area was classified as marginally suitable, followed by not suitable. Only a very small area in the Moervaart Depression was classified as moderately suitable. Two cultivation regimes with cereals were evaluated (emmer and barley in rotation, and mixed cropping of emmer and spelt), and two regimes with pulses (permanent cropping of pea and lentil, respectively). All systems were evaluated with and without cattle manure application. The effect of manure was the same as in the previous period: less than 0.001% of the area was classified with a higher suitability (only 1 class higher). In general, the cultivation regime of mixed cropping of emmer and spelt appeared to have the 'best' classification, meaning the lowest percentage of area classified as not suitable (22.7% compared to ca 31.0% for the other regimes). Considering the mixed cropping, spelt defined the suitability ranges for the moisture availability, since spelt was assumed to be more tolerant to deeper groundwater tables. The same limiting land qualities at equal locations as in the previous periods were found. Only for lentil, oxygen availability appeared to be responsible for the allocation of several locations to the class of lowest suitability. Lentil, however, was given different suitability ranges for OC and CEC than the cereals. This could have resulted in better suitability considering the nutrient availability, however, the overall suitability at the same locations was dominated by the acidity of the soils, prevailing over the effect of the different nutrient requirement.

For the Middle and Late Iron Age the effect of liming was applied in the soil formation modelling (with and without manure application). In the land evaluation, the impact of the use of the wooden ard with iron ardshare was now taken into account. Similar trends as in previous periods were found: moisture availability appeared to be the most limiting on the higher grounds, while nutrient availability and acidity of the soil posed the highest limitations on the lower lying part of the study area. Around rivers, for example the river Scheldt, degradation of the soil was limiting. Several spots in the Moervaart Depression appeared to be moderately suitable, because of the higher nutrient availability and higher pH values. Again, the mixed cropping of emmer and spelt performed better in terms of 'moderately suitable' surface area, than the other cropping systems, due to the higher tolerance to excessively drained soils. For the cultivation of pea on the other hand, a larger area (however still lower than 0.5%) than for the other cultivation systems was classified as moderately suitable. This was the result of different nutrient requirements for the pea than for the cereals. The effect of manure was very limited and comparable to previous periods.

A slight effect on the overall suitability classification due to liming as compared to manuring was found. Generally, a larger area was classified as moderately suitable, and less classified as marginally or not suitable. However, the difference amounts to less than 0.5% of the entire mapped area (for example, from 0.14% to 0.38% for the growth of pea in Late Bronze Age – Early Iron Age cultivation under manuring as compared to Middle – Late Iron Age cultivation under liming). The effect of the use of the wooden ard protected with the iron sheath as compared to the one without such protection, was evaluated for pea in the Middle – Late Iron Age. For this crop, only 0.04% of the mapped area was assigned a higher suitability (from marginally to moderately suitable) due to the use of the wooden ard with iron ardshare

.

6.4.2 The carrying capacity of the study area

Figure 6.3 illustrates the evolution of the amount of people supported by different macronutrients in function of the area under crop cultivation. With increasing areas for crop cultivation, the carbohydrate production increases as well as the number of people supported. Because NS classified land (here 21.64 % of the total study area) was reserved for extensive grazing, resulting only in protein and fat production, the carbohydrate production reaches a maximum when 78.36% of the area is under crop cultivation, which is the maximum area available for crop cultivation because NS classified land (21.64%) is assumed to be only used for extensive grazing.

Fat was assumed to be only delivered by the livestock (meat and milk). The amount of fat as well as the number of people supported by the fat production, decreases with increasing area for crop cultivation and hence decreasing area for livestock herding. A plateau is reached when the maximum area for crop cultivation is used. Proteins are delivered by animals and plants. The animal protein production follows the same trend as the fat production. Although the areal animal fat production exceeds the animal protein production (kg ha^{-1}), the amount of people supported by the latter is lower because humans need 1.8 times more proteins than fat (expressed in kg) to meet their dietary requirements. The total protein production increases with increasing area under crop production. However, the increase is slower than seen in the carbohydrates production due to the effect of decreasing animal protein production.

When less than 12% of the study area is under crop cultivation, the number of people supported by the study area is limited by the carbohydrate production. If the area under crop cultivation is larger, the production of animal proteins appears to be the most restrictive factor. The amount of total proteins (sum of animal and cereal proteins) and animal fat were never limiting. The maximum number of people fed by the most limiting macronutrient production was taken as the maximum number of people that can be supported by the study area. This resulted in a total of 9,490 people supported by the study area (50,592 ha; no data areas not taken into account), coinciding with 5.3 ha per person or a population density of 0.19 persons ha^{-1}. This was achieved when 12% of the study area was under agrarian cultivation, leaving 88% of the area for extensive grazing.

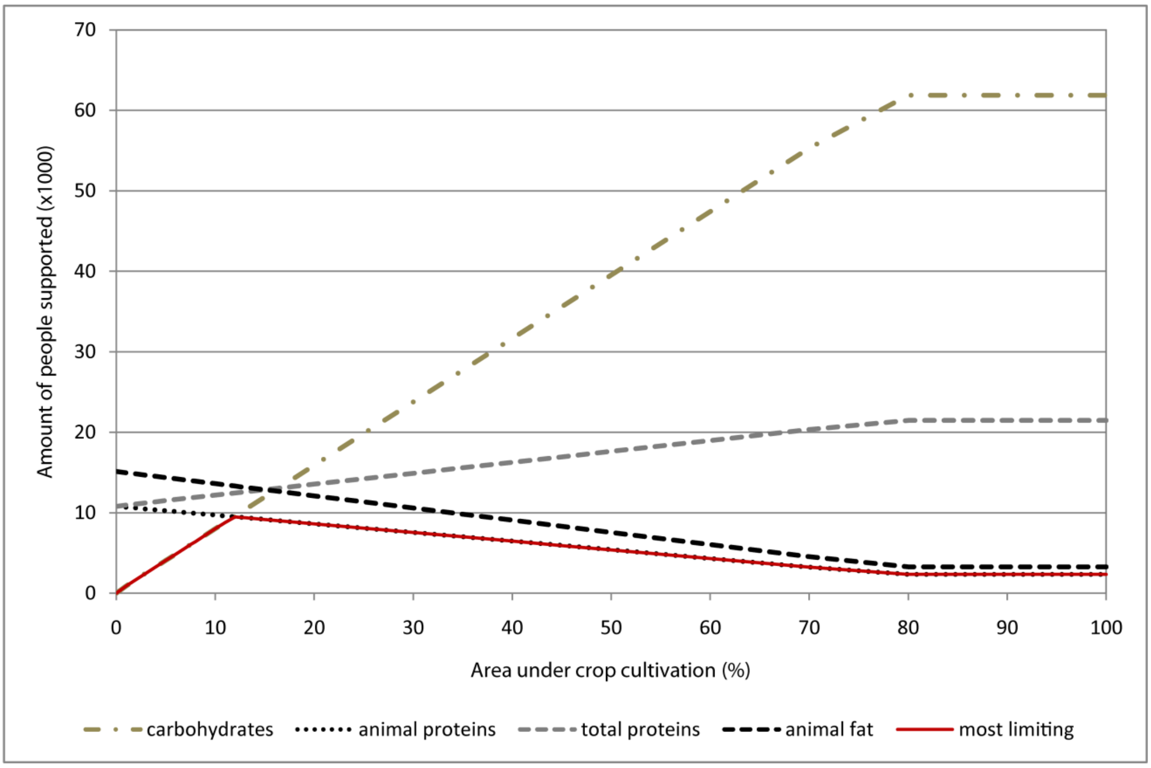

Figure 6.3 Carrying capacity (expressed in amount of people supported) of the study area based on a Middle Bronze Age cultivation of mixed emmer and spelt and animal husbandry, for varying areas under crop cultivation.

6.5 Discussion

6.5.1 Evaluation of the reconstructed land utilization types

A thorough literature analysis was performed in order to define several land utilization types for the region and for different time periods. Often, however, various hypotheses on the land use and cultivation practices are postulated in literature, based on sometimes restricted and indirect evidence. The same evidence has sometimes led to contradicting ideas (de Hing, 2000). Therefore, direct botanical evidence from weed assemblages, crops and gathered fruits and nuts is extremely useful to unravel past agricultural regimes. However, in several regions, archaeological evidence is limited, and hypotheses on the land use can only be formed by extrapolation from areas with more information.

The evaluated land utilization types were limited to agrarian production. However, this does not need to be the case. Kamermans (1993) performed an archaeological land evaluation for a study area in Italy, also considering generalist and specialist hunter-gatherer and fisher communities. This technique was concluded to be more fitting for agrarian communities, which was not that surprising since the land evaluation methodology was primary constructed from an agricultural point of view (Kamermans, 1993). Of course, in the study area, stockbreeding appeared to be an important aspect of the agrarian communities. The cattle did not only provide food and power (for example animal traction of the ard), but also supplied manure for the mixed-farming system, especially from the Middle Bronze Age onwards (de Hing, 2000; Fokkens, 2005c). However, the production of the land under extensive grazing should be taken into account in future research to have a better assessment the number of animals supported by the study area.

6.5.2 Evaluation of the reconstructed land characteristics

Ideally, each different land utilization type, when it comes to practices such as for example manuring, short one-year fallow, burning the vegetation and long-term fallow, should be supported by simulation results. However, the values for land characteristics used in this study were based on only one simulation: deciduous forest vegetation continuous up till 5960 BP, followed by continuous agriculture with no fertilizing, succeeded by liming starting in 2560 BP. Only one simulation was done because of computing limitations (the runtime of the model at a large number of locations; Zwertvaegher et al., in review$_b$). During fallow, OC content in the soil increases, which can be estimated from biomass crop residues left on the field and produced weeds biomass during the fallow period (Finke, 2012). The same would hold true for long-term fallow, where the biomass production of the secondary forest should be quantified. In this land evaluation, the effect of cow-dung application was estimated based on expected rises in OC, pH, CEC and base saturation, within the range of collected literature values. However, the complex interaction of chemical processes make this very hard to quantify. A process model, such as for example the applied SoilGen model, handles these interactions, therefore enabling a more thorough quantification of the impact of soil amendments and fallow periods than the now-used methodology. For example, for the Bronze Age, archaeological literature mentions 'wandering farms' that, after a time period of approximately 30 years, were relocated. The abandoned sites were most likely reforested or covered with grassland and heathland. Local heath development in Flanders was recorded by Verbruggen et al. (1996) near the end of the Subboreal. Regional heathland expansion has been identified in pollen diagrams and attested to the Late Bronze Age (Prøsch-Danielsen and Simonsen, 2000; Overland and

Hjelle, 2009; Olsson and Lehmdall, 2010). Therefore, an evaluation of the impact of reforestation, or of the establishment of grass- and/or heathland and the implementation of these different scenarios in the modelling of the soil variables would result in a better view on the potential suitability ranges of the study area.

6.5.3 Evaluation of the land evaluation approach

A qualitative approach to land evaluation was used, in which values for different land characteristics were classified and combined to land qualities, after which the most limiting land quality was assumed to define the overall land suitability. Values for the specific land characteristics were delivered by process models, subject to errors propagating in different steps and culminating in the land evaluation. The uncertainties in the outputs of the groundwater model and soil-formation model were elaborately discussed in the previous Chapters 4 and 5 and are not repeated here. However, the regions of highest uncertainty were situated in the industrial zone around the canal of Ghent-Terneuzen (due to original uncertainties in the reconstructed post-medieval DEM), and at the southern border of the Cuesta of the Waasland, where water tables were simulated that might have been too low as compared to present-day data. The use of suitability classes in the land evaluation, covering a range of possible simulated values for each land characteristic, might serve as a buffer for these uncertainties.

On the other hand, the end result of the used methodology is strongly influenced by the chosen class boundaries. To tackle this problem, a quantitative approach to land evaluation would be more preferred. Dynamic crop growth simulation models quantify crop yield and can be used as a part of a quantitative land evaluation. These models take the temporal variability of land use requirements and land qualities into account (de la Rosa and van Diepen, 2002), which is also pursued in this study. However, it must be clear that even these mechanistic models contain empirical components, especially for the description of the sub-systems (Rossiter, 2003). Furthermore, it is most likely that the problems concerning genetic alterations in the crops throughout time, pre- and protohistoric crop requirements, pests and diseases, encountered during this qualitative land evaluation will also occur when using dynamic crop growth simulation models.

In general, the quality of the land evaluation can be assessed by repeating the land evaluation procedure with minimum and maximum deviations from the simulated model parameters, in this way incorporating quantified model uncertainties (Zwertvaegher et al., 2010). This would allow to identify constant trends in suitability classification for a given type of land use, given the model errors. This is however, yet to be tested.

6.5.4 Evaluation of the suitability maps

Considering the land evaluation for the Neolithic – Early Bronze Age, the used land characteristics refer to the situation 40 years after the implementation of continuous agriculture, in which no soil amendments were applied. The resulting map of the suitability classification is therefore representative of a ‘worst case scenario’, i.e. the natural soil fertility without carbon and nutrient input by natural (primary or secondary) forests. Generally, limitations in the higher-lying area, as for example the cover sand area and river dunes, are the result of limited water availability for the crops, while in the lower-lying area limitations are due to limited nutrient availability and acidity of the soil. This general trend is a very logical for the sandy area of Flanders. The same trend is seen for the later periods as well. However, the application of cattle manure to the soil did not result in more area suitable for agriculture. The effects were limited to less than 1%. This can be due to an underestimation of the effect of manure on pH, OC, CEC and base saturation levels in the soil. As mentioned above, simulating the effect of manure by using process models is expected to better grasp the complex chemical interactions in the soil following manuring. The (simulated) liming in the Middle – Late Iron Age evaluation, as compared to the previous periods without liming, did not give rise to a large increase in more suitable area for agriculture (<0.5%). The evaluated period was situated some 358 years after the start of the liming in the simulations. This had resulted in a pH rise of several units (a maximum increase of 1.65. at the Cuesta of the Waasland; an average rise for the entire area of 0.4). Although several areas became more suitable for agriculture concerning the effect on the soil acidity, this effect was not translated into a higher suitability class for the area, due to the used methodology in which the most limiting condition determines the overall suitability.

Ideally, the resulting suitability maps are evaluated and tested with known archaeological sites in the region. However, for the Neolithic, the archaeological dataset of the study area comprises only surface finds with no direct evidence of agrarian land use, Bronze Age remains that are known for the study area, are mainly situated in the burial context, while only very few known Iron Age sites are situated in the study area. Therefore, the archaeological dataset appeared to be unsuited for the quality testing of the land evaluation methodology for this specific region.

6.5.5 Evaluation of the carrying capacity assessment

It is clear that a number of assumptions are made during several steps in the assessment of the carrying capacity. For example crop reference yield and grain production loss are now derived from literature and should optimally be derived from local measurements. This is especially true for the conversion of the land suitabilities into crop yields, which is now based on FAO formulated percentages (FAO, 1983) but should ideally be based on on-site experiments and measurements, as for example is done on the experimental Butser Ancient Farm (UK). Furthermore, the use of a dynamic crop growth simulation model as mentioned above, is proposed to directly link land characteristics to crop production.

