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Terrain and ecosystem modelling for the Forsmark area

Comparison of the regolith-lake development model and the Untamo model

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Abstract

The representation of the biosphere in radionuclide transport models is a key factor in radionuclide dose calculations. Landscape evolution models have been used to predict changes in the regolith distribution, shoreline, watercourses and lakes over the time-span examined in the safety analyses. For SR-Site and SR-PSU, the Regolith Lake Development Model (RLDM) was used to these ends. Following both internal and external critique of the landscape predictions used in both safety analyses, a different landscape development model called Untamo was adopted in order to help address the deficiencies of the RLDM. This study examines the similarities and differences of Untamo and the RLDM by comparing their respective modelling mechanics and model outputs for Forsmark. While discrepancies in modelling conditions prevented any quantification of how dissimilarities in modelling mechanics affected results, some effects were still discernable in the outputs.

Sammanfattning

Framställning av biosfären i transportmodellerna är en nyckelfaktor i beräkning av dos från radionuklider. Landskapsutvecklingsmodeller har använts i prediktion av fördelning av regoliten, förskjutning av strandlinjen, vattendrag och sjöar över tiden som undersöks i säkerhetsanalyserna. I både SR-Site och SR-PSU har ”Regolith Lake Development Model” (RLDM) använts för att beskriva dessa förändringar. Efter både intern och extern kritik av hur modellen har predikterat förändringar i landskapet i båda säkerhetsanalyserna har en annan landskapsutvecklingsmodell, Untamo, börjat användas för att åtgärda bristerna i RLDM. Denna studie undersöker likheter och skillnader mellan Untamo och RLDM genom att jämföra deras respektive modelleringsmekanismer och modellresultat för Forsmarksområdet. Avvikelser i modelleringsförhållanden förhindrade kvantifiering av hur skillnader i modelleringsmekanismer påverkade resultaten. Trots detta kunde viss skillnader utskiljas i resultaten.

Contents

1 Introduction

1.1 Background

The final repository for short-lived low- and intermediate-level radioactive waste, SFR, is in Forsmark in the Östhammar municipality (Figure 1-1), in the immediate vicinity of the Forsmark nuclear power plant. The SFR repository is situated in rock at ~60 m depth beneath the sea floor and is built to receive and after closure serve as a passive repository for low- and intermediate-level short-lived radioactive waste. The radioactive waste stored in SFR includes operational waste from Swedish nuclear power plants and from the interim storage facility for spent nuclear fuel, Clab, as well as radioactive waste from other industries, research institutions and medical care.

In order to be able to also store decommissioning waste from the Swedish nuclear power plants in SFR, an extension of the repository is planned.

As a part of the license application for the extension of SFR, the Swedish Nuclear Fuel and Waste Management Company (SKB) has performed the SR-PSU project (SKB 2015). The objective of SR-PSU was to assess the long-term radiological safety of the entire future SFR repository.

SR-PSU was based on knowledge gathered from site data, site modelling and the previous safety assessments, together with modelling performed and data collected during the SR-PSU project.

The biosphere is a key part of the system considered in a safety assessment of a nuclear waste repository because this is where the consequences of potential future radionuclide releases from the repository arise. Hence, near-surface radionuclide transport and dose calculations are performed within the framework of the biosphere assessment.

The SR-PSU Biosphere (SKB 2014a) was a sub-project of SR-PSU. SR-PSU Biosphere mainly described the information needed to calculate effects on humans and the environment in the case of a radionuclide release from SFR. The calculated effects were then used to show compliance with regulations related to future repository performance for time spans up to 100 000 years after closure. Because of the uncertainties associated with the prediction of future development of the site in this time frame, several calculation cases were analysed to describe a range of possible site developments.

Regolith is a term used to describe all of the unconsolidated deposits overlying the bedrock, regardless of their origin. The regolith at the Forsmark site has been characterised using both a map of regolith distribution (Hedenström and Sohlenius 2008) and different versions of the regolith depth model (RDM) that shows the stratigraphy and thickness of different deposits (Hedenström et al. 2008, Sohlenius et al. 2013). However, the map of regolith and the RDM for the Forsmark area consider only the present conditions and do not take the temporal change of the regolith into account. For this reason, a regolith-lake development model (RLDM) for the Forsmark area was constructed that described the surface geology, soil stratigraphy and thickness and succession of lakes during a glacial cycle (Brydsten and Strömgren 2010).

The RLDM was used in the safety assessment of the deep repository for spent nuclear fuel, SR-Site (SKB 2011). For the SR-PSU assessment, the RLDM was updated (Brydsten and Strömgren 2013) by using new data and by improving the description of some of the landscape development processes used in the model. The RLDM has been applied to three different climate cases to represent climate conditions during global warming, the early periglacial, and the Weichselian glacial cycle. These three climate cases are defined and described in Chapter 4 of the SR-PSU Climate report (SKB 2014b).

Simulation results from the RLDM provided key information for hydrogeological modelling (Werner et al. 2013), for modelling of the bedrock hydrogeology (Odén et al. 2014), for modelling radionuclide transport and release to the biosphere (Saetre et al. 2013). Moreover, RLDM simulation results in combination with site data also allowed the development of the landscape development model LDM (SKB 2014a), which is a model at landscape level that describes different variants of possible long-term landscape development at Forsmark. These variants cover different assumptions of land use and climate conditions. Since RLDM and LDM are closely linked with each other, results of both models

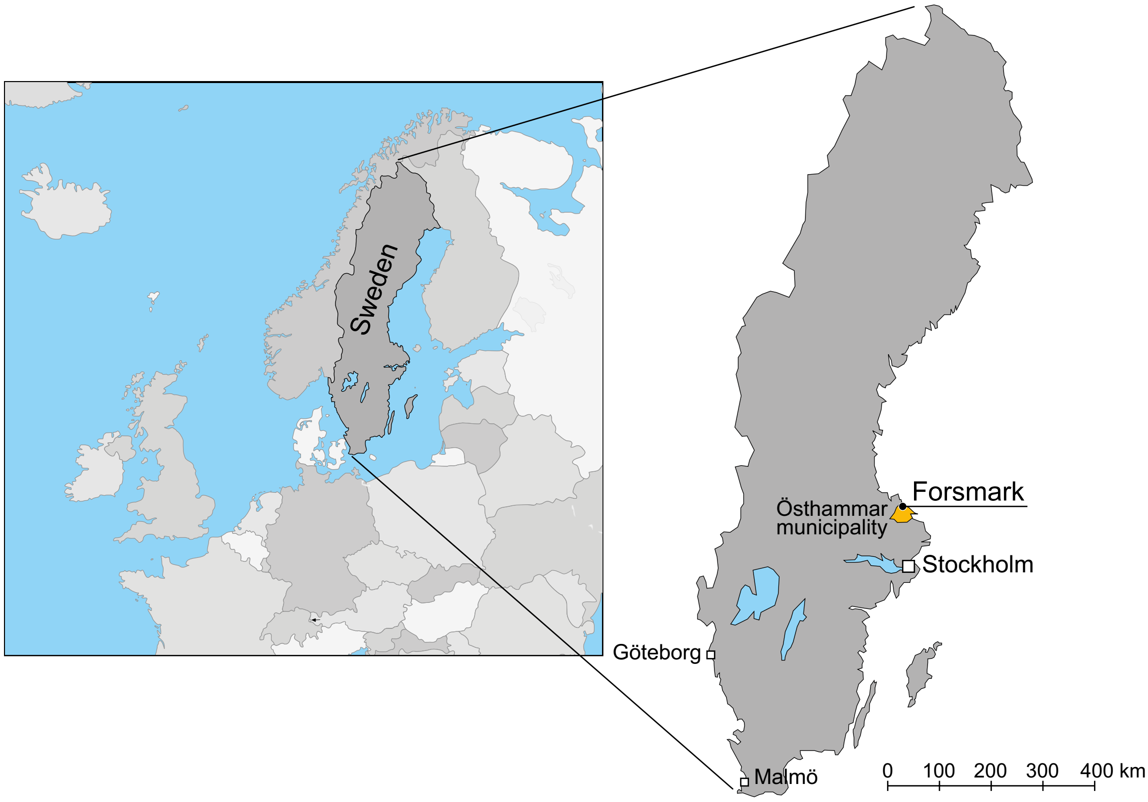

Figure 1-1. Location of the Forsmark site in Sweden (right) and in context with the countries in Europe (left). The site is situated in the Östhammar municipality, which belongs to the County of Uppsala.

were used for this study: RLDM-based data on regolith thickness and terrain elevation as well as landscape objects of the LDM such as streams, lakes, wetlands, croplands and the sea.

The simulations of the regolith development and the long-term landscape and ecosystem development provided by RLDM and LDM play a pivotal role for safety assessment but are difficult to validate using observed data. Therefore, the RLDM and LDM were compared to the Untamo model, which is an alternative development model. The Untamo model has been developed by Arbonaut Ltd. for Posiva Oy (http://www.posiva.fi/) to model the terrain and ecosystem development as part of the Safety Case for the Disposal of Spent Nuclear Fuel at the Olkiluoto site in Finland.

Untamo consists of several modules that integrate the processes of land uplift, surface water runoff, sediment dynamics in rivers, lakes, sheltered bays and the open sea, mire formation, peat accumulation, and associated land-use. In contrast to the RLDM/LDM, the landscape-forming processes in Untamo are interlaced with each other, and a sequence of processes is simulated for each considered time step, building upon the results of the previous time step.