The used composition of a prehistoric family was based on generalized archaeological evidence and is prone to uncertainties. The average energetic requirement of a family depends on for example the male-female ratio, the different age categories that are represented, as well as the activity levels of the members. Furthermore, the question remains in how far the current dietary requirements are comparable with the prehistoric ones. Uncertainties are also present in the macronutrient estimation of the meat and milk production of the prehistoric livestock. First of all, the composition of the prehistoric farm was estimated from general archaeological data. Furthermore, the amount of yearly slaughtered animals was estimated at 20% of the total livestock. However, this number may have varied between families, years and circumstances. Yearly meat and milk production was then calculated based on animal live and dead weight, as well as the meat and milk macronutrient composition. Pig and sheep weight were assumed to be relatively stable, but cattle weight and milk yield from cattle and sheep were set at lower values than the present-day production. Also, the number of LU per ha in extensive grazing is of importance in the calculation of the macronutrient production of the entire area. These numbers are however, based on present-day guidelines and regulations and information on prehistoric herding activities is lacking. In the future the production of the areas used for extensive grazing should also be taken into account in the land evaluation. Wild fruits and plants were also still part of the Middle Bronze Age farmers' diet (de Hing, 2000), although in more limited amounts than in previous times. This was not taken into account, because it was assumed to be a minimal part of the Middle Bronze Age diet.

The calculated population density deviates from population estimates based on ethnographic data, urnfields and Celtic field systems. For example, Louwe Kooijmans (2005) mentions for the Netherlands 10,000 persons (150 ha per person), 15,000-30,000 persons (100-50 ha per person) and 150,000 inhabitants at the end of the Stone Age, in the Iron Age and the Middle Roman Age, respectively. Based on the habitable area of the Netherlands at that time, being much smaller than at present, this would have coincided with 150, 100-50 and 10 ha per person for the corresponding time periods, representing much lower densities than the calculated 5.3 ha per person in the study area. This can be due to the discrepancy between the potential area for grazing (taken at 88% of the study area) and the actual area available for grazing. Several locations might have been unsuitable as grazing area: for example areas that were still under forest, areas at large distances of drinking water for the cattle, areas at large distances from the arable land where the farm was situated or isolated areas. The presence of for example forested areas, can also have decreased the amount of area available for crop production. Information on these areal percentages would help to get a clearer view on the actual population density of the region. Lastly, the discrepancy between actual and potential population densities might also be affected by socio-economic factors, such as pests and diseases, a high child mortality, or warfare.

6.6 Conclusions

It is concluded that the drawbacks in the current methodology are partly situated in the qualitative approach to the land evaluation. A more quantitative approach with the use of a dynamic crop growth simulation model is believed to enhance the translation of land characteristics into crop yield, which will also affect the assessment of the carrying capacity. Because of this, the following results are only preliminary.

Based on the performed land evaluation, the largest part of the study area was concluded to be marginally suitable (68.6-78.3%) for all evaluated land utilization types and time periods. Furthermore, a large part of the area was classified as not suitable (21.6-31.2%) and a very small part of the total area was classified as moderately suitable (0.01-0.38%). Based on the corresponding crop yield and livestock composition, 5.3 ha per person was found as the potential carrying capacity of the study region for the Middle Bronze Age, which relates to a total number of 9,490 persons in the 50,592 ha large study area. This was reached when 12% of the area was under crop cultivation. For smaller and larger areas under crop cultivation, carbohydrate production by crops and proteins production by livestock, respectively, appeared to mostly limit the number of people supported. Furthermore, this assessment only gives a potential carrying capacity of the study region, assuming that the entire region should have been available for crop and animal husbandry. The presence of for example forested areas, would have decreased the area available for agriculture. Other areas might have been unsuited as grazing areas, such as for example isolated areas, or areas with lack of nearby drinking water for cattle. Information on these areal percentages, as well as on socio-economic factors affecting population growth would help to get a clearer view on the actual population density of the region.

Nevertheless, the archaeological land evaluation based on reconstructed land characteristics appears to give promising results in terms of the assessment of the suitability of the land for pre- and protohistoric types of land use. Because land characteristics are constructed with process models, and when needed necessary spatial interpolation methods, full-cover maps of the land characteristics are used in the evaluation, instead of relying on sample surveys to quantify and qualify the suitability of previously identified land units in the study area. Furthermore, the use of models makes the methodology fully reproducible and provides the possibility to test several potential scenarios. It can also be used to evaluate several hypotheses postulated in archaeology, as for example 'wandering farms' and their possible relation with the exhaustion of the soil. As mentioned above, it would be interesting to add a dynamic crop growth simulation model to the existing framework of process models. In this way, the land evaluation will not only be based on a quantitative input of the land characteristics (current process models), but also on a quantitative output (dynamic crop growth simulation model) in terms of crop production. This will significanty enhance the carrying capacity assessment. Furthermore, more knowledge is required of the pre- and protohistoric land use and crop requirements, of which the latter might have changed over time as the result of genetic adaptations to specific conditions, independent of a qualitative or quantitative approach.

6.7 References

Adeleye, E.O., Ayeni, L.S. and Ojeniyi, S.O., 2010. Effect of poultry manure on soil physico-chemical properties, leaf nutrient contents and yield of Yam (*Diosorea rotundata*) on Alfisol in Southwestern Nigeria. Journal of American Science 6(10), 871-878.

Adeniyan, O.N., Ojo, A.O., Akinbode, O.A. and Adediran, J.A., 2011. Comparative study of different organic manures and NPK fertilizer for improvement of soil chemical properties and dry matter yield of maize in two different soils. Journal of Soil Science and Environmental Management 2(1), 9-13.

AGIV, 2002. Vectoriële versie van de VHA-waterlopen & -zones (versie 22/10/2002) 1/5,000. Vlaamse Milieumaatschappij - Afdeling Operationeel Waterbeheer (AGIV).

Annaert, R., Creemers, G., 2008. Onderzoeksbalans Onroerend erfgoed Vlaanderen – Archeologie, Hoofdstuk 4 Bronstijd/IJzertijd: Aspecten van de samenleving. (September 5, 2012) http://www.onderzoeksbalans.be/onderzoeksbalans/archeologie/

Bakels, C.C., 1997. The beginnings of manuring in western Europe. Antiquity 71, 442-445.

Bakels, C.C., 2005. Planten in de steentijd, in: Deeben, J., Drenth, E., van Oorsouw, M.-F. and Verhart, L. (Eds.), De steentijd van Nederland. Stichting Archeologie, pp. 67-79.

Bakels, C.C., 2009. The Western European Loess Belt. Agrarian History, 5300 BC - AD 1000. Springer.

Bakels, C., Zeiler, J., 2005. De vruchten van het land. De neolithische voedselvoorziening, in: Louwe Kooijmans, P., Van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 311-336.

Batjes, N.H., 1995. A global data set of soil pH properties. Technical paper 27, ISRIC, International Soil Reference and Information Centre, Wageningen.

Baxter, K., 2004. Extrinsic factors that effect the preservation of bone. Nebraska Anthropologist 19, 38-45. http://digitalcommons.unl.edu/nebanthro/62

Belford, R.K., Cannell, R.Q., Thomson, R.J., Dennis, C.W., 1980. Effects of waterlogging at different stages of development on the growth and yield of peas (Pisum sativum L.). Journal of the Science of Food and Agriculture 31(9), 857-869.

Berger, Y.M., 2004. Breeds of sheep for commercial milk production, Proceedings of 10th Great Lake Dairy Sheep Sympsosium, University of Wisconsin-Madison, Hudson, Wisconsin, pp. 14-20.

Bierkens, M.F.P., Finke, P.A. and de Willigen, P., 2000. Upscaling and downscaling methods for environmental research. Kluwer Academic Publishers, Dordrecht, 190 pp.

Bogaard, A., 2004. Neolithic farming in Central Europe. An archaeobotanical study of crop husbandry practices. Taylor and Francis Group, London, 209 pp.

Bogucki, P.I., 1988. Forest farmers and stockherders. Early agriculture and its consequences in North-Central Europe. New Studies in Archaeology. Cambridge University Press, Cambridge.

Boman, R.K., Taylor, S.L., Raun, W.R., Johnson, G.V., Bernardo, D.J., Singleton, L.L.. 1996. The Magruder Plots: A century of wheat research in Oklahoma. Published by Department of Agronomy, Oklahoma State University.

Burrough, P.A., McDonell, R.A., 1998. Principles of Geographical Information Systems. Oxford University Press, New York.

Cappers, R.T.J., Raemaekers, D.C.M., 2008. Cereal cultivation at Swifterbant? Neolithic wetland farming on the North European Plain. Current Anthropology 49(3), 385-402.

de Hingh, A.E., 2000. Food production and food procurement in the Bronze Age and Early Iron Age (2000-500 BC): the organisation of a diversified and intensified agrarian system in the Meuse-Demer-Scheldt region (The Netherlands and Belgium) and the region of the river Moselle (Luxemburg and France). Archaeological Studies Leiden University, Leiden University, Leiden, 235 pp.

de la Rosa, D., van Diepen, C.A., 2002. Qualitative and quantitative land evaluation, in: Verheye, W. (Ed.), 1.5. Land use and land cover, Encyclopedia of Life Support System (EOLSS-UNESCO), Eolss Publisher, Oxford, UK. http://www.eolss.net.

Dent, D., Young, A., 1981. Soil survey and land evaluation. George Allen and Unwin, London.

Department of food and agriculture, government of Western Australia, 2012. (12 September 2012). http://www.agric.wa.gov.au/PC_92466.html.

De Temmerman, L., Vanongeval, L., Boon, W., Hoenig, M. and Geypens, M., 2003. Heavy metal content of arable soils in Northern Belgium. Water, Air, and Soil Pollution, 148: 61-76.

European Convention, 1992. *European Convention on the Protection of theArchaeological Heritage (revised), Valletta, 16-1-1992.* Council of Europe, European Treaty Series 143.

FAO, 1976. A framework for land evaluation. Soils Bulletin 32. FAO, Food and Agriculture Organization of the United Nations, Rome, 94 pp.

FAO, 1983. Guidelines: Land evaluation for rain fed agriculture. Soils Bulletin 52, FAO Food and Agriculture Organization of the United Nations, Rome.

FAO, 1985. Guidelines: Land evaluation for irrigated agriculture. Soils Bulletin 55, FAO Food and Agriculture Organization of the United Nations, Rome.

FAO, 1986. Irrigation Water Management: Irrigation water needs. Irrigation water management, Training manuals 3.

FAO, 2001. Mixed crop-livestock farming. A review of traditional technologies based on literature and field experience. FAO Animal production and health papers 152.

FAO, 2007. Land evaluation. Towards a revised framework, Land and Water Discussion Paper 6. FAO, Food and Agriculture Organization of the United Nations Rome.

FAO Ecocrop, 2012. FAO, Food and Agriculture Organization of the United Nations (10-15 September 2012). http://ecocrop.fao.org/ecocrop/srv/en/home.

Finke, P.A., 2012. Modeling the genesis of luvisols as a function of topographic position in loess parent material. Quaternary International 266, 3-17.

Finke, P.A., Harding, J., Sevink, J., Sewuster, R.J., Stoddart, S.. 1994. Site territories and landuse, in: Malone, C., Stoddart, S. (Eds.), Territory, time and state: the archaeological development of the Gubbio Basin. Cambridge, United Kingdom. Cambridge University Press. ISBN 0-521-35568-0

Finke, P.A., Hutson, J.L., 2008. Modelling soil genesis in calcareous loess. Geoderma 145, 462-479.

Finke, P.A., Sewuster, R.J.E., 1987. A soil survey and land evaluation in a Bronze Age context for the central Gubbio basin, Italy. Amsterdam: University of Amsterdam, Laboratory for Physical Geography and Soil Science.

Fokkens, H., 1986. From shifting cultivation to short fallow cultivation: Late Neolithic culture change in the Netherlands reconsidered, in: Fokkens, H., Banga, P., Bierma, M. (Eds.), Op zoek naar mens en materiële cultuur. Feestbundel aangeboden aan J.D. van der Waals ter gelegenheid van zijn emiraat. Universiteitsdrukkerij RUG, Groningen, pp. 5-19.

Fokkens, H., 1991. Verdrinkend landschap. Archeologisch onderzoek van het westelijk Fries-Drents Plateau 4400 BC tot 500 AD. PhD Thesis, University of Groningen.

Fokkens, H., 1998. Occupation in a slowly drowning landscape, in: van Regteren Altena, J.F. (Ed.), Drowned landscape. The occupation of the Western part of the Frisian-Drentian Plateau, 4400 BC – AD 500, Van Gorcum & Comp. BV, Assen, pp. 134-150.

Fokkens, H., 2005a. Woon-stalhuizen op zwervende erven. Nederzettingen in bekertijd en bronstijd, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 407-428.

Fokkens, H., 2005b. Boeren met gemengd bedrijf: synthese, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 463-474.

Fokkens, H., 2005c. Laat-neolithicum, vroege en midden-bronstijd: inleiding, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 357-370.

Foth, H.D., Ellis, B.G., 1996. Soil Fertility (2nd ed). CRC press, Lewis, pp. 304.

Gardner, C.M.K., Laryea, K.B. and Unger, P.W., 1999. Soil physical constraints to plant growth and crop production, Land and Water Development Division, Food and Agriculture Organization of the United Nations Rome.

Gregg, S.A., 1987. Foragers and Farmers. Population interaction and agricultural expansion in prehistoric Europe. Prehistoric Archeology and Ecology Series. University of Chicago Press, Chicago.

Guimiere, S.J., Le Bissonnais, Y., Raclot, D., 2009. Soil resistance to interrill erosion: Model parameterization and sensitivity. Catena 77, 274-284.

Guttmann, E.B.A., 2005. Midden cultivation in prehistoric Britain: Arable crops in gardens. World Archaeology 37(2), 224-239.

Health Canada Federal department, 2012. (November 18, 2012) http://www.hc-sc.gc.ca/fn-an/food-guide-aliment/basics-base/1_1_1-eng.php

Hernandez-Soriano, M., Degryse, F., Lombi, E. and Smolders, E., 2012. Manganese toxicity in barley is controlled by solution manganese and soil manganese speciation. Soil Science Society of America Journal, 76(2): 399-407.

Hodges, S.C., 1995. Soil fertility basics. NC certified crop advisor training, North Carolina State University.

Huisman, D.J., Jongmans, A.G., Raemaekers, D.C.M., 2009. Investigating Neolithic land use in Swifterbant (NL) using micromorphological techniques. Catena 78, 185-197.

Institute of Medicine, 2002. Dietary, Functional, and Total Fiber. Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids. National Academies Press, Washington, D. C., pp. 265-334.

Kamermans, H., 1993. Archeologie en landevaluatie in de Agro Pontino (Lazio, Italië). PhD dissertation (in Dutch), Universiteit van Amsterdam, Amsterdam.

Kamermans, H., Loving, S.H., Voorrips, A., 1985. Changing patterns of prehistoric land use in the Agro Pontino, in: Malone, C., Stoddart, S. (Eds.), Papers in Italian archaeology, Volume 4, Part 1: The human landscape. BAR International Series 243. Archaeopress, Oxford, pp. 53-68.

Kirleis, W., Klooß, S., Kroll, H., Müller, J., 2012. Crop growing and gathering in the norhtern German Neolithic: a review supplemented by new results. Vegetation History and Archaeobotany 21, 221-242.

Kooistra, M.J., Maas, G.J., 2008. The widespread occurence of Celtic field systems in the central part of the Netherlands. Journal of Archaeological Science 35, 2318-2328.

Landon, J.R., 1991. Booker Tropical Soil Manual. Longman Scientific & Technical, New York.

Lauwerier, R.C.G.M., van Kolfschoten, T., van Wijngaarden-Bakker, L.H., 2005. De archeozoologie van de steentijd, in: Deeben, J., Drenth, E., van Oorsouw, M.-F., Verhart, L. (Eds.), De steentijd van Nederland. Stichting Archeologie, pp. 39-66.

Le Bissonnais, Y., Montier, C., Jamagne, M., Daroussin, J. and King, D., 2001. Mapping erosion risk for cultivated soil in France. Catena, 46: 207-220.

Louwe Kooijmans, L.P., 1993. Wetland exploitation and upland relations of prehistoric communities in the Netherlands, in: Gardiner, J. (Ed.), Flatlands and wetlands: current

themes in East Anglian archaeology (East Anglian archaeology 50), Norwich, pp. 71-116.
Louwe Kooijmans, L.P., 2005. Nederland in de prehistorie: een terugblik, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 695-719.
Milisauskas, S., 2011. Early Neolithic, the First Farmers in Europe, 7000-5500/5000 BC, in : Milisauskas, S. (Ed.), European Prehistory. A Survey. Springer Science+Business Media, New York, pp. 153-221.
Milisauskas, S., Kruk, J., 2011. Middle Neolithic/Early Copper Age, continuity, diversity, and greater complexity, 5500/5000-3500 BC, in: Milisauskas, S. (Ed.), European Prehistory. A Survey. Springer Science+Business Media, New York, pp. 223-290.
Nyakatawa, E.Z., Reddy, K.C. and Sistani, K.R., 2001. Tillage, cover cropping, and poultry litter effects on selected soil chemical properties. Soil & Tillage Research, 58: 69-79.
Olsson, F. and Lemdahl, G., 2010. A forest history for the last 10 900 years at the site Storasjö, southern Sweden: implications from beetle assemblages. Journal of Quaternary Science, 25(8): 1211-1221.
OTerm, 2003. Ordonnance sur la terminologie agricole et la reconnaissance des formes d'exploitation. Modification du 26 novembre 2003, Suisse.
Out, W.A., 2008. Growing habits? Delayed introduction of crop cultivation at marginal Neolithic wetland sites. Vegetation History and Archaeobotany 17, 131-138.
Out, W.A., 2009. Sowing the seed? Human impact and plant subsustence in Dutch wetlands during the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC). Archaeological Studies Leiden University, Leiden University Leiden, 481 pp.
Overland, A. and Hjelle, K.L., 2009. From forest to open pastures and fields: cultural landscape development in western Norway inferred from two pollen records representing different spatial scales of vegetation. Vegetation History and Archaeobotany, 18: 459-476.
Pearson, C.J., Norman, D.W. and Dixon, J., 1995. Sustainable dryland cropping in relation to soil productivity, FAO, Food and Agriculture Organization of the United Nations, Rome.
Prøsch-Danielsen, L. and Simonsen, A., 2000. Palaeoecological investigations towards the reconstruction of the history of forest clearances and coastal heathlands in south-western Norway. Vegetation History and Archaeobotany, 9: 189-204.
Raemaekers, D., 2007. Grondsporen 7. Standaardrapport opgraving Swifterbant S4, Rijksuniversiteit Groningen, Groningen.
Reynolds, P.J., 1992. Crop yields of the prehistoric cereal types emmer and spelt: the worst option, Prehistoire de l'agriculture - Nouvelles approches experiementales et ethnographic. Monographie du CRA, no. 6, CNRS.
Risse, L.M. et al., 2001. Land application of manure for beneficial reuse, White papers on animal agriculture and the environment. National Center for Manure and Animal Waste Manegement, Raleigh, N.C., pp. 7.1-7.46.
Rood, R.J., 1982. Spatial analysis in archaeology: Historical development and modern applications. Lambda Alpha Journal of Man, 14: 21-55.
Rossiter, D.G., 2003. Biophysical models in land evaluation, in: Verheye, W. (Ed.), 1.5. Land use and land cover, Encyclopedia of Life Support System (EOLSS-UNESCO), Eolss Publisher, Oxford, UK. http://www.eolss.net.
Roymans, N., Gerritsen, F., 2002. Landscae, ecology and mentalités: a long-term perspective on developments in the Meuse-Demer-Scheldt region. Proceedings of the Prehistoric Society 68, 257-287.
Schinkel, K., 2005. Buurtschappen in beweging. Nederzettingen in Zuid- en Midden-Nederland, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 519-542.

Sivapalan, M., 1993. Linking hydrological parameterizations across a range of scales: hillslope to catchment to region, Exchange processes at the land surface for a range of space and time scales. Proceedings of the Yokohama symposium. IAHS Publications, pp. 115-123.

Sys, C., Van Ranst, E., Debaveye, J., Beernaert, F., 1993. Land Evaluation. Part III : crop requirements. Agricultural Publications n° 7, G.A.D.C., Brussels, Belgium : 191 pp.

Theunissen, E.M., 1999. Midden-Bronstijdsamenlevingen in het zuiden van de Lage landen een evaluatie van het begrip "Hilversum-cultuur". Proefschrift Universiteit Leiden, Leiden.

Van den Broeke , 2005. IJzersmeden en pottenbaksters, Materieële cultuur en technologie, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 603-626.

Van Joolen, E., 2003. Archaeological land evaluation: a reconstruction of the suitability of ancient landscapes for various land uses in Italy focused on the first millennium BC. Unpublished PhD thesis, Rijksuniversiteit Groningen, Groningen.

van Wijngaarden-Bakker, L., Brinkkemper, O., 2005. Het veelzijdige boerenbedrijf. De voedselproductie in de metaaltijden, in: Louwe Kooijmans, L.P., van den Broecke, P.W., Fokkens, H., van Gijn, A. (Eds.), Nederland in de prehistorie. Uitgeverij Bert Bakker, Amsterdam, pp. 491-512.

Verbruggen, C., Denys, L., Kiden, P., 1996. Belgium, in: Berglund, B.E., Birks, H.J.B., Ralska-Jasiewiczowa, M., Wright, H.E. (Eds.), Palaeoecological events during the last 15000 years: regional syntheses of palaeoecological studies of lakes and mires in Europe. John Wiley and Sons, Chichester, pp. 553-574.

VIOE, 2012. Onderzoeksbalans Onroerend erfgoed Vlaanderen – Archeologie. Vlaams Instituut voor Onroerend Erfgoed. (September 5, 2012) http://www.onderzoeksbalans.be/onderzoeksbalans/archeologie/

Visser, W.C., 1958. De landbouwwaterhuishouding van Nederland. COLN-TNO, The Hague (in Dutch).

Whalen, J.K., Chang, C., Clayton, G.W. and Carefoot, J.P., 2000. Cattle manure amendments can increase the pH of acid soils. Soil Science Society of America Journal, 64: 962-966.

Wilkinson, K., Straker, V., 2008. Neolithic and Early Bronze Age environmental background, in: Webster, C.J. (Ed.), The archaeology of South West England. South West archaeological research framework. Resource assessment and research agenda. Somerset Heritage Service, Taunton, pp. 63-74.

Wright, R.L., 1987. Integration in land research for Third World development planning: An applied aspect of landscape ecology. Landscape Ecology, 1(2): 107-117.

Ye, L. and Van Ranst, E., 2009. Production scenarios and the effect of soil degradation on long-term food security in China. Global Environmental Change, 19: 464-481.

Zidan, Y.O.Y., 2008. Mapping phreatic water tables to update the drainage class map 1:20,000 in the Scheldt Valley near Ghent. Unpublished thesis, Department of Geology and Soil Science. Ghent University, Ghent, pp. 89.

Zwertvaegher, A., Finke, P.A., De Reu, J., Vandenbohede, A., Lebbe, L., Bats, M., De Clercq, W., De Smedt, P., Gelorini, V., Sergant, J., Antrop, M., Bourgeois, J., De Maeyer, P., Van Meirvenne, M., Verniers, J., Crombé, P., in review$_a$. Reconstructing phreatic palaeogroundwater levels in a geoarchaeological context: a case study in Flanders (Belgium). Geoarchaeology: An International Journal.

Zwertvaegher, A., Finke, P.A., De Smedt, P., Gelorini, V., Van Meirvenne, M., Bats, M., De Reu, J., Antrop, M., Bourgeois, J., De Maeyer, P., Verniers, J., Crombé, P., in review$_b$. Spatio-temporal modelling for soilscape reconstruction. Geoderma.

Zwertvaegher, A., Werbrouck, I.,Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, P., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the Use of Integrated Process Models to Reconstruct Prehistoric Occupation, with Examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal, 25(6): 784-814.

Chapter 7
General discussion

7.1 Introduction

The primary aim of this research was to understand the distribution of archaeological artefacts and therefore the human occupation in a study area situated in Sandy Flanders for a time period starting in the Late Glacial and covering the entire Holocene. The term 'occupation' was stressed because the overall exploitation of the land and land use of different kinds besides settlement were pursued. In order to achieve this, the construction, performance and appraisal of a methodological framework for an archaeological land evaluation taking into account reconstructed landscape attributes for the chosen study area and period was set as the major objective of this work. The conceptual elaboration on the framework was presented by Zwertvaegher et al. (2010; Chapter 3), the practical implementations of the framework and the related research themes were described in the previous chapters of this manuscript (Chapters 4-6; Zwertvaegher et al., in review$_{a,b}$). In this chapter it is evaluated to what extent the primary objective and the postulated concepts were realized and perspectives for future research are stipulated.

7.2 Individual components of the model framework and reconstructed boundary conditions

7.2.1 Elevation model

Several means to reconstruct the prehistoric elevation were suggested in the initial concept: the application of erosion and sedimentation models (for example landscape-evolution modelling by Temme et al., 2011) or space-time interpolation methods using point reconstructions in relation to a current natural DEM, such as spatio-temporal kriging (Heuvelink, et al. 1997; Kyriakidis and Journel, 1999) or space-time Kalman filtering (Heuvelink et al., 2006). However, neither methodology was applied in this research. The first proposal appeared unfeasible because no process models were known to the author in which the evolution of the relief by mainly aeolian actors is reconstructed, as was the case in the study area especially during the Late Glacial. The second method was started up by putting up a database in which profile descriptions collected from literature sources, especially student theses, and from the Flemish database on subsurface information (DOV) were assembled. However, the further execution appeared unfeasible in the time provided without detracting from other objectives. A first attempt, however, was made by Vermeer (2012), who stratigraphically interpreted the collected data and used a kriging technique (only in the spatial dimension) to provide a full-cover map of the thickness of the Holocene sediments. The subtraction of the calculated thickness from the present-day elevation resulted in a map of the elevation at the start of the Holocene.

A temporal DEM was created by means of ‘deconstruction’ instead of ‘construction’. In this case, the post-medieval DEM (Werbrouck et al., 2011) was stripped off a predefined value at locations with recorded plaggen soils and recorded deposits due to storm surges and Scheldt river influence. The resulting (pre)historic DEM was assumed to be representative of the Holocene prior to the 12th century CE. Hence, the reconstruction of the temporal DEMs was limited to the more stable Holocene period, while the more dynamic Late Glacial was not taken into account. However, it is clear that independent of the used methodology, the beginning of the Holocene appears to form a temporal limit before which the uncertainty in the elevation reconstruction becomes too high. This is in se a data problem. Especially the aeolian activity in the region and the formation of several cover sand dunes and dune complexes is difficult to quantify. Datings (for example with OSL, optically stimulated luminescence) at several depths and locations in and alongside topographical features, such as the cover sand ridge of Maldegem-Stekene, are believed to shed more light on this dynamical environment and its evolution. The work of Derese et al. (2010) showed that one specific location can be subject to huge sediment displacements (6 m) in short time periods (less than 2 ka). It would be interesting to find out if this pronounced phase of aeolian activity can be regarded as a trend also occurring at other locations during the same time period. If so, this could be of use for the reconstruction of the pre-Holocene elevation.

More information is also wanted on peat growth and sand drift in the study area. The major focus should be on the age, extent and thickness of the peat present in the Moervaart Depression. At present practically no data on this peat are available, although there are indications that peat extraction occurred in this area (Jongepier et al., 2011). The presence of a peat layer would not only affect the topography, but also the hydrology of the region.

7.2.2 Climate data

Time series on climate data served (directly or indirectly) as boundary conditions for the groundwater and pedogenetic model. Recharge to the groundwater table was calculated from precipitation and evapotranspiration time series outside the groundwater model. Climate reconstructions were therefore required for local conditions in the study area. It was opted to use the area-averaged reconstructed temperature and precipitation anomalies based on quantitative pollen series that were provided by Davis et al. (2003) and Davis (personal communication, 2008). These time series were adjusted for local conditions using present-day (2005 CE) measurements from local weather stations. Of course, various other palaeoclimate proxies exist, such as oxygen isotopes from ice cores (e.g. Petit et al., 1999) and speleothems (e.g. Maher and Thompson, 2012), tree-ring carbon isotopes (e.g. Young et al., 2012), and many others (e.g. Brooks et al., 2011; Clegg et al., 2010), each of them having their advantages and disadvantages. The advantage of the pollen-based reconstructed time series of Davis et al. (2003) and Davis (personal communication, 2008) was that the necessary climate information on both (seasonal – coldest and warmest month – and annual mean) temperature and precipitation was provided by the same proxy. Furthermore, it was indicated by Davis et al. (2003) that the temperature data presented large internal consistency and showed agreement with other proxy records, therefore implying that the impact of local climatic and non-climatic elements on the methodology was limited. Because the precipitation anomaly series was reconstructed following the same methodology as the temperature time series (Davis, personal communication, 2008) they were therefore concluded to be equally suitable for the climate reconstruction in the study area. The disadvantage was that the used time series encompassed area-averaged values for central western Europe, which therefore needed to be converted to local conditions. Ideally, local proxies should be used in the reconstruction of local climate conditions.