1.2 Model area

The model area for the RLDM (Figure 1-2) used in this study, extends over almost 300 km^2 and includes marine areas, terrestrial areas and lakes. The model area is identical to the area that Sohlenius et al. (2013) selected for producing the RDM and it is based on the spatial distribution of available data and on the location of present and future watershed divides.

The local relief within the model area is below 20 m height (RH2000). There are several recently isolated lakes and wetlands in the area. New lakes and wetlands are continuously being formed as a result of the ongoing shoreline displacement acting on the flat topography.

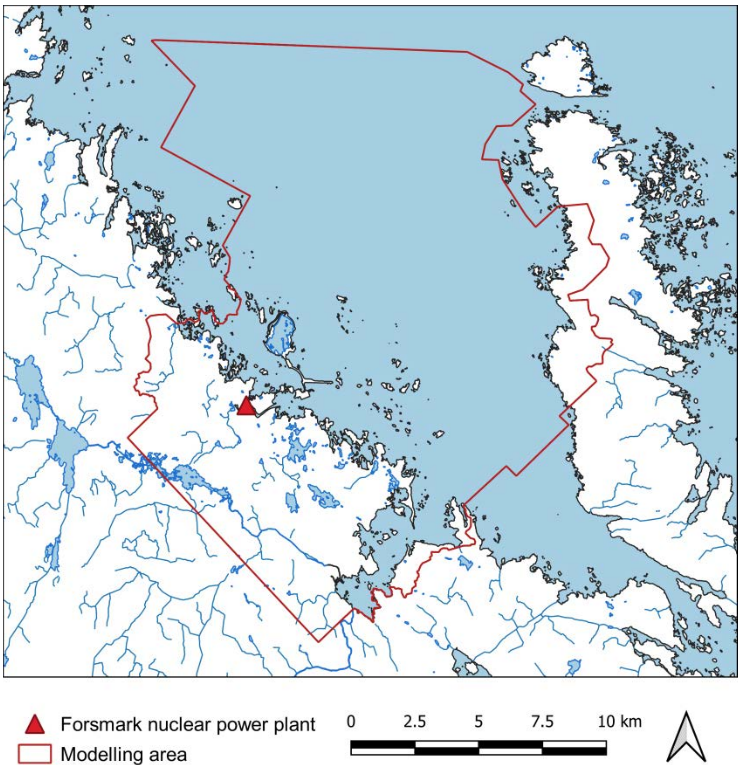

Figure 1-2. *Boundary of the model area in Forsmark for which simulation results were calculated in this project.*

The coastline consists of sheltered, shallow bays and small islands. The coast is exposed to 600 km of open sea towards the northeast, which creates fast water turnover and a long fetch for wave action (Brydsten 2009). Thus, the seabed in the coastal areas is dominated by erosion and transport bottoms with heterogeneous sediments, consisting mainly of sand and gravel with varying fractions of glacial clay. Most parts of the landscape are covered by a thin regolith layer dominated by till (Hedenström and Sohlenius 2008). The average regolith depth (i.e. depth to bedrock) in the terrestrial area is 3.8 m, and the corresponding value for the marine area is 5.7 m (Petrone et al. 2020). The regolith thickness on the sea floor above the SFR repository ranges from 1 to 4 m.

1.3 Objectives and contents of the report

This study identifies the differences in methodology and results between the RLDM and Untamo model. The processes and assumptions that are applied in Untamo are described in this report. The RLDM has been earlier described in various reports and will not be described in depth in this report. Main input data and parameters are presented and compared between the RLDM and Untamo.

Results have been calculated for both models by using similar input data and parameters. In particular, the development of selected biosphere objects in the Forsmark model area was studied with emphasis on the infilling of lakes with sediment. An additional comparison was made at the landscape level to identify the main differences regarding the spatial structure of the simulated future landscape.

2 Conceptual and mathematical models used by RLDM and Untamo

The following sections provide an overview of how land uplift, streamflow, terrestrialization of lakes, peat growth and land use are modelled in RLDM and Untamo. For the RLDM, the applied methodologies are summarized and a reference for further reading is given. For Untamo more detailed descriptions are provided if the modelling approach differs from RLDM.

2.1 Conceptual model of regolith

The RLDM considers following regolith types above bedrock: organic sediment (peat), lacustrine postglacial deposits, marine postglacial deposits, glacial clay, artificial fill, glacio-fluvial material, and till. However, the latter three regolith types are treated statically in the model. The bedrock surface is also part of the RLDM. More detailed information about the regolith depth model (RDM) for Forsmark is available from Petrone et al. (2020).

Untamo distinguishes between the regolith types presented in the table below. Glacio-fluvial sediments are not considered separately and have been treated as glacial clay in this study.

Table 2-1. Regolith types used in Untamo for this modelling work, from top to bottom.

Regolith type	Accumulation environment
Peat	Mires
Compacted peat	Drained mires
Gyttja	Lakes
Clay gyttja	Sea
Glacial clay	no accumulation
Till	no accumulation

2.2 Shoreline displacement

The shoreline displacement curve applied in the comparison analysis follows the global warming climate case of the SR-PSU which is described in the SR-PSU Climate Report (SKB 2014b). In this climate case, the contributions to sea-level rise in the Forsmark region from various processes are added. The shoreline displacement values are published in Brydsten and Strömgren (2013, Appendix 1).

Untamo has a separate land-uplift module which implements the equations developed by Påsse (2001). The results of this model were adjusted to fit with the shoreline displacement of the global warming climate case.

2.3 Streamflow

When modelling surface runoff, the task is to establish a hydrologically continuous flow field over the terrain surface. The terrain surface is represented by a digital elevation model (DEM), i.e. a geo-referenced raster map where each cell value shows the elevation of the terrain surface. Both models, Untamo and SKB's Regolith-Lake Development Model (RLDM), make use of the D-8 flow algorithm for overland flow routing using the method developed by Jenson and Domingue (1988). The surface water flow at each raster cell is set to take the route towards the lowest-lying neighbouring cell, i.e. in one of the eight possible directions giving the algorithm its name. To maintain continuity in the computed flow, the standard approach is to remove (fill) all sinks in the DEM prior to the flow calculation, for example using the method presented by Planchon and Darboux (2001). The flow routing algorithm must then be complemented by another approach in the filled areas, as they have zero gradient. In Untamo, flat areas in the DEM may also be introduced by some of the landscape evolution sub-models such as the lake in-filling module (see Section 2.5). It should be noted that, in most cases, the filled depressions are in reality either wetlands or lakes and we may not be interested in the flow direction as such. It is however important for the flow field to be continuous so that accumulated flow and contributing areas can be correctly calculated.

To route water flow over depressions, most common approaches include the shortest path to the outlet point or a "minimum cut" approach. The former is implemented in the ArcGIS hydrology toolbox and is also used in RLDM. Untamo implements the minimum cut approach and the aim is to allow the gradient to drive the flow as long as possible. However, we inevitably reach a point where water would have to flow upward, or we need to cut through the DEM to reach the outlet. To implement this, the gradient-driven flow is calculated using the original DEM (before depressions are filled). Flat areas are still identified using the depression-free DEM so that the pour point (outlet) can be located for each. Then, for all cells not resolved by the D-8 algorithm, the shortest-path route to the corresponding outlet is found by cost minimization. The advantage of this approach is that it greatly eliminates long, straight-flowing stream channels and produces more naturally looking flow. The principle of the two approaches is shown in Figure 2-1. Figure 2-2 shows the result of the flow routing and water accumulation calculated by Untamo for a flat area in comparison to the standard implementation of the D-8 algorithm as is used in RLDM.

In both models, RLDM and Untamo, the runoff is calculated from the flow direction field and precipitation data using the D-8 algorithm. Streams and rivers are identified from raster cells with sufficiently high accumulated flow. In addition to the catchment areas within the model area, Untamo can handle specified flow boundary-conditions as input discharge values for locations where an external catchment area discharges into the model area.

In this work, the runoff (see Section 2.3) was estimated with a simplified approach using the effective precipitation which is the portion of the rainfall that reaches stream channels. Precipitation data over a period of 13 years (2004–2016) from Örskär measurement station was used to derive the mean annual precipitation amount. The effective rainfall was calculated for the Olandsån watershed as the ratio between the mean annual discharge at Olandsån's river mouth and the mean annual precipitation received by the watershed.

In RLDM, only streams that are assumed to have flow all year around are included. This corresponds to at least a modelled mean discharge of 0.02 m^3/s. In Untamo a user-specified threshold is applied during the simulation which was set to 0.001 m^3/s for this study. While the GIS result data of Untamo contain all the streams considered in the simulation, the Untamo map-creation tool provides an additional option for selecting streams to be included in map presentations derived from the simulation results. This tool applies a user-specified minimum stream width for selecting the streams considered relevant to be shown on a map.