7.2.3 Groundwater model

The dynamics of shallow groundwater tables influence processes like pedogenesis and vegetation development. In this light, it is interesting to study the long-term evolution of the average groundwater table as well as its within-year seasonal dynamics. Therefore, it was initially intended to perform a steady state and transient/dynamic groundwater modelling. Within-year water table dynamics are expressed as MHWT and MLWT depths. They are calculated by selecting the 3 highest and 3 lowest water table levels occurring within one hydrological year (starting in April). The average of the highest water table levels over a period of at least 8 years results in the MHWT value; the average of the lowest water table levels for the same period gives the value of the MLWT (Finke et al., 2004). As a consequence, the transient groundwater modelling would need to provide monthly values for the water table over the entire extent of the study period, i.e. a total of 152,592 months (or time steps). Taken the large extent of the study area (584 km^2), this was concluded to be too time-consuming, not to mention the high demands to be placed on data storage and computer capacity. Therefore, it was decided not to take the water table dynamics into account, but only to assess the long-term evolution of the average groundwater table (MWT) by simulating in steady state mode and for a temporal resolution of 30 years (424 time steps instead of 152,592) using 30-year averaged recharge data. The MWT depth appeared a useful land characteristic in the land evaluation model. The water table depth during the most water demanding crop growth stage (mid-season stage, assumed to be in June-July) most likely corresponded to the MWT and not the MHWT or MLWT. However, in literature, suitability classes for land qualities are often expressed in terms of soil drainage classes. The derivation of drainage classes from palaeogroundwater table depths is, however, only possible when MHWT and MLWT depths are determined. For other reasons as well, for example the need for seasonal water table fluctuation time series in the pedogenetic model or the calibration of the groundwater model based on archaeological artefacts and recorded podzol occurences, it is advisable to perform further research to make the transient modelling of groundwater tables over large time periods feasible in terms of practicality (computer runtime, data storage, calculation of MHWT and MLWT from monthly output).

The construction of the palaeoriver network and its hydrological characteristics was limited by the available data. First of all, the exact location of the former rivers was based on historical sources, present-day mapping of the geomorphology of the area and streamflow analysis starting from the reconstructed (pre)historic DEM. It is clear that historical sources have their temporal limit. The most reliable of the pre-19th century maps is the detailed map of Ferraris (also called Cabinet Map of the Austrian Netherlands), which was finalized in 1777. The application of streamflow analysis on the temporal DEM in GIS was limited at several locations due to the presence of flat surfaces and closed depressions. For example, the depression of the Moervaart appeared in the temporal DEM as a closed depression, which needed to be filled up prior to the execution of the streamflow algorithm. The presence of the artificial flat areas resulted in straight and unnatural streamlines. This was also the case for interpolated surfaces in the DEM, which were the result of the removal of present-day large construction works and subsequent interpolation between vectorized contour lines. This was the case for the industrial zone around the canal of Ghent-Terneuzen. It is clear that both methodologies have their limitations. The combination of both was therefore assumed to give the best result of the reconstructed river network. The reconstructed hydrological network was not evaluated by fieldwork. This could be applied in the future to test the quality of the predictions.

In a groundwater model, rivers in the hydrological system are conceptualized as head boundaries, and groundwater fluxes towards the rivers and out of the groundwater system are dependent on the stage height (the height of the water level in the river) and the head of the groundwater in the aquifer. However, estimating the water balance for past hydrological systems was hindered by the availability of information. For example, nowadays, drainage of water out of the groundwater system is largely performed by artificial drainage pipes. This was however not the case during the 1950s and earlier times. Artificial open ditches crossing the landscape served a two-fold function: drainage of excess water at times of too high groundwater levels during winter and spring, as well as re-introduction of water to the groundwater system and controlling the groundwater level during summer. In the present situation, many of these ditches are filled in due to increased urbanisation and land consolidation (Flemish Government Report, 2001). Not to mention the many difficulties in sewer overflows, floodings and inefficient replenishment of the groundwater system (all relevant topics but not in this study), their passing into disuse and disappearing makes it very hard to assess their former capacity and impact on the past historical water balance. Furthermore, water level in present-day rivers is controlled by sluices and set at a fixed level. The assessment of the contribution of rivers to the overall water balance for periods in which no extensive ditch networks existed and in which rivers had a natural and uncontrolled regime (as in pre- and protohistoric times), as well as the impact of ditch networks in historical times, should therefore have more focus.

Coupled surface water-groundwater models might help to better quantify the mutual impacts of both systems in natural contexts. In such a model, groundwater discharge calculated with a groundwater model is at the end of each groundwater model time step passed to the surface-water model as a base flow boundary condition. The surface-water model then calculates the river discharge and water levels in the rivers for the surface-water model time step, which are passed back to the groundwater model for the next time step (Knapton, 2009). An example is given by Knapton (2009) for the Doper river catchment in Australia, in which a fully-automated coupling of the MIKE11 surface-water model and the FEFLOW groundwater model is executed. Several other models integrate overland flow and groundwater models, as for example GSFLOW (Markstrom et al., 2008), coupling the USGS Precipitation-Runoff Modeling System (PRMS) and MODFLOW-2005 (the USGS Modular-Water Flow Model), or WetSPass (Batelaan and De Smedt, 2001). These can be used to calculate spatial variations in groundwater recharge, which was now homogenously applied to the entire study area.

The calibration of the groundwater modelling was based on a two-step approach, in which the first step comprised the calibration of the 1924-1953 CE time period. The soil map (surveyed in the study area in 1949-1954 CE) served as a useful source of information on the historical soil drainage in the study area (deviating from the current one that was reported by Finke et al., 2010). A large asset of this map is that it provides multi-layered information on a full-cover extent. The map contains information on different attributes such as texture class, drainage class and profile development of the soil. The drainage class on its turn supplies information on the MHWT and MLWT depths, which can be used to calculate the depth of the MWT at the time of mapping. The soil map is therefore the most extensive data source for the study area on groundwater levels and dynamics in the recent past (around 1950 CE). For earlier time periods it is necessary to rely on other information to evaluate the simulated groundwater table depths. However, not many proxies of past groundwater levels are known. We have proposed the use of archaeological find spots and recorded podzol locations as indications for phreatic palaeogroundwater levels. The advantage of archaeological data is that they are generally situated in a temporal frame. The drawback is that only minor assumptions on the water table depth can be made. In this case we assumed that the MHWT at the archaeological find location must have been below surface during the entire chronological period to which the artefact was subscribed to.

Another approach would be to use ecological information (for example pollen and macrobotanical analyses) as a proxy of past groundwater levels. However, we believe this method will be limited by the amount of available data and their spatial distribution (probably most information coming from organic layers such as rivers/lake infillings, and very likely few data from sandy grounds). Furthermore, it is expected that the reconstructed vegetation would only enable a more qualitative estimation of the groundwater table (deep versus shallow) instead of quantitative data (for example, the model outputs are expressed in absolute elevations). However, this should be further investigated concerning its feasibility.

In the future more attention should be paid to more automated and reproducible methods of the model calibration. This can be performed with for example PEST (Parameter ESTimation; Doherty, 2002) where the parameters are estimated in an iterative procedure. However, we propose a Bayesian approach using Markov Chain Monte Carlo (MCMC), which enables the quantification of the uncertainties in the model output. The procedure incorporates prior knowledge on the parameters based on either expert judgment, literature data or actual measurements or a combination of these and yields an updated posterior probability distribution on the calibrated parameters, quantifying the uncertainties. The method has already been applied to a wide range of models in ecological and environmental sciences, for example in ecosystem studies

(Klemedtsson et al., 2008; Lehuger et al., 2009; Svensson et al., 2008; Van Oijen et al., 2005), in soil research (Reinds et al., 2008) and hydrological studies (Vrugt et al., 2009b). Practically, this would require the coupling of the groundwater model with, for example, the DiffeRential Evolution Adaptive Metropolis (DREAM) MCMC scheme (Vrugt et al., 2009a).

7.2.4 The pedogenetic model

The SoilGen2 model (thoroughly tested for loess) was used in this study for sandy soils. Implementation of the podzolisation process – mobilization and precipitation of dissolved organic matter together with Al(-silicates) and Fe, as well as slow and fast organic carbon dynamics (Buurman and Jongmans, 2005) – is believed to enhance the modelling results in coarser textured soils. Podzol formation is associated with restricted fertility, high acidity and limited rooting depth. Therfore, simulating this process could help to accomplish a more complete view of the suitability of the land in the land evaluation procedure. Furthermore, soil fertility and nutrient availability in the land evaluation was currently assed from CEC, OC and base saturation. Including plant available N, P and K contents in the evaluation would complement this evaluation. This would require the incorporation of soil nitrogen and phosphorus cycles in the pedogenetic model.

In the presented study seasonal dynamics of the shallow water table, influencing the soil formation within the profile, were mimicked in the pedogenetic model by imposing a reduced permeability at the MWT depth, simulating a perched water table. This was necessary because only time series of the MWT depths were available instead of MHWT and MLWT depths. First of all, extra model testing and evaluation of the simulated groundwater table dynamics is advisable. However, the use of MHWT and MLWT depth time series as boundary conditions is equally (or even more) preferable. At present, model calibration was performed on the solubility constant of calcite. Additional calibration of other model parameters is preferable. The Bayesian approach with MCMC is an interesting method because parameter uncertainties are quantified. This is however complicated by the long runtime of the pedogenetic model and will require additional practical implementations.

A regression kriging framework following the work of Hengl et al. (2004) was used to produce full-cover maps starting from the simulation results. Owing to the combination of the soil formation model and the kriging framework, maps were made for different soil characteristics, and for various times and depths. Future research should focus on additional and improved auxiliary maps, especially for in-depth kriging predictions.

Regression kriging is an unbiased predictor: it will predict the value of the target value at the target location. It is therefore expected that enhanced model predictions and consequently less inconsistencies in the target data will result in improved kriging predictions.

The Aardewerk database, as collected during the soil survey campaign and described by Van Orshoven et al. (1988, 1993), provided an interesting data source of present-day (ca 1950 CE) soil measurements. Furthermore, chemical and physical soil properties of the parent material were derived from the database. The large number of locations that were available through this database for the simulations was an advantage because sampling and soil surveying is time consuming and can require high financial inputs. The selected sample locations were evaluated for clustering by comparing the sampling plan with a random design and were concluded to be representative of the geographical space (falling within the confidence limits of a CSR – Complete Spatial Randomness – test). However, several texture classes were not adequately represented (less than 5 observations per class), indicating that the feature space was not well-represented. In the future additional care should be taken when sampling (the Aardewerk database or the real space) for pedogenetic modelling, especially when spatial interpolation is to be applied afterwards.

7.2.5 The land evaluation and carrying capacity assessment

The land evaluation formed the final component of the model framework. Here, the reconstructed land characteristics were evaluated in term of pre- and protohistoric kinds of land use and more explicitly agrarian land use. The encountered limitations in reconstructing past LUTs from archaeological literature and the assessment of requirements by pre- and protohistoric tools (such as the ard) as well as crops that are most likely genetically altered throughout time, were elaborately discussed in Chapter 6. It was pointed out that more direct data sources on potential LUTs as well as past requirements and crop yields should be investigated. For example, the studies from de Hingh (2000) and Out (2009) on weed assemblages from archaeological sites gave direct evidence on cultivation and management regimes. Experimental archaeological sites and ancient farms, as for example Butser Ancient Farm in the UK (e.g. Reynolds, 1982), prove interesting and useful initiatives to increase our knowledge on for example crop yield under pre- and protohistoric working conditions.

Ideally, different scenarios representing different LUTs should be simulated. This was not the case in this study where the used land characteristics were based on only one scenario simulated with the SoilGen model. This was due to the long runtime of the pedogenetic model and the large number of locations needed to perform the kriging (which was now set at 96 locations). It is possible to decrease the runtime at one location by starting up the new scenario from the point in time where it deviates from a previous scenario at the same location. For example, when two scenarios are regarded both with equal boundary conditions up till the Neolithic, model output from the first scenario for the end of the Mesolithic can be used as starting point for the second scenario. This would have reduced the period to be simulated in the second scenario by half. Furthermore, a smarter sampling of the locations might reduce the number of necessary locations to perform the regression kriging.

The potential of archaeological land evaluation as tool for predictive modelling should be further investigated. It would be especially useful to test this for areas with higher amounts of recorded sites with agricultural evidence and certain patterns in the spatial distribution of these sites. Although the latter criterion is met in this research, hard evidence for agrarian agriculture in the study region for Neolithic and Bronze Age times is generally lacking. However, land evaluation and resulting suitability maps can support preliminary assumptions on the carrying capacity of a region and thus its potential population density. These in their turn can be compared with other methods of population estimations, for example based on urnfields. Emerging discrepancies or similarities are believed to give rise to new hypothesis or insights and will stimulate future research. However, the qualitative approach applied in this study has its shortcomings, especially when the results are to be used in a carrying capacity assessment. Therefore, a quantitative land evaluation partly based on a dynamic crop growth simulation model is suggested to directly link land characteristics to a quantified crop production. Furthermore, uncertainties are present in the assessments of the energetic requirement of a prehistoric family, the composition of the livestock and its meat and milk production. In the future the production of the areas used for extensive grazing should also be taken into account in the land evaluation. Finally, results from the (qualitative or quantitative) land evaluation should ideally be evaluated based on on-site experiments and measurements.

7.3 Model framework

It is clear that in the process of reconstructing former landscape attributes uncertainties occur in data input as well as model output. Furthermore, the reconstructions are sometimes hard to evaluate because almost no direct measurements exist of pre- and protohistoric target variables. As already mentioned by Zwertvaegher et al. (2010; Chapter 3) error propagation through the sequence of modelling, up- and downscaling and interpolation steps, could be investigated using Monte Carlo techniques (Heuvelink, 1998). This appeared unfeasible given the complexity of the framework as well as long model runtimes because high accuracies with the Monte Carlo method are only attained when the number of runs is ample. In this chapter, recommendations were made to better estimate model uncertainty per individual model component of the framework, which is believed to be more practical. Independent of the method by which model errors are estimated, the land evaluation approach and preceding model simulations can be repeated for parameter values at the minimum and maximum range of the defined errors. This might reveal the continuous and persistent trends in the suitability classification. Furthermore, it is believed that by classifying land characteristics and qualities into suitability classes the impact of uncertainties will be reduced in the overall suitability map. It must also be noted that the application of models allows the quantification of uncertainties, which is not always the case for less formal ways of landscape reconstruction.

7.4 References

Batelaan, O., De Smedt, F., 2001. WetSpass: a flexible, GIS based, distributed recharge methodology for regional groundwater modelling, Sixth IAHS Scientific Assembly. Impact of Human Activity on Groundwater Dynamics, Maastricht, The Netherlands.

Brooks, S.J., Matthews, I.P., Birks, H.H., Birks, H.J., 2012. High resolution Lateglacial and early-Holocene summer air temperature records from Scotland inferred from chironomid assemblages. Quaternary Science Reviews 41, 67-82.

Buurman, P., Jongmans, A.G., 2005. Podzolisation and soil organic matter dynamics. Geoderma 125, 71-83.

Clegg, B.F., Clarke, G.H., Chipman, M.L., Chou, M., Walker, I.R., Tnner, W., Sheng Hu, F., 2010. Six millenia of summer temperature variation based on midge analysis of lake sediments from Alaska. Quaternary Science Reviews 29, 3308-3316.

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., data-contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 1701-1716.

de Hingh, A.E., 2000. Food production and food procurement in the Bronze Age and Early Iron Age (2000-500 BC): the organisation of a diversified and intensified agrarian system in the Meuse-Demer-Scheldt region (The Netherlands and Belgium) and the region of the river Moselle (Luxemburg and France). Archaeological Studies Leiden University, Leiden University, Leiden, 235 pp.

Derese, C., Vandenberghe, D.A.G., Zwertvaegher, A., Verniers, J., Crombé, P., Van den haute, P., 2010. The timing of aeolian events near archaeological settlements around Heidebos (Moervaart area, N Belgium). Netherlands Journal of Geosciences - Geologie en Mijnbouw 89, 173-186.

Doherty, J., 2002. PEST: Model-Independent Parameter Estimation. Fourth edition of user manual., Brisbane, Australia.

Finke, P.A., Brus, D.J., Bierkens, M.F.P., Hoogland, T., Knotters, M., de Vries, F., 2004. Mapping groundwater dynamics using multiple sources of exhaustive high resolution data. Geoderma 123, 23-39.

Finke, P.A., Van de Wauw, J., Baert, G., 2010. Development and testing of a method to update the drainage class map of Flanders. Final report (in Dutch). Ghent University, Ghent.

Flemish Government Report, 2001. Report WAT/L 2000 S 0002 X, Herwaardering van het grachtenstelsel. Fase 2 - Inventarisatie en opbouw van een GIS. Deel uitvoering, Department Environment and infrastructure, AMINAL - Division Water, Brussel.

Hengl, T., G.B.M., H., Stein, A., 2004. A generic framework for spatial prediction of soil variables based on regression kriging. Geoderma 120, 75-93.

Heuvelink, G.B.M., 1998. Error propagation in environmental modelling with GIS. Taylor and Francis, London.

Heuvelink, G.B.M., Musters, P., Pebesma, E.J., 1997. Spatio-temporal kriging of water content, in: Baafi, E., Schofield, N. (Eds.), Geostatistics Wollongong '96, Volume 1. Kluwer Academic Publishers, Dordrecht, pp. 1020-1030.

Heuvelink, G.B.M., Schoorl, J.M., Veldkamp, A., Pennock, D.J., 2006. Space-time Kalman filtering of soil redistribution. Geoderma 133, 124-137.

Klemedtsson, L., Jansson, P.-E., Gustafsson, D., Karlberg, L., Weslien, P., von Arnold, K., Ernfors, M., Langvall, O., Lindroth, A., 2008. Bayesian calibration method used to elucidate carbon turnover in forest on drained organic soil. Biogeochemistry 89, 61-79. DOI: 10.1007/s10533-007-9169-0.

Knapton, A., 2009. Gulf Water Study. An integrated surface-groundwater model of the Roper River Catchment, Northern Territory. Part A: Coupled surface-groundwater model, Northern Territory Department of Natural Resources, Environment, The Arts & Sports.

Kyriakidis, P.C., Journel, A.G., 1999. Geostatistical space-time models: A review. Mathematical Geology 31, 651-684.

Lehuger, S., Gabrielle, B., Van Oijen, M., Makowski, D., Germon, J.-C., Morvan, T., Hénault, C., 2009. Bayesian calibration of the nitrous oxide emission module of an agro-ecosystem model. Agriculture, Ecosystems and Environment 133, 208-222. DOI: 10.1016/j.agee.2009.04.022.

Maher, B.A., Thompson, R., 2012. Oxygen isotopes from Chinese caves: records not of monsoon rainfall but of circulation regime. Journal of Quaternary Science 27(6), 615-624.

Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., Barlow, P.M., 2008. GSFLOW - Coupled ground-water and surface-water flow model based on the integration of the precipitation-runoff modeling system (PRMS) and the modular ground-water flow model (MODFLOW-2005) U.S. Geological Survey Techniques and Methods 6-D1.

Out, W.A., 2009. Sowing the seed? Human impact and plant subsustence in Dutch wetlands during the Late Mesolithic and Early and Middle Neolithic (5500-3400 cal BC), Leiden University Leiden.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature 399(3), 429-436.

Reinds, G.J., van Oijen, M., Heuvelink, G.B.M., Kros, H., 2008. Bayesian calibration of the VSD soil acidification model using European forest monitoring data. Gedoderma 146, 475-488.

Reynolds, P.J., 1982. Crop yields of the prehistoric cereal types emmer and spelt: the worst option, Prehistoire de l'agriculture - Nouvelles approches experiementales et ethnographic. Monographie du CRA, no. 6, CNRS.

Svensson, M., Jansson, P.-E., Gustafsson, D., Kleja, D.B., Langvall, O., Lindroth, O., 2008. Bayesian calibration of a model describing carbon, water and heat fluxes for a Swedish boreal forest stand. Ecological Modelling 213, 331-344. DOI: 10.1016/j.ecolmodel.2008.01.001.

Temme, A.J.A.M., Peeters, I., Buis, E., Veldkamp, A., Govers, G., 2011. Comparing landscape evolution models with quantitative field data at the millenial time scale in the Belgian loess belt. Earth surface processes and landforms 36, 1300-1312.

Van Oijen, M., Rougier, J., Smith, R., 2005. Bayesian calibration of process-based forest models: bridging the gap between models and data. Tree Physiology 25, 915-927. DOI: 10.1093/treephys/25.7.915.

Van Orshoven, J., Deckers, J.A., Vandenbroucke, D., Feyen, J., 1993. The completed database of Belgian soil profile data and its applicability in planning and management of rural land. Bulletin des Recherches Agronomiques de Gembloux 28, 197-222.

Van Orshoven, J., Maes, J., Vereecken, H., Feyen, J., Dudal, R., 1988. A structured database of Belgian soil profile data. Pedologie 38(2), 191-206.

Vermeer, J., 2012. A final Pleistocene palaeotopography: The construction of a temporal (G)DEM as a process model for environmental reconstruction and auxiliary spatial variable for predictive modelling in the Flemish Valley (NW Belgium) (in Dutch). MSc-thesis, Ghent University.

Vrugt, J.A., ter Braak, C.J.F., Diks, C.G.H., Robinson, B.A., Hyman, J.M., Higdon, D., 2009a. Accelerating Markov Chain Monte Carlo Simulation by Differential Evolution with Self-Adaptive Randomized Subspace Sampling. International Journal of Nonlinear Sciences & Numerical Simulation 10(30), 271-288.

Vrugt, J.A., ter Braak, C.J.F., Gupta, H.V., Robinson, B.A., 2009b. Equifinality of formal (DREAM) and informal (GLUE) Bayesian approaches in hydrologic modeling? Stochastic Environmental Research and Risk Assessment 23, 1011-1026.

Young, G.H.F., Bale, R.J., Loader, N.J., McCarroll, D., Nayling, N., Vousden, N., 2012. Central England temperature since AD 1850: the potential of stable carbon isotopes in British oak trees to reconstruct past summer temperatures. Journal of Quaternary Science 27(6), 606-614.

Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital elevation model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.

Zwertvaegher, A., Finke, P.A., De Reu, J., Vandenbohede, A., Lebbe, L., Bats, M., De Clercq, W., De Smedt, P., Gelorini, V., Sergant, J., Antrop, M., Bourgeois, J., De Maeyer, P., Van Meirvenne, M., Verniers, J., Crombé, P., in review$_a$. Reconstructing phreatic palaeogroundwater levels in a geoarchaeological context: a case study in Flanders (Belgium). Geoarchaeology: An International Journal.

Zwertvaegher, A., Finke, P.A., De Smedt, P., Gelorini, V., Van Meirvenne, M., Bats, M., De Reu, J., Antrop, M., Bourgeois, J., De Maeyer, P., Verniers, J., Crombé, P., in review$_b$. Spatio-temporal modelling for soilscape reconstruction. Geoderma.

Zwertvaegher, A., Werbrouck, I., Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, P., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the Use of Integrated Process Models to Reconstruct Prehistoric Occupation, with Examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal 25(6), 784-814.

Chapter 8
General conclusion

8.1 Introduction

This study primarily aimed to construct a methodological framework in order to perform an archaeological land evaluation starting from reconstructed landscape components and to test this for a study area in Sandy Flanders for a time period from the final part of the Younger Dryas and covering the entire Holocene. It was concluded from on a evidence-filtered predictive modelling that the explanatory and predictive potential of the current landscape provided insufficient information considering the found distributions of archaeological material, therefore implying the need for a reconstruction of the former landscape and its attributes. Starting from an evaluation of the data necessity to understand past human occupation the following models were proposed in order to reconstruct the required information and to help understand the influence of the landscape on observed occupation patterns and past human exploitation of the region: a temporal DEM, a groundwater model, a pedogenetic model, and finally a land evaluation model.

8.2 General conclusions

The soil map was concluded to provide useful information on historic (ca 1950 CE) groundwater table depths. From the recorded drainage classes not only mean highest and mean lowest water table depths, but also mean water table (MWT) depths could be deducted. These observations can be used for groundwater model calibration as well as model quality testing for time periods around 1950 CE (in this case the 1924-1953 time period). Archaeological artefacts and recorded podzol locations and depths can serve as proxies for palaeogroundwater levels. A model quality of the groundwater model of 1.8 cm and 65.6 cm, for the mean error (ME) and root mean squared error (RMSE), respectively, was achieved. At 96.28% of the archaeological sites and at 96.88% of the podzol locations of an independent dataset, the simulated MWT depths were in accordance with settlement and podzolisation conditions.

The reconstruction of the groundwater table indicated that MWT level rose from Younger Dryas to Boreal and that it is relatively stable for the rest of the Holocene. It appeared that locations where strong spatial MWT gradients were attested, were of large interest to Meso- and Neolithic man. The archaeological sites are situated on the drier cover sand ridge, where freshwater seepage in the vicinity of the southern border possibly occurred. A slight drying occurs in the modelling at the transition from the Boreal to the Atlantic. This coincides with a marked decrease in archaeological sites dating to the Middle Mesolithic (Crombé et al., 2011). This might indicate that water level in the area, especially in the river channel, limited the availability of drinking water. This is an interesting hypothesis and needs to be further evaluated. Considering the Bronze Age, no clear relation between the distribution of the barrows and the MWT depth was found. Of course, the location of burial barrows might have been instructed by other demands than the ones placed on daily-life, non-ritual activities. The study of De Reu et al. (2011) showed that burial mounds were built on the more prominent locations in the landscape. In general, higher topographic locations are to be expected to coincide with deeper MWT levels. It was concluded that the spatial grain of the MWT maps (100 m x 100 m) was too high and further research with downscaled maps would be necessary. The relation between the MWT depth and the Iron Age site location could not be investigated due to the low amount of Iron Age sites in the study area.

Especially the region of parallel small ridges and depressions to the south of the Moervaart Depression remained void of archaeological evidence for all periods investigated. Crombé et al. (2011) and De Reu et al. (2011) for the Stone Age and the Bronze Age, respectively, concluded this to be the result of an archaeological reality and not of biased sampling or different preservation conditions. Ameryckx and Leys (1962) mention seasonally high groundwater tables and even flooding of the neighbouring grounds in winter, in the specific area, due to poor conditions of the ditch network. It was concluded that in earlier times, when artificial drainage networks were absent, these seasonally high groundwater tables must have restricted settlement in the area. Although higher and drier ridges were present between the lower and wetter depressions, due to their limited extent they most probably did not serve as suitable locations for settlement. In addition, the absence of major open water systems, such as lakes and large streams, might have restricted the occupation of this area as well.

The evolution of several soil variables at various depths at 96 profile locations was simulated for the study period, using the SoilGen2 model. It was concluded that fine earth fractions were reasonably well predicted. Clay fractions were however, generally underestimated in the upper part of the soil due to overestimated clay migration, but illuviation depth was estimated well. Overestimation of the physical weathering resulted in under- and overestimated sand and silt fractions, respectively. The values for CEC, calcite and pH were underestimated as compared to measurements from around 1950 CE, as recorded in the Aardewerk database. This database (Van Orshoven, 1988, 1993) proves to be an important data source useful for the reconstruction of parent material composition at a large number of locations. The regression kriging framework, based on the method proposed by Hengl et al. (2004), was accepted as a useful procedure to produce full-cover maps of simulated soil characteristics for the upper part of the soil at several points in time. Regional variation presented on the resulting regression kriging maps reflected the expected spatial patterns well. The combination of the SoilGen model, providing point-location soil data, and the regression kriging framework is believed to be an interesting methodology that will extend the spatial prediction of soil variables with a temporal and in-depth dimension.

The execution of an archaeological land evaluation proved to be an interesting and useful tool to integrally compare different (reconstructed) land characteristics in order to assess the suitability of the land in terms of pre- and protohistoric human occupation/exploitation of a region. The human factor and human perception of the land is to some degree also taken into consideration. The largest part of the study area was concluded to be marginally suitable (68.6-78.3%) for all tested land utilization types and all evaluated times. A large part of the area was classified as not suitable (21.6-31.2%) and a very small area (0.01-0.38%) was found to be moderately suitable. A preliminary carrying capacity assessment of the study region for the Middle Bronze Age was executed. Based on the estimated crop yield and livestock composition, 5.3 ha per person was found as the potential carrying capacity of the study region for the Middle Bronze Age. This relates to a total number of 9,490 persons in the 50,592 ha large study area, which was reached when 12% of the area was under crop cultivation. For smaller areas under crop cultivation, the carbohydrate production by crops appeared to be limiting the number of persons supported. For larger areas under crop cultivation, the number of people supported by the study region would be limited by the protein production by the livestock. The calculated population density deviated from literature values based on for example, urnfield or Celtic fields calculations. This was probably due to the potential available area and the actual area in use. More information on the presence of for example forested areas, would probably give more conclusive results on the actual population density.

It is believed that the use of simulated land characteristics makes the evaluation less subjective as compared to when general assumptions on land qualities are made, especially when land management practices, for example manuring, are applied. In some studies (e.g. Van Joolen, 2003), marginally suitable soils such as Cambisols, are classified as suitable when manure was regularly applied. However, simulated liming in the study area did not result in higher suitability classes for the largest part of the study area. This was most probably due to underestimated liming levels (based on the work of Plinius The Young) with an only temporally effect. Therefore, we believe that it is appropriate to be careful when allocating suitabilities and that these should be supported by measured and, if not available, simulated values.

In general, it is concluded that the proposed model framework, although not entirely executed as initially stated, proved an interesting tool to better understand past landscapes and their impact on the previous human occupation/exploitation of a region. Some first steps were made, but several tracks are yet to be exploited. We refer, for example, to the implementation and simulation of different land management scenarios (manure, fallow, etc.). One of the largest advantages is that the methodology is fully reproducible. We believe the execution of this framework can help to increase our understanding of past occupation and can help to evaluate postulated hypothesis in archaeology. The largest drawback in the current approach is the high data necessity. Each model is subject to various boundary conditions whose spatial and temporal variabilities need to be assessed. This broad range of required input needs to be delivered by various disciplines. Therefore, there is a perpetual need for interdisciplinary communication and collaboration. The proposed framework of integrated process models was concluded to be feasible and useful and several points were mentioned for its improvement (Chapter 7). These are summarized in the following section and provide an outlook on future work.