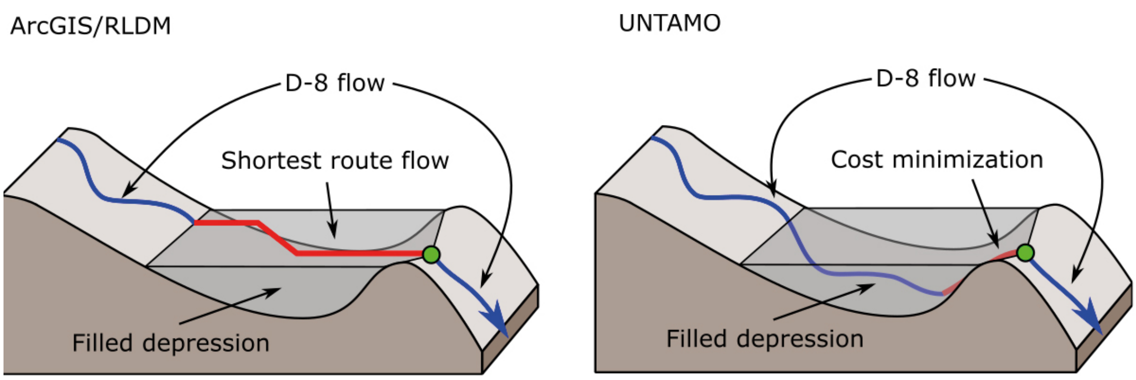

Figure 2-1. *Principle of the overland flow routing algorithms implemented in RLDM (left) and Untamo (right). Gradient-driven flow is shown with a blue line, flow that cannot be resolved by the D-8 method is shown in red. The distance metric for the shortest route is also based on the D-8 algorithm and the stream consists of straight linear segments. The outlet of the depression is indicated by the green dot.*

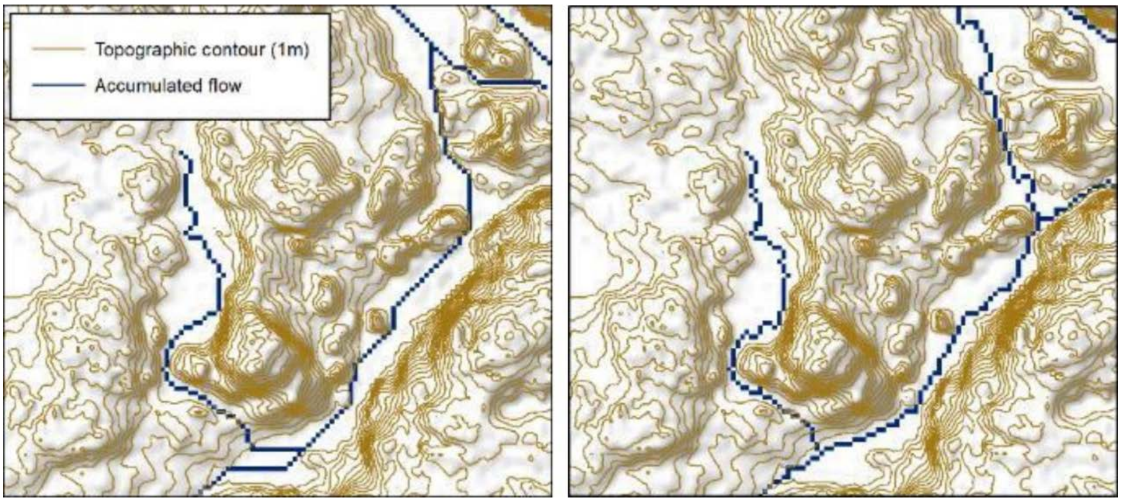

***Figure 2-2.** Comparison of standard flow routing (as applied in the RLDM) and Untamo flow routing over a low slope area. Left: Accumulated flow using Flow Direction and Flow Accumulation tools from ArcGIS. Right: Accumulated flow using Untamo.*

A crucial difference between the two models is that SKB's RLDM derives flow directions only once at the simulation start, based on DEM representing the initial condition. Thereafter, the flow direction field is considered to be time-invariant. Untamo estimates flow directions at each time step and stream channels may therefore change course over time, for example due to tilting of the landscape (if spatially-varying land uplift rate is applied).

Soil loss and transport on land is not accounted for in RLDM nor Untamo. However, the Untamo model offers an option to apply channel incision over the entire stream network to account for the fact that channel geometry might not be present in the DEM and for the absence of a more advanced land soil loss and transport model. This is especially relevant for future streamflow channels that will form on emerging sea floor. The channel erosion option has been applied in the Untamo simulations for the current analysis.

To remove stream channels from the DEM and regolith profile, Untamo first estimates the dimensions of the channel needed to convey the discharge using Manning-Strickler formula for open channel flow (Manning 1891).

$$Q = \frac{1}{n} A R_h^{\frac{2}{3}} \sqrt{I} \qquad (2\text{-}1)$$

where Q (m^{-3} s^{-1}) is the discharge, n (s $m^{-1/3}$) is the Gauckler-Manning roughness coefficient, R_h (m) is the hydraulic radius and I (m m^{-1}) is the energy slope (Untamo calculates this as the mean hydraulic gradient). The hydraulic radius is a measure of the channel flow efficiency and can be expressed as

$$R_h = \frac{A}{P}$$

where P (m) is the wetted perimeter.

The equation (2-1) is used to compute the necessary channel cross-section area from known discharge and subsequently the stream channel width and depth. A roughness coefficient of 0.04 s/($m^{1/3}$) was applied for the current analysis. The discharge Q used in the calculation is the *mean high discharge*, i.e. the average of the yearly discharge maxima. In other words, the mean high discharge is assumed to correspond to the full-bank flow and effectively defines the channel. The water level does not reach the top edge of the channel under normal discharge conditions. The erosion of stream channel also affects the delineation of lake basins and more detail is given in Section 2.4 . More background information about the choice of parameters can be found from Posiva (2014).

2.4 Identification of lakes

The delineation of future lakes in the RLDM is made from hydrological sinks in the present-day DEM. Only sinks with volumes greater than the volume of the smallest existing lake *Labboträsket* (16 211 m^3) that has been included in the RDLM are considered as lakes. Depth, area or shape are not used as criteria for classification of lakes in the RLDM.

Untamo follows a dynamic approach and locates hydrological sinks in the DEM at every time step. Sinks are classified as lakes based on minimum water surface area, minimum mean depth and, optionally, minimum water volume. Furthermore, minimum diameter limit can be imposed so that very thin lakes are avoided (such areas are classified as streams instead if the discharge criteria is met).

Only areas with water depth larger than 30 cm are considered a part of a lake. Therefore, if a lake exists within a basin, parts with a shallow water column (less than 30 cm) are classified as mires and instantly filled with peat up to the basin threshold. The remaining aquatic part of the basin is classified as either open water or littoral zone (classification of littoral zones is described in Section 2.5.2.1). The conceptual division of a lake basin is shown in Figure 2-3.

The water level (surface elevation) and subsequently also the surface area and depth of a lake is defined by the elevation of the outlet from which water exits from the lake (also called the threshold). This is typically calculated from the DEM raster by identifying hydrological sinks. Untamo performs several additional steps to improve the water level estimate. First, the outlet is subject to sediment erosion caused by flow in the stream channel as described in Section 2.3 There is currently no limit as to which regolith layers can be eroded this way and all regolith layers down to the bedrock can theoretically be eroded. The thickness of the removed sediment corresponds to the depth of the stream channel. Additionally, Untamo can be instructed to remove specific regolith layers from the outlet. This is typically used for removing soft sediments and to prevent them from accumulating in the first place. The two approaches are combined together so that the soft sediment that is being removed also counts towards the erosion depth caused by the channel erosion. The principle is demonstrated in Figure 2-4.

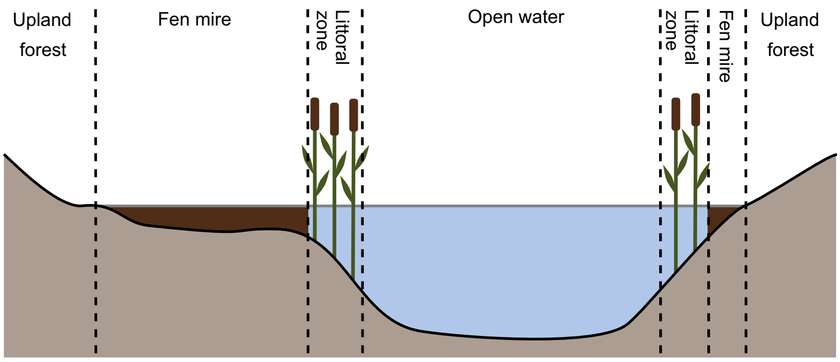

Figure 2-3. *Zones within a basin with a lake. Areas with shallow water column are classified as fen mire while the remaining aquatic part is classified as open water or littoral zone.*

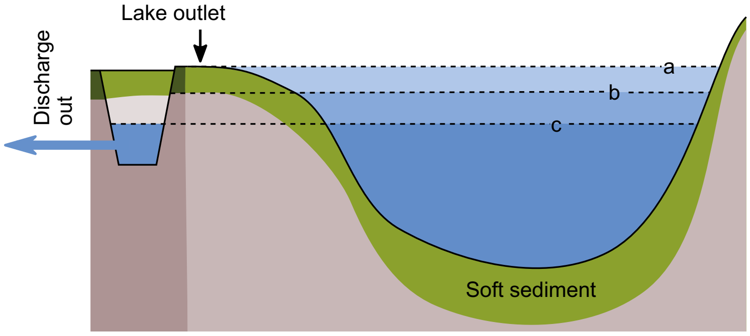

Figure 2-4. *Erosion of lake outlet and its effect on the lake water level. The water level as defined by the DEM alone (a) is lowered by erosion of soft sediment from the outlet (b) and the combined effect of soft sediment erosion and channel erosion (c).*

2.5 Infilling of shallow basins and lakes

Infilling and consequent terrestrialization of shallow coastal basins and lakes is one of the key processes controlling landscape development. The sections below describe how sedimentation processes are handled by both models. The RLDM comprises two modules: the marine module to simulate sediment dynamics in the open sea and the lake module to simulate the lake infilling processes. In Untamo, sedimentation processes are handled differently in vegetation-dominated shallow aquatic environments and open waters.