8.3 Outlook on future work

In Chapter 7, the several steps in the framework were discussed and elements for future work were identified. These are summarized in this section.

Considering the reconstruction of the temporal DEMs:

- Supplementary datings of features would enhance the reconstruction of temporal DEMs. This requires exact information of 4 dimensions: knowledge on time (age), planimetric location (x and y coordinates) and depth/elevation (z coordinate).
- Further methodological research on space-time interpolation methods, such as the work of Heuvelink et al. (1997; 2006) and Kyrikakidis and Journel (1999), as well as landscape evolution modelling (e.g. Temme, 2008; Temme and Veldkamp, 2009) in aeolian settings is necessary.

Considering the reconstruction of the climate data:

- The reconstruction of local temperature (seasonal warmest and coldest month values, as well as annual values), precipitation and evapotranspiration time series based on local proxies is believed to reduce the uncertainties of the reconstructed climate time series.

Considering the reconstruction of the phreatic palaeogroundwater levels:

- The performance of a transient groundwater modelling and the calculation of MHWT and MLWT depths is considered useful in terms of groundwater model calibration as well as in terms of boundary conditions to the pedogenetic model. Translating the values to drainage classes will result in an useful land characteristic to asses for example moisture availability in the land evaluation procedure. This would require several practical implementations to make the transient modelling of groundwater tables over large time periods feasible in terms of practicality. This concerns computer runtime, data storage, calculation of MHWT and MLWT levels from output on a monthly temporal resolution and the calculation of drainage classes based on MHWT and MLWT depths.

- More information is required on the hydrological characteristics of ditch networks and their contribution to the water balance in historical (pre-drainage pipe) times. Furthermore, more exact data on the river network contribution to the water balance in natural contexts (no drainage pipes, no ditch network, no canalization) is required. This might be assessed by using coupled surface-water – groundwater models.

- Reconstructed climate series as well as reconstructed land cover can be used in coupled overland-flow – groundwater models to take spatial variation in recharge to the groundwater table into account.

- Other proxies should be evaluated for their predictive potential of past groundwater levels. These can be helpful in model calibration as well as model-quality testing for past situations.

- Further attention should be placed on calibration methods. We propose a Bayesian approach with MCMC by which uncertainties in the model output are quantified. Practically, coupling of the groundwater model with, for example the DiffeRential Evolution Adaptive Metropolis (DREAM) MCMC scheme (Vrugt et al., 2009b), is suggested.

Considering the reconstruction of the soil variables:

- Incorporation of the podzolisation process in the SoilGen model is believed to enhance model predictions in sandy soils.

- Implementation of nitrogen and phosphorus cycles in the SoilGen model is assumed to broaden the range of possible land characteristics to integrate in the soil fertility assessment of the land evaluation procedure.

- Additional model testing and evaluation of the simulated groundwater table dynamics is advisable. The application of MHWT and MLWT depth time series as model boundary conditions to the SoilGen model is equally (or even more) preferable.

- Extending the model calibration procedure of the SoilGen model is advisable. A Bayesian approach is suggested, which needs firstly to be assessed for its feasibility (for example in terms of the long runtime of the model).

Considering the reconstruction of full-cover maps from simulated soil variables at point locations:

- Future research should be concentrated on additional and improved auxiliary maps, especially for in-depth kriging predictions.

Considering the land evaluation:

- More direct data sources on potential LUTs as well as past requirements and crop yields should be investigated.

- Additional scenarios of different LUTs should be simulated (especially with SoilGen, considering the application of cattle dung manure, or the presence of fallow periods). The suitability maps can then be interpreted in function of their carrying capacity and the results should be compared with other estimations of population densities, for example based on archaeological artefacts.

- The production of areas used for extensive grazing should also be taken into account in the evaluation.

- The use of a quantitative land evaluation instead of a qualitative land evaluation should be investigated to overcome shortcomings related with the use of classes (loss of variation).

- The (qualitative or quantitative) land evaluation results should be evaluated based on on-site experiments and measurements.

Considering the assessment of the carrying capacity:

- Additional information on the energy requirements of prehistoric families, the livestock composition and the production of meat and milk is required.

- The use of a dynamic crop growth simulation model is suggested to calculate crop reference yield and crop production based on the reconstructed land characteristics.

Considering the entire model framework:

- Investigate methods to better quantify the model uncertainties and the error propagation.

8.4 References

Ameryckx, J., Leys, R., 1962. Verklarende tekst bij het kaartblad Zeveneken 41 W, Bodemkaart van België. Instituut tot aanmoediging van het Wetenschappelijk Onderzoek in Nijverheid en Landbouw, Brussel, pp. 87.

Crombé, P., Sergant, J., Robinson, E., De Reu, J., 2011. Hunter-gatherer responses to environmental change during the Pleistocene-Holocene transition in the southern North Sea basin: Final Palaeolithic-Final Mesolithic land use in northwest Belgium. Journal of Anthropological Archaeology 30(3), 454-471.

De Reu, J., Bourgeois, J., De Smedt, P., Zwertvaegher, A., Antrop, M., Bats, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2011. Measuring the relative topographic position of archaeological sites in the landscape, a case study on the Bronze Age barrow in northwest Belgium. Journal of Archaeological Science 38(12), 3435-3446.

Hengl, T., G.B.M., H., Stein, A., 2004. A generic framework for spatial prediction of soil variables based on regression kriging. Geoderma 120, 75-93.

Jongepier, I., Soens, T., Thoen, E., Van Eetvelde, V., Crombé, P., Bats, M., 2011. The brown gold: a reappraisal of medieval peat marshes in Northern Flanders (Belgium). Water History 3(2), 73-93.

Van Orshoven, J., Deckers, J.A., Vandenbroucke, D., Feyen, J., 1993. The completed database of Belgian soil profile data and its applicability in planning and management of rural land. Bulletin des Recherches Agronomiques de Gembloux 28, 197-222.

Van Orshoven, J., Maes, J., Vereecken, H., Feyen, J., Dudal, R., 1988. A structured database of Belgian soil profile data. Pedologie 38(2), 191-206.

Samenvatting

De toepassing van geïntegreerde procesmodellen in een geoarcheologische context: een proeve van haalbaarheid

Deze studie kadert in een geoarcheologische context, waarin de relatie tussen het land enerzijds, met zijn specifieke kenmerken en kwaliteiten, en de pre- en protohistorische menselijke aanwezigheid anderzijds, het hoofdthema van dit onderzoek vormt. Centraal staat de reconstructie van het pre- en protohistorische landschap en de verschillende landschapsattributen met behulp van procesmodellen.

Dit onderzoek is deel van een interdisciplinair project getiteld 'Prehistorische bewoning en landgebruikssystemen in Zandig Vlaanderen (NW België): een diachrone en geoarcheologische aanpak'. Dit project is een samenwerking tussen de vakgroepen Archeologie, Bodembeheer, Geografie en Geologie en Bodemkunde van de Universiteit Gent. Aan de basis van dit project ligt een uitgebreide databank van archeologische vondstlocaties, verzameld tijdens verschillende decennia van intensief archeologisch veldwerk uitgevoerd door de vakgroep Archeologie (Universiteit Gent). De gekende Steentijd vondsten vertonen een opvallende spreiding met enerzijds gebieden met hoge densiteit en anderzijds, ondanks herhaaldelijk prospecteren, gebieden die slechts een beperkte hoeveelheid of geen archeologisch materiaal opleverden. Dezelfde trend blijkt eveneens van toepassing op de verspreiding van de Bronstijd grafheuvels. Hieruit volgt de vraag in hoeverre landschapsfactoren hebben bijgedragen tot deze onregelmatige spreiding. Op internationaal niveau, sluit dit project nauw aan bij de doelstellingen van het Europese Verdrag van Valetta, dewelke een aantal standaarden en principes uitschrijft ter bescherming van het archeologisch erfgoed. Binnen de richtlijnen van deze conventie wordt de laatste jaren meer en meer gebruik gemaakt van predictieve kaarten die het archeologisch potentieel van een locatie benoemen. In **Hoofdstuk 1** wordt dit breder kader meer belicht, alsook de specifieke onderzoeksvragen van deze studie en de doelstellingen.

Het project focust op de Vlaamse zandstreek, ook wel Zandig Vlaanderen genoemd. Deze term bakent per definitie een landbouwkundige eenheid in België af, gelegen in het Vlaams Gewest en gekarakteriseerd door zandige bodems. Binnen deze regio is een gebied geselecteerd ten noorden van de Schelde en ten zuiden van de polders nabij de Nederlandse grens, liggend tussen de gemeenten Evergem in het westen en Sint-Gillis-Waas in het oosten. De bestudeerde tijdsperiode van het interdisciplinaire project omvat zowel het Laat Glaciaal als het Holoceen. Om bepaalde redenen, zoals databeschikbaarheid voor de reconstructie van het vroegere reliëf en toenemende onzekerheid op de reconstructies in een sterk dynamische context, is in deze specifieke studie een tijdsperiode bestudeerd die begint in het laatste deel van de Jonge Dryas en het volledige Holoceen omvat. Het uitschuren en opvullen van de Vlaamse Vallei tijdens verschillende opeenvolgende ijstijden en tussenijstijden heeft sterk bijgedragen tot de vorming van het huidige reliëf. Tijdens het Laat Pleniglaciaal (de eindfase van het Pleniglaciaal, de koudste fase van de laatste ijstijd, het Weichseliaan) waren er periodes van zeer intense eolische activiteit. Dit leidde tot de vorming van een groot duinencomplex bestaande uit verschillende quasi parallelle dekzandruggen. Langsheen de zuidrand van de dekzandrug Maldegem-Stekene bevonden zich tijdens het Laat Glaciaal verscheidene meren, waaronder het paleomeer van de Moervaart depressie. Het Holoceen, de huidige tussenijstijd, wordt beschouwd als een meer stabiele periode. Wel traden er eventuele plaatselijke zandverstuivingen op ten gevolge van ontbossing en werd er in Vlaanderen tijdens de middeleeuwen, maar ook later, op grote schaal ontveend. De exacte locaties hiervan zijn echter niet altijd met zekerheid gekend. Volgens sommige auteurs lag de grens van het veengebied grotendeels ten noorden van het door ons bestudeerde studiegebied. Tijdens de studieperiode werd het gebied bezocht door Finaal Paleolithische en nadien Mesolithische jager-verzamelaar groepen, maar ook jongere archeologische vondsten behorend tot het Neolithicum, de Bronstijd en IJzertijd worden aangetroffen. Uiteraard zijn Romeinse, middeleeuwse en recentere archeologica eveneens vertegenwoordigd, deze vormen echter niet het onderwerp van dit onderzoek. Een meer uitgebreide beschrijving van het studiegebied, de evolutie van de verschillende geofactoren of landschapscomponenten, en de archeologie, worden beschreven in **Hoofdstuk 2**.

Om de bovengenoemde distributie in vondstlocaties beter te begrijpen werd in een eerste stap gekeken in hoeverre het huidige landschap deze verspreiding van archeologische sites kan verklaren. Dit gebeurde met behulp van een predictieve modellering. Hieruit bleek dat het verklaren van vroegere menselijke occupatie aan de hand van huidige landkarakteristieken zijn tekortkomingen heeft en dat er nood is aan gereconstrueerde landschapscomponenten. In eerste instantie werd bepaald welke landkarakteristieken menselijk landgebruik bepalen/aantrekken, opdat deze kunnen gereconstrueerd worden. Het uitvoeren van landbouw, of de bewoning van een plaats, wordt verondersteld gerelateerd te zijn aan verschillende bodemeigenschappen, de diepte van de grondwatertafel en dergelijke. Deze eigenschappen kunnen met behulp van verschillende procesmodellen gesimuleerd worden. Deze modellen maken gebruik van kennis van fysische en chemische processen (zoals bijvoorbeeld de Richards vergelijking voor het beschrijven van de beweging van water in de onverzadigde zone van de bodem). Om het scala aan vereiste parameters te leveren werden een grondwater- en een bodemvormingsmodel voorgesteld. Beide modellen hebben o.a. gereconstrueerde klimaatsdata en een temporeel digitaal hoogtemodel (DHM), op een rechtstreeks of onrechstreekse manier, als input nodig. De verschillende gesimuleerde karakteristieken kunnen finaal in een landevaluatie met elkaar vergeleken worden, met als doel het produceren van geschiktheidskaarten voor een welbepaald landgebruikstype. Dit volledige concept waarin een stelsel van verschillende procesmodellen wordt opgezet en de verschillende tussenstappen om dit te bereiken zijn neergeschreven in **Hoofdstuk 3**. Hierbij worden ook de concepten als extensie, korrel, bedekking, op-en neerschaling, aangehaald en nader toegelicht.

De opstelling en uitwerking van de freatische paleogrondwatermodellering wordt uiteengezet in **Hoofdstuk 4**. Verschillende parameters werden aan het model opgelegd als randvoorwaarden. Indien niet gekend, dienden deze eerst gereconstrueerd te worden. Op basis van hedendaagse klimaatsgegevens en tijdsseries van neerslag- en temperatuursanomalieën geleverd door Davis et al. (2003) en Davis (persoonlijke communicatie, 2008), werden tijdsreeksen van temperatuur, neerslag en evapotranspiratie opgesteld. Het vegetatieverloop doorheen de bestudeerde tijdsperiode, geldig voor het studiegebied, werd geconceptualiseerd en vertaald naar o.a. interceptie van de neerslag. Met behulp van deze informatie werd een tijdsreeks van de grondwatervoeding voor de hele studieperiode opgesteld. Hiervan werden 30-jarige gemiddelden genomen om de gemiddelde grondwaterstand te berekenen met een temporele resolutie van 30 jaar. Tengevolge van veranderingen in het reliëf en het rivierennetwerk, dienden ook deze gereconstrueerd te worden. Onderzoek uitgevoerd door Werbrouck et al. (2011) produceerde reeds twee DHMs bruikbaar voor de hedendaagse en de post-middeleeuwse periode. Tijdens de Belgische bodemkartering in de jaren 1950, werden o.a. diktes genoteerd van plaggenbodems en dieptes tot aan het pre-alluviale zand in de Scheldepolders. Op basis van deze waarden en kaarten waarop deze afzettingen – Quartairkaart en bodemkaart (verspreid door het Agentschap voor Geografische Informatie Vlaanderen of AGIV) – gesitueerd zijn, kon een temporeel DHM voor de (pre)historische periode gereconstrueerd worden. Nadien werd het freatische grondwatermodel gekalibreerd in twee stappen. De eerste stap betrof de periode 1924-1953 CE. De drainageklasse van de bodem (opgenomen tijdens de Belgische bodemkartering) werd hierbij gebruikt om een kaart van de gemiddelde grondwatertafel voor de 1924-1953 periode te reconstrueren. In een iteratief proces werden de waarden voor verschillende parameters aangepast om nadien het modelresultaat te vergelijken met de berekende kaart van de gemiddelde grondwatertafel op basis van de gemiddelde fout, gemiddelde absolute fout en de 'root mean square error' (RMSE: wortel van de gemiddelde gekwadrateerde fout). Na de kalibratie werden deze berekend voor een onafhankelijke dataset en gebruikt om de modelkwaliteit voor de 1924-1953 tijdstap te bepalen. Het model met de gekalibreerde modelparameters werd nadien uitgevoerd voor de volledige 12720 jaar in tijdstappen van 30 jaar. De resultaten werden getest met behulp van archeologische vondstlocaties en podzol locaties. Beiden werden beschouwd als 'proxies' van lokale drainagecondities in het verleden. Modeluitkomsten werden getoetst aan vooropgestelde criteria gerelateerd aan deze archeologische vondsten en podzol locaties. Een extra kalibratie van de hydrologische geleiding van de bovenste 0,20 m van de bodem, werd hierbij uitgevoerd. De modelkwaliteit voor de periode van de bodemkartering, uitgedrukt als gemiddelde fout en RMSE bedroegen 1,8 cm en 65,6 cm respectievelijk. Voor 96% van de validatie locaties betreffende de archeologische sites gaande van het Mesolthicum tot de Romeinse tijd, was aan de vooropgestelde criteria voldaan. Dit was eveneens zo voor 97% van de validatie locaties van goed gedraineerde podzolen.

Hoofdstuk 5 behandelt de reconstructie van de bodemkarakteristieken met behulp van het SoilGen model (Finke, 2012; Finke en Hutson, 2008). Hiermee werd op 96 puntlocaties de evolutie van verschillende bodemvariabelen geconstrueerd voor profielen tot 1,75 m diep. Op basis van lineaire interpolatie van de gereconstrueerde 30-jarige gemiddelde freatische grondwaterstanden werden tijdsreeksen van de jaarlijkse gemiddelde grondwatertafel op verschillende puntlocaties opgesteld. Andere randvoorwaarden zoals klimaatsgegevens, vegetatietypes en kenmerken van het moedermateriaal werden eveneens gereconstrueerd. De modelkwaliteit werd geoptimaliseerd door de oplosbaarheidsconstante van calciet aan te passen. Hierbij werd de tijdsperiode nodig om 1100 mm bodemprofiel te ontkalken bij een specifieke oplosbaarheidsconstante, vergeleken met literatuurwaarden (Egli en Fitze, 2001). Dit werd getest onder verschillende neerslagoverschotten die de mogelijke uiterste waarden in de bestudeerde tijdsperiode dekken. De resultaten van een aantal gesimuleerde variabelen werden vergeleken met historische metingen (Aardewerk databank; Van Orshoven et al., 1988, 1993). Nadien werden met behulp van regressie kriging, gebaseerd op de methode van Hengl et al. (2004), kaarten van verschillende bodemvariabelen voor een specifieke tijdsperiode en diepte aangemaakt. Textuurkaarten konden geproduceerd worden door de kaarten van zand-, silt- en kleigehalten te combineren en te classificeren op basis van de USDA (United States Department of Agriculture) textuurdriehoek.

De laatste stap in het eerder genoemde stelsel van procesmodellen, bestaat uit de uitvoering van een archeologische landevaluatie (**Hoofdstuk 6**). Landevaluatie is, vrij vertaald naar de FAO (1976), 'de procedure waarin de prestatie van het land onder een specifiek type landgebruik ingeschat wordt, gebruik makend van gebiedskarteringen en studies van geomorfologie, bodem, vegetatie, klimaat, en andere aspecten van het land, om zodoende veelbelovende soorten landgebruik te identificeren en verschillende alternatieve types van landgebruik onderling te evalueren naar hun geschiktheid voor de vooropgestelde doelstellingen van de evaluatie'. In een landevaluatie worden menselijke factoren enerzijds en het land met zijn verschillende attributen anderzijds met elkaar gecombineerd. In deze archeologische landevaluatie werden potentiële landgebruiktypes gedefinieerd voor verschillende periodes in het Neolithicum, de Bronstijd en de IJzertijd, op basis van literatuuronderzoek. Hiervoor werden landvereisten opgesteld en getoetst aan het toenmalige land op basis van geschiktheidklassen. De verschillende landkarakteristieken, nodig voor het bepalen van de specifieke landkwaliteiten in de evaluatie, werden geleverd door de geproduceerde kaarten van de gemiddelde diepte van de grondwatertafel, alsook van de gesimuleerde bodemvariabelen (pH, organisch koolstof, basenverzadiging, kleigehalte, kationenuitwisselingscapapciteit, bulkdensiteit en textuurklasse), uitgemiddeld over de bovenste 0,40 m van de bodem. De helling werd afgeleid van het temporele (pre)historische DHM. Uit de uitgevoerde landevaluatie bleek dat het studiegebied voor de geëvalueerde periodes (Neolithicum, Bronstijd, IJzertijd) grotendeels marginaal (68,6-78,3%) geschikt en niet geschikt (21,6-31,2%) was voor het verbouwen van verschillende granen (emmer, gerst, spelt) en peulvruchten (erwt, linze). Een zeer beperkt deel van het gebied (0,01-0,38%) bleek matig geschikt voor landbouw. De uitgevoerde beoordeling van de draagkracht van het gebied voor de Midden Bronstijd, toonde aan dat, onder de opgegeven voorwaarden, 5,6 ha vereist was om in de macronutrientenbehoefte (koolhydraten, eiwitten, vetten) van 1 persoon te voorzien. Bij een volledig gebruik van het gebied (50592 ha) voor gewasgroei (7%) en extensieve begrazing (93%), zou er in de voedselbehoefte van in totaal 9026 mensen kunnen worden voorzien. De productie van dierlijke eiwitten bleek de meest beperkende factor voor grotere populaties te zijn. Door de archeologische landevaluatie te baseren op gereconstrueerde paleo-landkarakteristieken wordt deze veel objectiever dan wanneer inschattingen gedaan worden vertrekkende vanuit de huidige kenmerken. De koppeling met het bodemvormingsmodel SoilGen bijvoorbeeld, laat toe scenario's te evalueren waarbij verschillende landbouwpraktijken (types bemesting, braak versus geen braak) getest worden.

Algemeen werd uit dit onderzoek geconcludeerd dat voorgestelde stelsel van geïntergreerde procesmodellen een haalbare en interessante methode vormt om het inzicht in vroegere landschappen en hun impact op menselijke bewoning, te verhogen en eventueel vooropgestelde hypothesen te evalueren. Een van de grootste voordelen aan het stelsel van procesmodellen is dat de methode volledig reproduceerbaar is. Het grootste nadeel aan het stelsel van procesmodellen, is de hoge datavereiste: verschillende randvoorwaarden, met zowel een temporele als spatiale variatie, dienen opgesteld te worden. Het is duidelijk dat deze brede range aan modelinput geleverd dient te worden door verschillende disciplines, waardoor interdisciplinaire communicatie en samenwerking steeds moet nagestreefd worden. Het stelsel van geïntegreerde procesmodellen is haalbaar en bruikbaar, hoewel er ook ruimte is voor verbetering. Deze aandachtspunten werden opgelijst in **Hoofdstukken 7 en 8**.

Summary

The use of integrated process models in a geoarchaeological context: a proof of concept

This research is situated in a geoarchaeological setting, in which the relationship between land on the one hand, characterized by its specific properties and qualities, and on the other hand, the pre- and protohistoric human presence, are the main theme of this research. The central point of the study is the reconstruction of the pre- and protohistoric landscape and the different landscape components/attributes, using process models.

The research is part of an interdisciplinary project entitled ‘Prehistoric occupation and land-use systems in Sandy Flanders (NW Belgium): a diachronic and geoarchaeological approach’. It is based on the collaboration of de departments of Archaeology, Soil Management, Geography and Geology and Soil Science at Ghent University. Several decennia of intensive archaeological investigations in the region, performed by the department of Archaeology (Ghent University) resulted in a extensive database of the archaeological find locations. The known Stone Age sites are distributed over areas with high site density on the one hand, while other areas, despite repeated prospection, only display a low amount of (or non) archaeological material. The same trend was found for the distribution of the Bronze Age barrows. Starting from this diachronic and spatial pattern, the question arises to what extent this distribution was influenced by the landscape and the several landscape components. Investigating this impact, requires the reconstruction of the then landscape and the different landscape components. Internationally, the project aims correspond with objectives set forth in the European Valetta Treaty, in which standards and principals for the protection of the archaeological heritage are subscribed. As a consequence of the ratification of this convention by several countries, predictive maps defining the predictive potential of a

location, become more and more in use. **Chapter 1** elaborates on the broader setting and on the objectives and research questions of the study.

The projects' study area is situated in the sand area of Flanders, also called Sandy Flanders. This defines an agricultural unit in Belgium, part of the Flemish Region and characterized by its sandy soils. Within this area, the study area was selected, lying to the north of the Scheldt river and to the south of the polder area near the Dutch border. In the east and west, the study area is situated between the municipalities of Evergem and Sint-Gillis-Waas, respectively. The study period of the interdisciplinary project encompasses the Late Glacial and the Holocene. However, because of restricted data availability to reconstruct past topographies, as well as the increasing uncertainty of the reconstructions for dynamical settings, the study period in this specific study was limited to the final part of the Younger Dryas and the entire Holocene. During glacial and interglacial periods, the Flemish Valley was eroded and subsequently filled in. During the Late Pleniglacial (the latest phase of the Pleniglacial, the coldest period of the Weichselian, the last ice age), intense aeolian activity occurred. This resulted in the formation of large dune complexes of several parallel cover sand ridges. Along their southern border, several lakes existed during the Late Glacial. The Holocene, the current interglacial, is seen as geomorphologically more stable. Anthropogenic influence has left his mark on the region. Deforestation had led to local sand drifting. Furthermore, during the Middle Ages, as well as in later periods, depeating occurred in the region. These exact locations are however not always known. According to some authors, the peat area only extended up till the northern border of the study area. In the area, archaeological artefacts from Final Palaeolithic and Mesolithic hunter-gatherer groups are found. Younger archaeological finds dating to the Neolithic, Bronze and Iron Age are also present. More recent archaeological remains, dating to Roman, medieval and more recent times are also present in the study area, but are not part of the investigated period. The study area, the evolution of several geofactors or landscape components, as well as an overview on the relevant archaeological periods, is given in **Chapter 2**.

In a first step, the predictive potential of the current landscape for archaeological site locations, was tested by the execution of a predictive Bayesian modelling. It was concluded that the use of present-day land attributes has its limitations when trying to explain past human occupation, thus indicating the need for reconstructed landscape components. Firstly, the landscape attributes that attract/define the human land use were identified. The performance of agricultural practices or the inhabitation of a site, are expected to be related to various soil characteristics, the depth of the groundwater tables, etc. Such variables can be simulated using different process models, which use the knowledge on physical and chemical processes (for example, the Richards equation to describe water flow in the unsaturated soil). A groundwater model and a soil formation model were proposed to provide all necessary parameters. Both models (directly or indirectly) need, amongst other things, reconstructed climate data and a temporal digital elevation model (DEM) as input. In the final step, the reconstructed and simulated values can be compared and classified in a land evaluation, in order to produce suitability maps for a specific type of land use for a given time period. The concept of the model framework and the different necessary inter-model steps are described in **Chapter 3**. In this chapter, terms as extent, grain, coverage, up- and downscaling are also explained.

The construction and execution of the phreatic palaeogroundwater modelling is explained in **Chapter 4**. Various parameters serve as boundary conditions of the model. When these are not known, they need to be reconstructed. Based on present-day climate data and time series of temperature and precipitation anomalies from Davis et al. (2003) and Davis (personal communication, 2008), time series of local temperature, precipitation and potential evapotranspiration were constructed. The evolution of the vegetation in the study period and study area, was conceptualized and implemented in the model as for example interception of the precipitation. The reconstructed time series of precipitation and evapotranspiration were used to calculate a time series of the recharge to the groundwater. The series was rescaled to 30-year averages, in order to simulate the mean water table in a static model state with a temporal resolution of 30 years. Relief and river network changes through time, resulted in the need for temporal reconstructions of these attributes. Two temporal DEMs were supplied by Werbrouck et al. (2011): a present-day and a post-medieval DEM. During the Belgian soil survey during the 1950s, thicknesses of plaggen soils and depths to pre-alluvial sandy sediments in the Scheldt polders were recorded. Based on these values and the mapped locations of the sediments – derived from the Quaternary map and the soil map (provided by the AGIV, the Flemish GIS Agency), a temporal DEM of the (pre)historic period was reconstructed. Subsequently, the phreatic palaeogroundwater model was calibrated in a two-step approach. The first step concerned the 1924-1953 CE period. A map of the mean water table for the 1924-1953 CE period was derived from the mapped soil drainage classes (as recorded during the national soil survey campaign) and served as observation map. In an iterative process, the various model parameters were adjusted and the model result was compared with the calculated map of the mean water table by calculation and evaluation of the mean error (ME), mean absolute error (MAE) and root mean square error (RMSE). After calibration, the ME, MAE and RMSE were calculated for an independent dataset, to test the model quality for the 1924-1953 CE time step. Afterwards, the model with the calibrated model parameters, was executed for the entire 12,720-year long time period, with a temporal resolution of 30 years. Archaeological find spots and recorded podzol locations were used as proxies of local drainage conditions in the past. Model results were evaluated according to predefined criteria related to the location of these archaeological and podzol sites. A calibration of the hydrological conductance of the upper 0.20 m of the soil was performed. Model quality was expressed as mean error (ME) and root mean square error (RMSE): 1.8 cm and 65.6 cm, respectively, at the time of soil mapping. At total of 96% of the archaeological site locations collected in an independent validation dataset of archaeological find spots dating from the Mesolithic to the Roman Age, the predefined criteria was met. This was also the case at a total of 97% of the validation locations concerning the well drained podzols.

Chapter 5 considered the reconstruction of the soil formation, using the SoilGen model (Finke, 2012; Finke and Hutson, 2008). Soil formation was modelled at 96 point locations in the study area, for soil profiles of 1.75 m depth. A local time series of annual values of the MWT depth served as boundary conditions for each point simulation. The time series was calculated based on linear interpolation of the reconstructed MWT depths on a 30-year temporal resolution. Boundary conditions, such as climate series, vegetation type and composition of the parent material were also reconstructed. Model quality was optimized by adjusting the solubility constant of calcite. The necessary time to decalcify 1100 mm of soil at a specific solubility constant was compared with literature values and was furthermore tested for different precipitation surpluses, representative for the study period. Several simulated soil variables were compared with measurements at the exact locations from historical sources (the Aardewerk database; Van Orshoven et al., 1988, 1993). A regression kriging, based on the work of Hengl et al. (2004), was used to produce full-cover maps of several soil variables and for specific time periods and depths. Based on the maps of sand, silt and clay contents, texture maps were produced based on the USDA (United States Department of Agriculture) texture triangle.