2.5.1 Sedimentation processes in the RLDM

This section provides a brief summary of the sedimentation processes in the RLDM. These processes are described thoroughly in Brydsten and Strömgren (2013).

In the RLDM the sediment dynamics in the sea (erosion, transport and accumulation) are handled in a marine module and the lake infill processes (sedimentation and vegetation growth) in a lake module. These two modules are run at different temporal resolutions. A time step of 500 years is used in the marine module a time step of 100 years is used in the lake module.

In the marine module fine-grained sediments are accumulated (postglacial clay-gyttja/silt) or eroded (postglacial clay-gyttja/silt or glacial clay) based on the sediment dynamic environment at that time. The sediment dynamic environment for a specific time step is obtained as the output from the sediment dynamic model (Brydsten 2009). In an erosion environment, postglacial clay-gyttja/silt or glacial clay are transported out. In accumulation areas between 0.06 – 0.39 m of postglacial clay-gyttja/silt is accumulated during each 500-year time step. The net sedimentation rate varies over time and is calibrated using the sediment dynamic model and measured postglacial clay-gyttja thickness determined from a marine geological survey (Hedenström and Sohlenius 2008).

The period between the time step in the marine module and the lake isolation is managed manually for each lake. During this period, both the marine accumulation and the lake infill processes are ongoing. Those parts of lakes that are accumulation environments in the last time step in the marine module before lake isolation are filled with sediment. The sediment thickness is calculated as the sediment rate for that time step multiplied by the number of years between the time step and the isolation year.

Reeds areas are established and begin to fill the basin when the water depth in the shallow sea bay within the extent of a future lake decreases to 1.3 m due to the land upheaval (Brydsten and Strömgren 2013). This infilling by vegetation is modelled in the same way as is done for infilling with vegetation of lakes after separation from the sea.

The RDLM distinguishes two types of lake-basin infilling processes that occur simultaneously after lake isolation: Infilling by growth of vegetation and sedimentation of material (gyttja and/or silt). Each lake is modelled separately and only lakes with volumes larger than the smallest existing modelled lake are included in the lake module. In Forsmark, the depth limit for vegetation colonisation is 2 m in lakes (Brunberg et al. 2004). The potential rate of infill by vegetation is calculated with an equation that is dependent on the lake area and is based on the present pattern of 25 lakes in the Forsmark area (Brydsten and Strömgren 2013). The potential vegetation infilling rate is, however, limited by the available lake bottom area that is shallower than 2 m. The areas of the lakes infilled by vegetation are treated as mire and no further accumulation of sediment takes place in these areas.

The sedimentation process in lakes is modelled with an equation that is dependent of the water volume in the lake. If the lake water volume decreases due to the infilling, the sedimentation rate also decreases. The accumulation of gyttja only occurs in parts of the lakes that are not colonized by vegetation but is otherwise independent of the depth.

Accumulation of sediment in reed beds

Untamo has a separate module to deal with sediment accumulation in shallow waters, which are dominated by densely populated colonies of vascular plants, such as the common reed. This model assumes an upper limit of water depth up to which vegetation can grow, and a limit related to physical exposure from wind-induced waves that prevent the vegetation from attaching permanently to the sea or lake bottom. Due to the lack of data, gyttja is accumulated at a constant annual rate in areas classified to contain reed vegetation.

To define physical exposure to waves, Untamo uses a fetch limit which is defined as the maximum mean distance over open water in which reed can still grow. In areas with a mean fetch distance higher than this limit reed will not grow. In addition, a maximum fetch distance is applied, which limits the fetch line length so that when the limit is reached, the maximum fetch distance is assumed, and the fetch line is not continued further. Also, if a fetch line reaches outside of the model area without hitting a barrier, the maximum fetch distance is assumed. The fetch limit and maximum fetch distance are separately defined for lakes and shallow sea areas. Both parameters are calibrated to local conditions, see Section 3.2.3

Furthermore, very shallow parts of a basin that do not fulfil a given minimum depth requirement for a lake are treated as a mire. While reed beds accumulate gyttja, peat accumulation is limited to areas outside the lakes. This is in contrast with the RLDM where reed beds accumulate peat, and gyttja deposits are limited to the deeper open-water areas of lakes.

Sediment dynamics in open waters

Within a lake, coastal bay or at the open sea, sediment transport is modelled empirically based on the properties of the water body such as water depth and shear stress at the bottom. In addition, the model includes a simple module to estimate suspended sediment load, which is transported further downstream into objects such as lakes or the coastal areas. Sheltered bays are identified based on the geometry of the coastline so that the width of the connection to the open sea is smaller than a given limit as shown in Figure 2-5. In addition, the area of the bay must fulfil a minimum area requirement.

The quantity and quality of the suspended sediment carried by a river will vary depending on the properties of the upstream contributing area such as relief characteristics, channel slopes, basin size, land use patterns and soil properties, among other factors (Chakrapani 2005). Untamo uses a simplified approach where the concentration of suspended solids (kg/m^3) is expressed as a function of the area of croplands within the upstream contributing area alone. Alternatively, Untamo provides the option of using the entire contributing area to derive the concentration.

The sediment balance within the open-water areas of a lake or sheltered, shallow bay (a flad, for example) is established from the incoming and outgoing sediment load as well as from sediment produced within the water body itself. This biological production is here referred to as ‘background’ sediment production. In the open sea, only the influx from rivers and the background sediment production are used as it is not feasible to estimate the suspended sediment flux into and out from the area. In other words, it is assumed that the average net sediment flux over the boundary of the open sea region is zero. The sediment balance, in turn, defines the sediment accumulation rate.

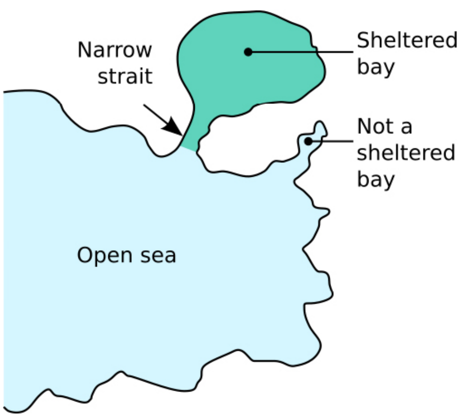

Figure 2-5. *Schematic representation of a sheltered bay.*

Lakes and sheltered bays are considered accumulation and transport environments, whereas open sea waters are classified into accumulation, transport and erosion environments as follows:

- *Accumulation environment* – areas of uninterrupted sediment accumulation, where resuspension does not occur;
- *Transport environment* – areas where both sediment accumulation and resuspension happen interchangeably. For simplification, it is assumed that the net accumulation in transport environments is zero and the suspended sediment is eventually moved away into an accumulation environment;
- *Erosion environment* – areas that experience continuous sediment erosion due to constant or frequent resuspension of fine-grained particles. Suspended particles do not settle but are transported to calmer environments over time.

To distinguish between the different sea environments, Untamo models the shear stress as a result of the water movement near the bottom caused by wind-induced waves. The model quantifies the shear stress based on the theoretical relationship given by Komar and Miller (1973) and based on the spectral parameters of the propagating waves (wave length, height and period) as well as water depth, and to a lesser degree water density and viscosity, following the equations presented in the US ACER Shore Protection Manual (U.S. Army Coastal Engineering Research Center 1984, Chapter 3, Equations 3-33 to 3-41).

To define the different sea bottom types, Untamo uses parameters (speed, duration, direction) of wind events that occur frequently enough to cause continuous resuspension, so-called 'erosion-limiting winds', and of wind events that occur infrequently and thus define the wind conditions at which accumulation or particles can still occur, so-called 'accumulation-limiting winds'. The wind parameters are extracted from weather station data.

If the shear stress exerted on the sea bottom under erosion-limiting wind conditions is larger than a given limit, the area is classified as erosion environment. Likewise, if the shear stress exerted on the bottom under the accumulation-limiting wind conditions is smaller than this limit, the area will be classified as accumulation bottom. All remaining areas are considered transport environments.

Optionally, Untamo also considers the local topography of the sea as a proxy for the likelihood of reduced or increased shear stress when classifying erosion and accumulation environments. This is achieved by computing the mean curvature (Spivak 1999) of the sea or lake bottom at sufficiently large spatial scale (here: 1 km) (Figure 2-6). Areas with strong positive curvature (locally elevated areas) are assumed to experience sediment erosion (even if the wave-induced shear stress alone would not be sufficient). Correspondingly, areas with strong negative curvature (local depressions) are assumed to be protected from both the wave action and water currents, allowing sediment particles to settle.

Following the bottom type classification given above, sediment accumulation only occurs within the accumulation environments while transport environments remain unchanged. Because shear stress is affected both by the water depth and wave properties, which are in turn controlled by the geometry of the shoreline, the distribution of the abovementioned environments will inevitably change over time. As land is slowly emerging from the sea and basins are becoming shallower, the typical progression is from an accumulation environment to transport and finally erosion environment when the area becomes very shallow, unless it is sufficiently sheltered from the effects of wind and waves.

Within an accumulation environment (which may be a lake, sheltered bay or the sea), sediment accumulation happens with a constant rate which is derived from the sediment balance of the water body. In reality, sediment accumulates as uniform layer but typically is the thickest in the deepest parts of the water basin. To reproduce this, the model starts by generating a hypothetical surface that is thought of as the sediment accumulation limit – a surface to which the basin bottom would eventually converge given sufficient sediment input. This limit surface is computed iteratively by first smoothing the original surface with a two-dimensional Gaussian filter, and then taking the maximum elevation of the original and smoothed surface at each pixel. The process is repeated with the radius of the Gaussian filter halved until convergence. Therefore, the smoothness of the limit surface is controlled by the choice of the initial smoothing filter radius and the surface is guaranteed to be above the original surface, or at the same elevation.

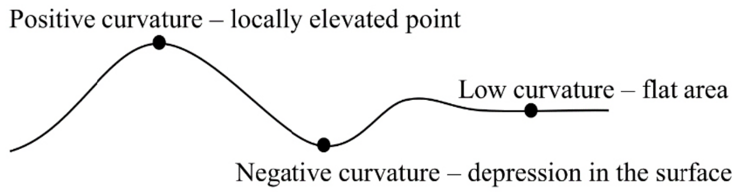

Figure 2-6. *Classification of a surface based on its mean curvature.*

The final surface is then calculated as a combination of the basin bottom and the limit surface such that the volume between the two surfaces is equal to the volume of the sediment to be deposited. This approach also avoids sharp, staircase-like artefacts being created in the DEM which are likely to cause problems in subsequent modelling. The calculation of the accumulated sediment surface is demonstrated in Figure 2-7.

In contrary to the RLDM, sediment is therefore not accumulated in a uniform/constant layer but accumulates faster in the deeper parts of a basin.

Within erosion environments in the sea, sediment is assumed to be frequently resuspended by moving water and transported away into calmer environments, resulting in net sediment loss. Unlike the sediment accumulation rate, which is expressed in kg m^{-2} a^{-1}, the sediment erosion rate is given directly as the annual volume lost per unit area per year, in other words $m^3 \cdot m^{-2} \cdot a^{-1}$ or $m \cdot a^{-1}$. This simplification makes it easier to calibrate the loss rate using present-day sediment observations since data on which sediment that existed on the site in the past and has been eroded away cannot be reliably obtained (beyond relatively coarse educated guesses). The calibration of the sediment accumulation and erosion parameters is described in Section 3.2.4 .

2.6 Peat growth

RLDM: In the lake module of the RLDM, mire formation is part of the infilling of lakes. In each time-step, areas covered with lake vegetation are assumed to be transformed to a mire. The mire part of the lake is then filled with peat to the height of the water level. This peat volume represents the fen stage of mire development and no further accumulation of sediments or peat is modelled. However, only hydrological sinks in the present-day DEM with volumes larger than the smallest existing lake (*Labboträsket*) are described in the lake module. Smaller sinks are therefore handled separately in a sub-model. These sinks are assumed to be infilled with peat after 500 year.

Mires, forming directly after sea regression, so called primary mire formation, are identified using a topographical wetness index (TWI). Areas having an index value above 13.2 are assumed to develop into mires and this limit is based on the present-day pattern above the shoreline in the Forsmark area (Brydsten 2006). In contrast to Untamo, the lateral expansion of peat is not considered in the RLDM.

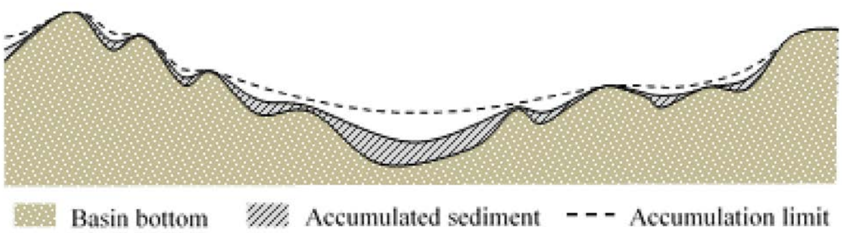

Figure 2-7. *Principle of the sediment accumulation. The space between the fill limit and the basin bottom is filled proportionally.*

Untamo: In Untamo, the development of mires and accumulation of organic sediment from decaying plants is described with a model proposed by Clymo (1984). In the model, a peat bog is composed of two layers. On the surface, an aerobic layer several dozen centimetres thick, called the acrotelm, is found in which peat-producing plants grow. Underneath lies a usually much thicker layer called catotelm, where anaerobic conditions prevail. Dead plant matter reaching the catotelm is subject to slow anaerobic decay and eventually an equilibrium state is reached when the rate of production in the acrotelm layer is equal to the rate of decay in the expanding catotelm layer. At this point the mire effectively ceases to grow. Also the lateral expansion of a mire stops once the equilibrium state is reached.

In the model of Clymo, a circular or elliptical mire starts growing from a single focal point. The focal points or areas of mire formation are located based on the mean curvature (Spivak 1999) of the terrain surface at any given point. In addition to Clymo's original model, the growth focus and age of existing peat formations can be given as input parameters to the model in Untamo, and a wave effect buffer (distance from shoreline) can be specified to exclude peat growth along the shoreline where physical exposure (e.g. to waves and ice) would prevent seasonal deposits.

In Untamo, lake basins may start to transform into a mire only after the basin has been fully infilled with sediment or, in other words, if the basin does not fulfil the given minimum mean depth criteria for a lake.

2.7 Land use

While potential croplands are identified in a post-processing step in the LDM, Untamo allocates land use during the simulation in every time step. The sections below describe the two different ways in which land use is implemented in both models.

2.7.1 Land use in the LDM

The RLDM does not include land-use and models the landscape development without human impact. In the LDM, the land use is based on the regolith layers from the RLDM. The LDM is modelled in 3 different climate variants in which the land use is more or less influenced by human activities and in one case no human influence is assumed at all (SKB 2014a).

The areas that can be cultivated in a future landscape in Forsmark are delimited on knowledge from previous and existing arable land in the Forsmark area and in the county of Uppland. Criteria for potential land use are: Suitability of the regolith type for cultivation, thickness of the cultivable soil, height above sea level and size of the cultivable area. Different types of vegetation are assigned to areas that cannot be cultivated, depending on the regolith type and the climate variant being modeled.

2.7.2 Land use in Untamo

Untamo handles the land use of the future landscape with a simple stylized model. Presently, only the "agricultural" and "other" land use classes are distinguished. Several suitability and geometry criteria are combined into an overall suitability for cultivation, which is used as a basis for the allocation of individual field plots. The suitability criteria include soil suitability (regolith type), sediment thickness, and elevation above sea level. The geometry of the allocated field plots resembles present-day practice. Following geometry criteria are considered: Simple shape, minimum area and width, and target mean area.

Based on the criteria listed above, all areas that can potentially be used for agriculture, i.e. all areas that fulfil the suitability criteria mentioned above, are split into field plots. The average field plot size (target area) is defined via user input. For each field plot, the suitability for agricultural use is calculated as the arithmetic mean of the soil suitability scores (depending on the regolith type) over the area of the plot. For the current analysis, a simple score system was applied by assigning the same value to all suitable regolith types. The final set of field plots is then selected by taking the plots with highest suitability such that their combined area corresponds to the desired allocation area (expressed as a fraction of dry land, including all areas regardless whether they are suitable for the crops or not).

If large areas of very suitable soil are emerging from the sea which are assumed to be taken into agricultural use, older field plots that have a lower soil suitability than the emerging land may be abandoned by the model. An example of the resulting set of field plots is provided in Figure 2-8.

The land use model provides the option to retain the allocated field plots until the end of the modelling time frame. This option was chosen for this study.

After agricultural fields have been allocated on the most suitable soils, different vegetation types can be assigned to the remaining land areas if defined so, based on the characteristics of the top-regolith layer.

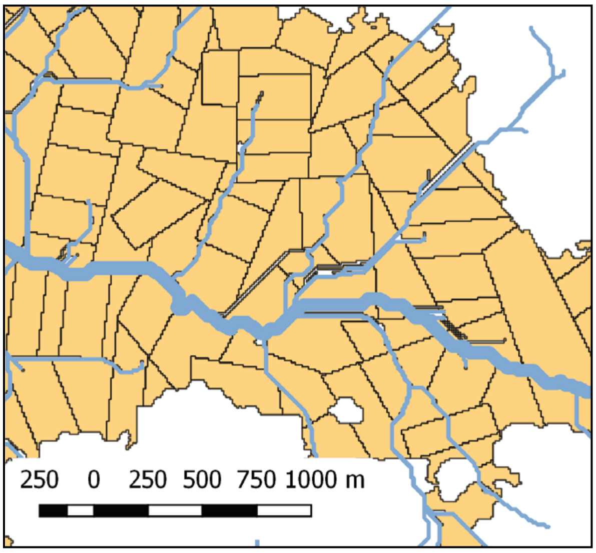

Figure 2-8. *Example of allocated field plots in Untamo with mean target area 2.5 ha. The most suitable plots are shown in yellow, overlaid by delineated streams in blue colour. Areas of lower suitability and unsuitable areas are represented in white.*

3 Model parameters and initial conditions applied in RLDM and Untamo

3.1 Data for initial condition

3.1.1 Digital elevation model (DEM)

The same digital elevation data as described in detail by Strömgren and Brydsten (2013) was applied for both models. The DEM covers the terrestrial and marine areas and has a resolution of 20 m. For Untamo, the DEM was re-sampled to 10 m resolution using bilinear interpolation to facilitate the delineation of lake boundaries and the application of stream channel erosion.