The final component of the model framework, was formed by an archaeological land evaluation (**Chapter 6**). Land evaluation, according FAO (1976) is 'the process of assessment of land performance when used for specified purposes involving the execution and interpretation of surveys and studies of landforms, soils, vegetation, climate and other aspects of land in order to identify and make a comparison of promising kinds of land use in terms applicable to the objectives of the evaluation'. In this evaluation, human factors on the one hand, and the land on the other hand, with its various attributes, are combined. In this archaeological land evaluation, potential land utilization types were defined for several periods in the Neolithic, Bronze Age and Iron Age, based on literature information. Land requirements and suitability classes were defined, examined and evaluated considering the then land and land characteristics. The necessary land characteristics were provided by the produced maps of the simulated MWT depths and soil variables (pH, OC, base saturation, clay percentage, CEC, bulk density, texture class), calculated for the upper 0.40 m of the soil. The slope percentage was derived from the temporal (pre)historic DEM. Based on the performed land evaluation, it was concluded that the largest part of the study area was marginally suitable (68.6-78.3%) and not suitable (21.6-31.2%) for crop cultivation (emmer, spelt, barley, pea, lentil), for the evaluated periods (Neolithic, Bronze Age, Iron Age). Only a very limited part of the study area (0.01-0.38%) was classified as moderately suitable. Based on the performed carrying capacity assessment for the Middle Bronze Age, it was suggested that 5.6 ha per person was necessary to provide in the human dietary requirements (carbohydrates, proteins, fat). A total of 9,026 persons could have been supported, when the entire area (50,592 ha) was in use for crop growth (7%) and extensive grazing (93%).The production of animal proteins appeared to be the most limiting factor on the support of larger populations. The application of reconstructed land characteristics in the land evaluation, results in a more objective methodology than when the evaluation is based on land characteristics directly derived from their current status. The use of for example the SoilGen model, enables the evaluation of different scenarios of land management (different types of manuring, fallow versus no fallow).

In general, the proposed model framework of integrated process models was concluded to be a feasible and useful methodology to increase our understanding of previous landscapes and their impact on human occupation and may help in the evaluation of different hypotheses. One of the greatest advantages of the framework is that the methodology is fully reproducible. The largest drawback is the high data requirement: boundary conditions, often having a temporal and spatial variation, need to be reconstructed. It is clear that this broad range of input must be provided by several disciplines, and that interdisciplinary communication and collaboration is required. The framework of integrated process models was concluded to be feasible and useful. A list of possible improvements is suggested in **Chapters 7 and 8**.

References

Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., data-contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews 22, 1701-1716.

Egli, M., Fitze, P., 2001. Quantitative aspects of carbonate leaching of soils with differing ages and climates. Catena 46, 35-62.

FAO, 1976. A framework for land evaluation, FAO, Food and Agriculture Organization of the United Nations, Rome.

Finke, P.A., 2012. Modeling the genesis of Luvisols as a function of topographic position in loess parent material. Quaternary International 265, 3-17.

Finke, P.A., Hutson, J.L., 2008. Modelling soil genesis in calcareous loess. Geoderma 145, 462-479.

Hengl, T., Heuvelink, G.B.M., Stein, A., 2004. A generic framework for spatial prediction of soil variables based on regression-kriging. Geoderma 120, 75-93.

Van Orshoven, J., Deckers, J.A., Vandenbroucke, D., Feyen, J., 1993. The completed database of Belgian soil profile data and its applicability in planning and management of rural land. Bulletin des Recherches Agronomiques de Gembloux 28, 197-222.

Van Orshoven, J., Maes, J., Vereecken, H., Feyen, J., Dudal, R., 1988. A structured database of Belgian soil profile data. Pedologie 38(2), 191-206.

Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Zwertvaegher, A., 2011. Digital elevation model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.

Overzicht van de bijdragen

Overzicht van de bijdragen van Ann Zwertvaegher in hoofdstukken van haar doctoraatsthesis "The use of integrated process models in a geoarchaeological context: a proof of concept"

Chapter 1: General Introduction
Geheel door AZ geschreven (correcties door P.A. Finke)

Chapter 2: The study area
Geheel door AZ geschreven (correcties door P.A. Finke)

Chapter 3: Conceptual model framework
Dit hoofdstuk is een bewerking door AZ van het gepubliceerde artikel *Zwertvaegher, A., Werbrouck, I., Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, P., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the use of integrated process models to reconstruct prehistoric occupation, with examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal 25, 784-814.*
Dit artikel betreft de formulering van een theoretische aanpak om met modelinstrumenten een landschapsreconstructie voor diverse (pre-)historische perioden uit te voeren, waarbij enkele voorbeelden worden gegeven en de resultaten van een uitgebreide case-study van predictieve modellering wordt beschreven. De formulering van de theoretische aanpak is van de hand van P.A. Finke en AZ; de case-study is uitgevoerd door AZ met assistentie van P.A. Finke en I. Werbrouck en de overige auteurs hebben gegevens toegeleverd en conceptteksten geëvalueerd.

Chapter 4: Reconstructing phreatic palaeogroundwater levels
Dit hoofdstuk is een bewerking door AZ van een artikel in review (14-11-2012) *Zwertvaegher, A., Finke, P.A., De Reu, J., Vandenbohede, A., Lebbe, L., Bats, M., De Clercq, W., De Smedt, P., Gelorini, V., Sergant, J., Antrop, M., Bourgeois, J., De Maeyer, P., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Reconstructing phreatic palaeogroundwater levels in a*

geoarchaeological context: a case study in Flanders (Belgium). Geoarchaeology: An International Journal.
Dit artikel is geheel geschreven door AZ en gecorrigeerd door P.A. Finke. AZ heeft ook de modelstudie uitgevoerd. Gegevens en model zijn aangeleverd door L. Lebbe en A. Vandenbohede. De overige auteurs hebben gegevens toegeleverd en/of conceptteksten geëvalueerd.

Chapter 5: Spatio-temporal modelling of soil characteristics for soilscape reconstruction
Dit hoofdstuk is een bewerking door AZ van een artikel in review (14-11-2012) *Zwertvaegher, A., Finke, P.A., De Smedt, P., Gelorini, V., Van Meirvenne, M., Bats, M., De Reu, J., Antrop, M., Bourgeois, J., De Maeyer, P., Verniers, J., Crombé, P., in review. Spatio-temporal modelling for soilscape reconstruction. Geoderma.*
Dit artikel is geheel geschreven door AZ en gecorrigeerd door P.A. Finke. AZ heeft ook de modelstudie uitgevoerd. Gegevens en model zijn aangeleverd door P.A. Finke. De overige auteurs hebben conceptteksten geëvalueerd.

Chapter 6: Land evaluation
Geheel door AZ uitgevoerd en geschreven (correcties door P.A. Finke).

Chapter 7: General discussion
Geheel door AZ geschreven (correcties door P.A. Finke).

Chapter 8: General conclusions
Geheel door AZ geschreven (correcties door P.A. Finke).

Prof. Dr. P.A. Finke
Promotor

Publication List

Bats, M., De Reu, J., De Smedt, P., Antrop, M., Bourgeois, J., Court-Picon, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Werbrouck, I., **Zwertvaegher, A.**, Crombé, P., 2009. Geoarchaeological research of the large palaeolake of the Moervaart (municipalities of Wachtebeke and Moerbeke-Waas, East Flanders, Belgium). From Late Glacial to Early Holocene. Notae Praehistoricae 29, 105-112.

Bats, M., De Smedt, P., De Reu, J., Gelorini, V., **Zwertvaegher, A.**, Antrop, M., Bourgeois, J., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2011. Continued geoarchaeological research at the Moervaart palaeolake area (East Flanders, B): field campaign 2011. Notae Praehistoricae 31, 201-211.

Bats, M., De Smedt, P., Werbrouck, I., **Zwertvaegher, A.**, Court-Picon, M., De Reu, J., Serbruyns, L., Demiddele, H., Antrop, M., Bourgeois, J., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2010. Continued geoarchaeological research at the Moervaart palaeolake area (East Flanders, Belgium): preliminary results. Notae Praehistoricae 30, 15-21.

Crombé, P., Van Strydonck, M., Boudin, M., Van Den Brande, T., Derese, C., Vandenberghe, D., Van Den Haute, P., Court-Picon, M., Verniers, J., Gelorini, V., Bos, J., Verbruggen, F., Antrop, M., Bats, M., Bourgeois, J., De Reu, J., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., **Zwertvaegher, A.**, 2012. Absolute dating (14C and OSL) of the formation of coversand ridges occupied by prehistoric hunter-gatherers in NW Belgium. Radiocarbon.

Derese, C., Vandenberghe, D.A.G., **Zwertvaegher, A.**, Court-Picon, M., Crombé, P., Verniers, J., Van Den Haute, P., 2010. The timing of aeolian events near archaeological settlements around Heidebos (Moervaart area, N Belgium). Netherlands Journal of Geosciences - Geologie en Mijnbouw 89, 173-186

De Reu, J., Bats, M., Bourgeois, J., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Werbrouck, I., **Zwertvaegher, A.**, Crombé, P., 2010. Digitizing, inventorying, reviewing and analyzing the 'Bronze Age barrows database' of East and West Flanders (Belgium). Lunula: Archaeologica protohistorica 18, 43-47.

De Reu, J., Bats, M., Crombé, P., Antrop, M., Court-Picon, M., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Werbrouck, I., **Zwertvaegher, A.**, Bourgeois, J., 2011. Een GIS benadering van de bronstijdgrafheuvel in Zandig-Vlaanderen: enkele voorlopige resultaten (België). Lunula: Archaeologia protohistorica 19, 3-8.

De Reu, J., Bats, M., De Smedt, P., Bourgeois, J., Antrop, M., Court-Picon, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Werbrouck, I., **Zwertvaegher, A.**, Crombé, P., 2010. Bronze and Iron Age landscapes in Sandy Flanders (NWBelgium): a geoarchaeological approach. Lunula: Archaeologica protohistorica 18, 17-22.

De Reu, J., Bourgeois, J., Bats, M., De Smedt, P., Gelorini, V., **Zwertvaegher, A.**, Antrop, M., De Maeyer, P.,Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Beyond the unknown. Understanding prehistoric patterns in the urbanised landscape of Flanders. Journal of Historical Geography.

De Reu, J., Bourgeois, J., De Smedt, P., **Zwertvaegher, A.**, Antrop, M., Bats, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., 2011. Measuring the relative topographic position of archaeological sites in the landscape, a case study on the Bronze Age barrows in northwest Belgium. Journal of Archaeological Science 38 (12),3435-3446.

De Reu, J., Bourgeois, J., De Smedt, P., **Zwertvaegher, A.**, Antrop, M., Bats, M., De Maeyer, P., Finke, P.A., Gelorini, V., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Mind heterogeneous landscapes, a review of the "Topographic Position Index". Geomorphology.

De Reu, J., Bourgeois, J., Gelorini, V., De Smedt, P., Zwertvaegher, A., Antrop, M., Bats, M., De Maeyer, P., Finke, P.A., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Towards Bronze Age burial landscapes: a comprehensive study of the Bronze Age barrow phenomenon in the sandy lowlands of northwestern Belgium. Journal of Anthropological Archaeology.

De Reu, J., Deweirdt, E., Crombé, P., Bats, M., Antrop, M., De Maeyer, P., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., **Zwertvaegher, A.**, Bourgeois, J., 2011. Les tombelles de l'âge du bronze en Flandre sablonneuse (nord-ouest de la Belgique): un status quaestionis. Archaeologisches Korrespondenzblatt 41, 491-505.

De Smedt, P., Van Meirvenne, M., Davies, N., Bats, M., Meerschman, E., Saey, T., De Reu, J., Gelorini, V., **Zwertvaegher, A.**, Antrop, M., Bourgeois' J., De Maeyer, P., Finke, P.A., Verniers, J., Crombé, P., 2013. A multidisciplinary approach to reconstructing Late Glacial and Early Holocene landscapes. Journal of Archaeological Science 40, 1260-1267.

De Smedt, P., Van Meirvenne, M., Meerschman, E., Saey, T., Bats, M., Court-Picon, M., De Reu, J., **Zwertvaegher, A.**, Antrop, M., Bourgeois, J., De Maeyer, P., Finke, P.A., Verniers, J., Crombé, P., 2011. Reconstructing palaeochannel morphology with a mobile multicoil electromagnetic induction sensor. Geomporphology 130, 136-141.

Frankl, A., **Zwertvaegher, A.**, Poesen, J., Nyssen, J., 2012. Transferring Google Earth observations to ArcGIS: an example for the study of gully erosion. International Journal of Digital Earth. Online early view. DOI: 10.1080/17538947.2012.744777 (5y IF 1.427)

Vandecasteele, B., Willekens, K., **Zwertvaegher, A.**, De Grande, L., Du Laing, G., Tack, F.M.G., in review. The use of wood chips from a short rotation coppice and ground bark: effect of composting on the Cd, Zn and Mn content and fractionation. Science of the Total Environment.

Werbrouck, I., Antrop, M., Van Eetvelde, V., Stal, C., De Maeyer, P., Bats, M., Bourgeois, J., Court-Picon, M., Crombé, P., De Reu, J., De Smedt, P., Finke, P.A., Van Meirvenne, M., Verniers, J., **Zwertvaegher, A.**, 2011. Digital Elevation Model generation for historical landscape analysis based on LiDAR data, a case study in Flanders (Belgium). Expert Systems with Applications 38, 8178-8185.

Zwertvaegher, A., Finke, P.A., 2010. On the use of integrated process-models to reconstruct prehistoric occupation with examples from Sandy Flanders. Poster presented at the Landscape Archaeology conference 2010, Amsterdam (The Netherlands), January 26-29, Book of Abstracts, 102.

Zwertvaegher, A., Finke, P.A., De Reu, J., Vandenbohede, A., Lebbe, L., Bats, M., De Clercq, W., De Smedt, P., Gelorini, V., Sergant, J., Antrop, M., Bourgeois, J., De Maeyer, P., Van Meirvenne, M., Verniers, J., Crombé, P., in review. Reconstructing phreatic palaeogroundwater levels in a geoarchaeological context, a case study in Flanders (Belgium). Geoarchaeology: An International Journal.

Zwertvaegher, A., Finke, P.A., De Smedt, P., Gelorini, V., Van Meirvenne, M., Bats, M., De Reu, J., Antrop, M., Bourgeois, J., De Maeyer, P., Verniers, J., Crombé, P., in review. Spatio-temporal modelling for soilscape reconstruction. Geoderma.

Zwertvaegher, A., Finke, P.A., Lebbe, L., 2009. A methodology for the reconstruction of palaeogroundwater regimes in Sandy Flanders throughout the Holocene and the Late Glacial. Poster presented at Geoarchaeology conference 2009: From landscape to laboratory and back again, Sheffield (UK), April 15-17, Book of Abstracts, 148.

Zwertvaegher, A., Werbrouck, I., Finke, P.A., De Reu, J., Crombé, P., Bats, M., Antrop, M., Bourgeois, J., Court-Picon, M., De Maeyer, P., De Smedt, P., Sergant, J., Van Meirvenne, M., Verniers, J., 2010. On the use of integrated process models to reconstruct prehistoric occupation, with examples from Sandy Flanders, Belgium. Geoarchaeology: An International Journal 25, 784-814.