The DEM serves as the initial condition for the Untamo simulations which start from the present time. In contrast, the RLDM simulations start already at the end of the last glaciation in 8500 BC, therefore the DEM was modified to resemble the conditions at that time (see next section).

3.1.2 Regolith stratigraphy

The RLDM simulations are based on the regolith depth model (RDM) for the Forsmark area as described by Sohlenius et al. (2013). The model shows the stratigraphy and thickness of different deposits at present. However, since the RLDM simulations start from the end of the last glaciation, the RDM of Forsmark was modified to resemble the conditions at 8500 BC. Thus, the thickness of all post-glacial deposits and peat was subtracted from the model. In addition, the thickness of the glacial clay layer was increased to 2 m in areas where glacial clay was less than 2 m thick, to ensure a glacial-clay layer thickness of at least 2 m throughout the model area.

For the Untamo simulations a more recent version of the Forsmark RDM which was completed in 2018 (Petrone et al. 2020) was used as starting point for the modelling (2000 AD), representing the regolith stratigraphy and thickness at present. For the Untamo simulations, the RDM layers were reclassified into the following types: Peat, (lacustrine) gyttja, clay gyttja (marine post-glacial clay), glacial clay, till, and bedrock. It should be noted that a more recent version of the DEM was used by Petrone et al. (2020) when developing the RDM. However, that DEM could not be used in the current analysis since it has not yet been approved for public use.

Some differences in the modelling results can be attributed to the use of two different RDM versions for the initial condition in RLDM and in Untamo (i.e., RDM versions 2013 and 2018). The modification of the RLDM at the start of the simulation (to resemble conditions in 8500 BC), as opposed to starting the simulations with present conditions (at 2000 AD) had an impact on the landscape predictions. An example of the effect is shown in Figure 3-1, which depicts the RLDM simulation result of the regolith stratigraphy for year 2000 AD in comparison to the recent version of the RDM, which defines the condition at 2000 AD when the Untamo simulation starts. Differences are largest for the regolith thickness of glacial clay.

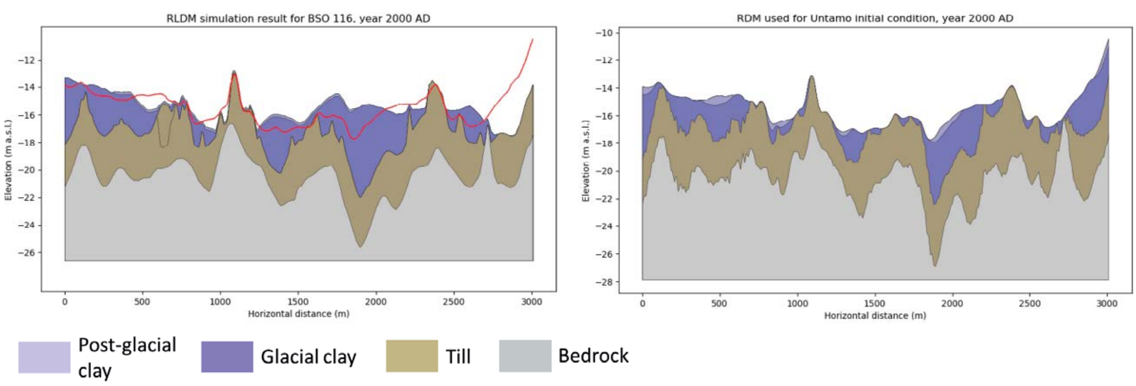

Figure 3-1. *Differences in the regolith stratigraphy between RLDM (left) and Untamo (right); example for year 2000. The red line marks the relief in year 2000 (DEM 2000).*

3.2 Parameters for the terrain and ecosystem modelling

3.2.1 Land uplift parameters

The shoreline displacement values applied in both models correspond to the global warming climate case of the SR-PSU (SKB 2014b), see Section 2.2 .

3.2.2 Parameters for the delineation of lakes and sheltered bays

The parameter values applied in this study to delineate lakes in Untamo are listed below.

Table 3-1. Parameter values for lake delineation applied in the Untamo simulations.

Parameter	Value used in this study	Justification
Minimum depth of a basin location to be considered as part of a lake	0.3 m	Expert judgement
Minimum surface area of the lake	1 ha	Minimum size of Forsmark reference lakes studied by Brunberg et al. (2004)
Minimum mean depth of the lake	0.8 m	Expert judgement
Minimum volume of the lake	16 211 m^3	Same as used by RLDM; based on smallest reference lake *Labboträsket*
Minimum diameter of the lake (optional, see Section 2.4)	30 m	Expert judgement

Delineation of sheltered bays was not relevant for this analysis since sediment suspended in rivers which would accumulate in a sheltered bay such as the Olandsån bay, has not been considered.

3.2.3 Parameters for reed bed classification

In both models, the limiting water depth for reed colonization was set to 1.3 m in case of coastal areas and to 2.0 m in case of lakes (Brydsten and Strömgren 2013). These values are based on the mapping of reed distribution in shallow sea bays (Strömgren and Lindgren 2011) and the mapping of vegetation in lakes (Brunberg et al. 2004) in the Forsmark area.

In the RLDM, the colonization of reed is modelled first in the shallow sea bay phase within the extent of the future lakes and then after the lakes have been separated from the sea. The area of vegetation ingrowth is controlled by the limiting water depth and the lake area.

The ingrowth by vegetation in the shallow sea bay is calculated using the following equation:

Ingrowth rate = 100 + 8.3/10 000 × "the lake basin area",

in which ingrowth is expressed in m^2/year and the forthcoming lake basin area in m^2 (eq. 2-2 in Brydsten and Strömgren 2013).

The ingrowth by vegetation in the lake phase is modelled using the following equation:

"Ingrowth rate" = 36 372 + 1.169 × 10^{-4} × "the lake basin area",

in which ingrowth rate is expressed as m^2 $year^{-1}$ and the lake basin area as m^2 (eq. 2-3 in Brydsten and Strömgren 2013).

In Untamo, the area colonized by reed is controlled by the limiting water depth and by the mean fetch distance over open water. For lakes, the mean fetch distance over open water which allows reed growth can be at maximum 100 m. This limiting value was derived through a calibration based on the comparison of Untamo model results with mapped vegetation in the littoral zone of 18 lakes in the Forsmark area derived through field survey (Andersson 2010). In addition, aerial photographs were considered for the calibration. For coastal zones, 70 m was found to be a suitable limiting mean fetch when comparing Untamo results with reedbed areas visible from aerial imagery. Since better reference data were not available for coastal areas, this parameter estimate is relatively approximate and could be improved based on field survey.

For the calculation of the mean fetch distance for a coastal or lake shore location, the maximum considered fetch distance was set to 180 m, i.e. any fetch distance exceeding this threshold was reduced to 180 m. The choice of this value was based on expert judgement to achieve results that are more comparable to the RLDM.Parameters for mire formation and peat growth.

In the RLDM, the topographical wetness index (TWI) is used to help denote where mires are formed. In mires formed by primary mire formation, the peat thickness is assumed to be zero unless the area is located in a topographical depression that does not fulfill the minimum lake volume criteria.

In the RLDM, the minimum area for a peat-filled depression or primary mire is 2400 m^2. The minimum depth of the depression is not used as criteria. This minimum area threshold is based on the minimum area criteria applied for the allocation of agricultural plots in the RLDM (Section 3.2.5).

Untamo identifies the areas of mire formation based on the mean curvature of the terrain surface (see Section 2.6). The minimum depth for a hydrological sink to be considered for mire formation was set to 0.2 m. A threshold of 0.3 m minimum peat thickness was applied for the classification of peatlands. Both values have been based on expert judgement. In addition, to be comparable to the RLDM approach, a minimum area of 2000 m^2 is required for a peatland to be considered for peat growth modelling during the simulation. Parameters related to mire hydrology and peat production and decay as used by the Clymo model are described in Clymo (1984).

3.2.4 Parameters for sediment dynamics model

Marine sedimentation

RLDM: In the RLDM, the marine part of the sediment dynamics is modelled as erosion of post-glacial fine-grained sediments and glacial clay and accumulation of marine post-glacial sediments. The sediment dynamic module (Brydsten 2009) provides U_{max} (the highest orbital velocity at the sediment surface in m/s) for all raster cells in the marine area. To determine specific U_{max} values for erosion or accumulation of different sediment types, a calibration was performed where the results from the sediment dynamics module for 2000 AD were compared with the regolith map for Forsmark. In this report these U_{max} values are referred to as critical U_{max}.

The boundary between glacial clay and post-glacial fine-grained sediments was used to calibrate critical U_{max} for erosion of post-glacial fine-grained sediments, while for erosion of glacial clay the boundary between glacial clay and silt was used. The boundary between postglacial clay-gyttja and silt was used to calibrate a critical U_{max} for accumulation of postglacial fine-grained sediments. The calibration resulted in critical U_{max} which are > 0.53 and > 1.09 for erosion of postglacial fine-grained sediments and glacial clay, respectively, and ≤ 0.53 for accumulation of postglacial fine-grained sediments. Erosion thus occurs if erodible material is available and $U_{max} > 0.53$ or > 1.09. However, if $U_{max} \leq 0.53$, sediment always accumulates.

The amount of suspended particles in seawater varies greatly over time. It was therefore necessary to calculate the net sedimentation rate for each modelled 500-year time step. The total area of post-glacial sediment and unwashed moraine located above the wave base at each time step was used as a measure of sedimentation rate. The rate was calibrated to reach a good agreement between modelled and measured sediment thickness. The calculated net sedimentation varies between 0.06 – 0.39 m $500a^{-1}$ for all time steps.

Untamo: The main parameters controlling the sedimentation dynamics in Untamo are the limiting wind speeds and wind durations which allow continuous resuspension and undisturbed settling of sediment particles, respectively. In addition, the minimum shear stress for resuspension and the maximum fetch distances over open water in different wind directions are used to delineate erosion and accumulation environments, see Section 2.5.1.2 .

The speed at which sedimentation happens is regulated by the background sedimentation rate, which defines the net accumulation amount per unit area in accumulation environments. The rate was calibrated by modelling the sediment dynamics from the end of the last glaciation (8500 BC) until year 2000 AD using Untamo tools, and then comparing the modelled amount of accumulated fine-grained sediment against present-day thickness of post-glacial clay gyttja in the sea accumulation bottoms taken from reference data (Petrone et al. 2020). The sedimentation rate was adjusted until the modelled and reference thickness coincided (Table 3-3). This calibration included the entire sea area covered by the regolith model for Forsmark. The sedimentation rate was adjusted so that the modelled volume of post-glacial clay gyttja in the calibration area was similar to that in the reference data. The DEM and regolith stratigraphy representing the conditions in 8500 BC were prepared in a similar way as was done for the RLDM simulations, see Sections 3.1.1 and 3.1.2.

An erosion rate of zero was used for the glacial clay for the main simulation results. An alternative variant was modelled which considers erosion of glacial clay. The erosion rate of the glacial clay was estimated by comparing the glacial clay thickness between non-erosion and erosion environments based on the regolith stratigraphy for the present day (Petrone et al. 2020). The mean thickness of glacial clay in marine areas which did not experience erosion since the last glaciation (Figure 3-2) was assumed to be the original amount of glacial clay. The mean thickness of glacial clay in areas which experienced at least 2 500 years of erosion since the last glaciation was subtracted from this original amount to derive the assumed thickness of eroded material and to estimate the yearly erosion rate, taking into account also the mean erosion duration in the same area. The erosion duration for each location was derived from Untamo model outputs of erosion and accumulation environments in each time step (Figure 3-2). During the simulation the lowest erodible regolith layer was limited to glacial clay.

Accumulation of organic material in coastal zones which are dominated by reed vegetation is controlled by a separate parameter. The accumulation rate (see '*Accumulation rate in reedbeds*' in the table below) is the same as applied for reed areas in lakes and was taken from Posiva (2014) Section 11.6.

The applied values for all mentioned parameters are listed in the table below.

Table 3-2. Parameter values for marine sedimentation applied in the Untamo simulations.

Parameter	Value applied for this study
Erosion-limiting wind speed	9 m/s
Erosion-limiting wind duration	9 hours
Accumulation-limiting wind speed	20 m/s
Accumulation-limiting wind duration	12 hours
Direction range for erosion- and accumulation-limiting winds	0–160 degrees
Maximum fetch distance in North direction	280 000 m
Maximum fetch distance in North-East direction	220 000 m
Maximum fetch distance in East direction	120 000 m
Maximum fetch distance in South-East direction	50 000 m
Maximum fetch distance in South direction	50 000 m
Maximum fetch distance in South-West direction	50 000 m
Maximum fetch distance in West direction	30 000 m
Maximum fetch distance in North-West direction	80 000 m
Mean shear stress for resuspension	40 N/m^2
Background sedimentation rate (sea)	0.018 kg/m^2/year*
Erosion rate (applied only in a simulation variant)	0.000956 m/year
Accumulation rate in reedbeds	2.7 mm/year

*Bulk densities are listed in Section 3.2.6.1

Lacustrine sedimentation

RLDM: A statistical analysis of sediment cores from six lakes in the Forsmark area (Hedenström 2004) shows that the sedimentation rate in lakes depends on the water volume. In the RLDM, the accumulation of gyttja is modelled using an equation created from this relationship:

Sedimentation rate = 49.967 + 102.786 × Water volume (eq. 2-1 in Brydsten and Strömgren 2013),

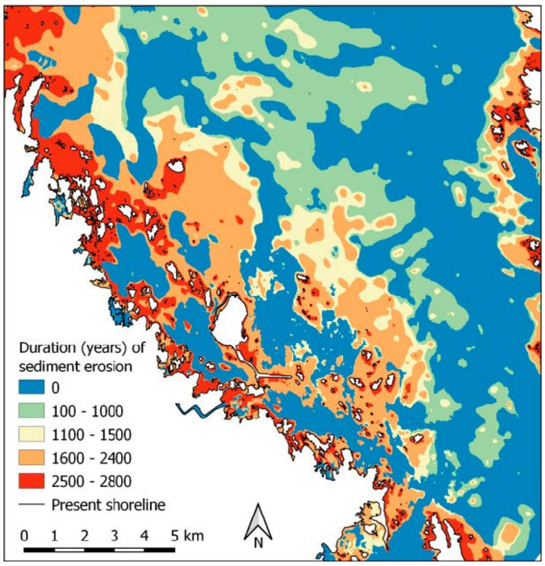

***Figure 3-2.** Modelled erosion duration (in years) between 8500 BC and 2000 AD in the marine area used for deriving the erosion rate.*

in which the sedimentation rate is expressed as m^3/year and water volume as Mm^3.

Untamo: In this study, the infilling of the open-water parts of a lake or sheltered bay with post-glacial sediment in Untamo is only controlled by the background sedimentation rate which defines the net sediment accumulation amount per unit area. The background sedimentation rate is applied to the open-water areas of the delineated lakes, i.e. lake areas that are not covered by reed vegetation. For lake delineation criteria refer to Section 3.2.2 It considers sediment that originates from the water column, for example caused through resuspension, biological production or shoreline erosion. Incoming and outgoing sediment of rivers was not considered here (see Section 3.2.4.3). In Untamo, accumulation of sediment originating from the water column happens only in those parts of the lake that are deeper than the specified depth limit for accumulation bottoms. The background sedimentation rate was calibrated by modelling the accumulation of gyttja for 24 reference lakes in the Forsmark and Långanäs area using Untamo tools, starting from the time of their isolation from the sea until year 2000 AD. The modelled thickness of accumulated sediment was compared to the thickness in the regolith depth model (Petrone et al. 2020) and the sedimentation rate was iteratively adjusted until modelled and reference thickness coincided.

A different accumulation rate is applied to the lake areas where reed vegetation is growing. The reed accumulation rate defines the amount of organic material (here: gyttja) that accumulates in the reedbeds and has in this study the same value as for the sea environment.

The applied values for the mentioned parameters are listed in the table below.

Table 3-3. Parameter values for lacustrine sedimentation applied in the Untamo simulations.

Parameter	Value applied for this study
Depth limit for accumulation bottoms	1.5 m
Background sedimentation rate (lake/coastal bay)	0.75 kg/m^2/year*
Accumulation rate in reedbeds	2.7 mm/year

*Bulk densities are listed in Section 3.2.6.1

Sediment in rivers

Since river sedimentation is not considered in the RLDM, incoming and outgoing sediment load (suspended river sediment) has not been considered in the comparison analysis between Untamo and RLDM. Therefore the sediment balance of the water bodies in Untamo is equal to the background sediment production. This means that incoming sediment from Olandsån river is has not been taken into account when modelling the sedimentation processes the downstream located sea areas.

3.2.5 Parameters for cropland allocation

RLDM: In the RLDM, the allocation of arable land in the LDM is based on following criteria:

There must be 0.5 m glacial clay or at least 2 m undrained gyttja or at least 1.5 m undrained peat, where each layer corresponds to 0.5 m compacted material. The compaction rates for peat and gyttja are therefore 33 % and 25 %, respectively. Alternatively, the sum of the clay/clay-gyttja and peat deposits must amount to at least 0.5 m compacted material. In the RLDM there is no further vertical peat growth above the lake basin hight, meaning that the suitability for cropland will not be changed after that last stage. i.e. due to further vertical increase of fen peat or establishment of acid bog peat with low or no hydrological contact with the groundwater

All areas larger than 0.24 ha with deposits suitable for cultivation and which can be drained if necessary are used as arable land. These areas also must be more than 1 m above sea level in order to be cultivated.

Untamo: The same values for minimum soil thickness (0.5 m of compacted soil), minimum field size (0.24 ha) and minimum elevation (1 m) as in the RLDM were applied in the Untamo simulations. Rocky soils and till soils were excluded from the cropland allocation, while all other regolith types were considered equally suitable. Peat soils that are taken into agricultural use are compacted to 33 % of their original thickness, adopting the compaction factor used by from SKB. In contrast to RLDM, gyttja compaction has not been applied in this work since it is not implemented in the current Untamo version. The total thickness of all suitable regolith layers is used to evaluate the minimum soil-thickness requirement. The compaction factor for peat soils is considered during that evaluation.

For the scenario variant of extensive agriculture, the simulation was set up so that allocated croplands do not change over time, i.e. they will stay in agricultural use even if conditions changes. Furthermore, croplands were allocated only on newly emerged land in each time step in order to maintain a uniform cropland density. The targeted dry-land fraction to be allocated to agriculture was set to 1, i.e. all new emerging dry-land areas fulfilling the minimum requirements for agricultural use were converted to croplands (see Section 2.7.2).

A second scenario variant assuming natural development was calculated which did not allocate any croplands.

3.2.6 Other parameters

Sediment bulk densities

The bulk densities applied by Untamo for the different regolith types are listed in Table 3-4. The values for gyttja and marine clay gyttja are based on lake samples from Finland (Ilus et al. 1993). The value of glacial clay was adopted from SKB's earlier modelling work for Forsmark (Grolander 2013). At the moment, bulk densities used by Untamo for sedimentation modelling are only those of peat/compacted peat, gyttja and clay gyttja since sediment accumulation is modelled only for those layers. The bulk densities are considered when calibrating the background sedimentation for the sea and lakes. A change of the given bulk densities will therefore require the recalibration of the sedimentation rates.

In comparison, the RLDM uses bulk densities of 182 kg/m^3 for gyttja and clay gyttja, and 274 kg/m^3 for compacted peat.

Table 3-4. Dry bulk densities of the sediment types applied in Untamo.

Regolith type	Dry bulk density, kg/m^3
Peat	93
Compacted peat	281
Gyttja (lacustrine)	138
Clay gyttja (marine)	260
Glacial clay	673*
Till	2 115*

*Currently not used by Untamo

4 Comparison of the simulation results

4.1. Considered climate scenario, time frame and temporal resolution

The study applies two alternative variants under a global warming climate scenario which is described in SKB (2014b). The climate scenario represents temperate conditions until 50 000 AD followed by natural variability and cooling of the climate until 100 000 AD. The two modelled alternatives include a variant that assumes extensive agricultural use and a variant solely based on natural development. Under the scenario of extensive agriculture, two Untamo simulation variants were derived: One that neglects erosion during marine stage (i.e. erosion rate of zero) and one that allows erosion of post-glacial and glacial clays (see Section 3.2.4).

For this comparison study, Untamo simulations for both scenarios were run until 12 000 AD. However, for that time period, results from the landscape development model (LDM) that show the land use for the scenario of natural development, are only available for years 3 000, 5 000 and 12 000 AD. As described earlier, the starting time of the simulation differs between both models (see 3.1.1 and 3.1.2).

The RLDM applies 500-year time steps for modelling the sedimentation dynamics in the marine parts and 100-year time steps to model the infilling of lakes. Untamo results were calculated using 500-year time steps between 2 000 AD and 3 500 AD until the lakes of interest formed, after which the simulation was run at 100-year time steps until 12 000 AD.

The results from the Untamo model are compared to regolith thicknesses and cross-sections of the regolith from RLDM and to maps from LDM which show the development over time for sea, lake, streams, wetlands and arable land.

4.2 Development of selected biosphere objects

The focus of this study was on the development of selected future lake basins in the two models. Hence, the simulation results were analysed regarding the time of isolation, their area and water volume over time, the duration until a former lake basin is completely infilled with vegetation and sediment, and the thickness of the resulting sediment layers.

Seven biosphere objects, including one large and six smaller lakes, of interest were selected based on SKB's suggestion, building upon past and ongoing safety assessment studies (Figure 4-1). In addition to the aforementioned object properties, profiles of the simulated regolith layers were extracted for each object along specified cross-sections (see Section 4.2.2).

4.2.1 Water volume and mean regolith thickness

Figure 4-2 and Figure 4-3 depict how the water volume in the objects of interest decreases over time. The three basin objects 116, 159 and 160 develop as lakes in both models and the timepoints of lake formation are similar. The duration of infilling is comparable for the largest of them (116) while for 159 and 160 the process of terrestrialization lasts significantly longer in the RLDM. For the two objects 121_1 and 157_1 there is a clear difference between both models because RLDM results show a lake stage while Untamo does not. Objects 121_2 and 157_2 are not basin objects and therefore do not isolate as lakes in neither of the models.

Figure 4-4. shows the mean thickness of different regolith layers for the different biosphere objects after infilling. For the marine deposits, object 157_1 shows the largest difference in the thickness of the regolith estimated by the two models. Much of this may have to do with the differences in the regolith stratigraphy defining the initial condition (see Section 3.1.2). When looking at the net change in regolith thickness between 2 000 AD and 10 000 AD as shown in Figure 4-5, it is noticeable that the RLDM accumulates more clay gyttja during that period. However, the difference to the accumulated amount in Untamo stays in the order of 20-30 cm.

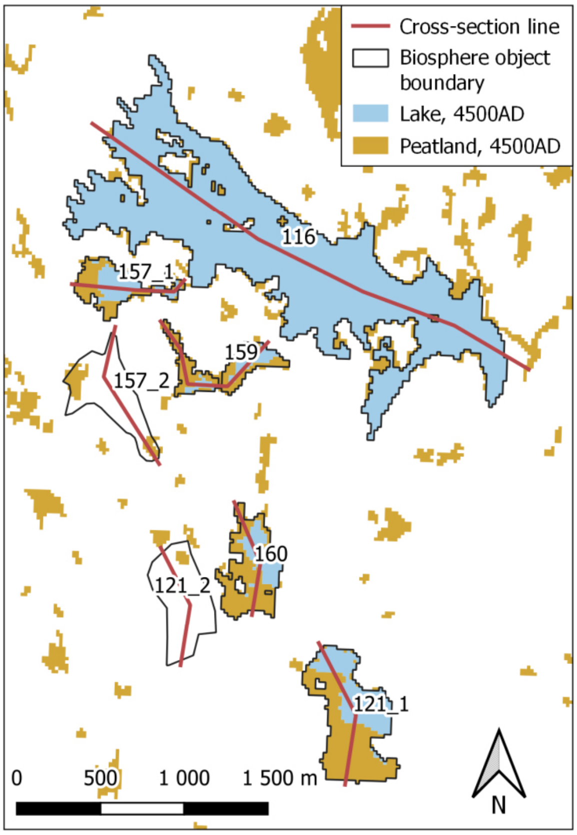

***Figure 4-1.** Boundaries of selected biosphere objects, overlaid over RLDM modelling results for year 4 500 AD, and the location of cross-sections for which regolith profiles are presented in the sections below. The numbers in the map relate to the names of the biosphere objects.*

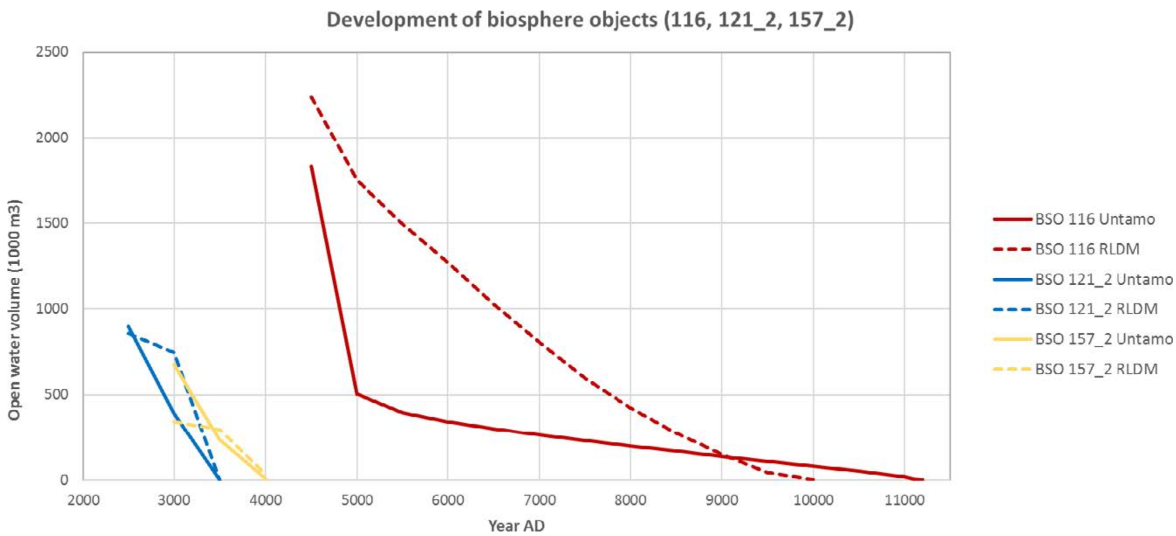

***Figure 4-2.** Volume of the open-water parts of the biosphere objects 116, 121_2 and 157_2. Note: In case of 116 the graph shows the development from time of isolation from the sea to a mire. Objects 121_2 and 157_2 are not lake basins and the graph depicts the process of emergence of the area from the sea.*

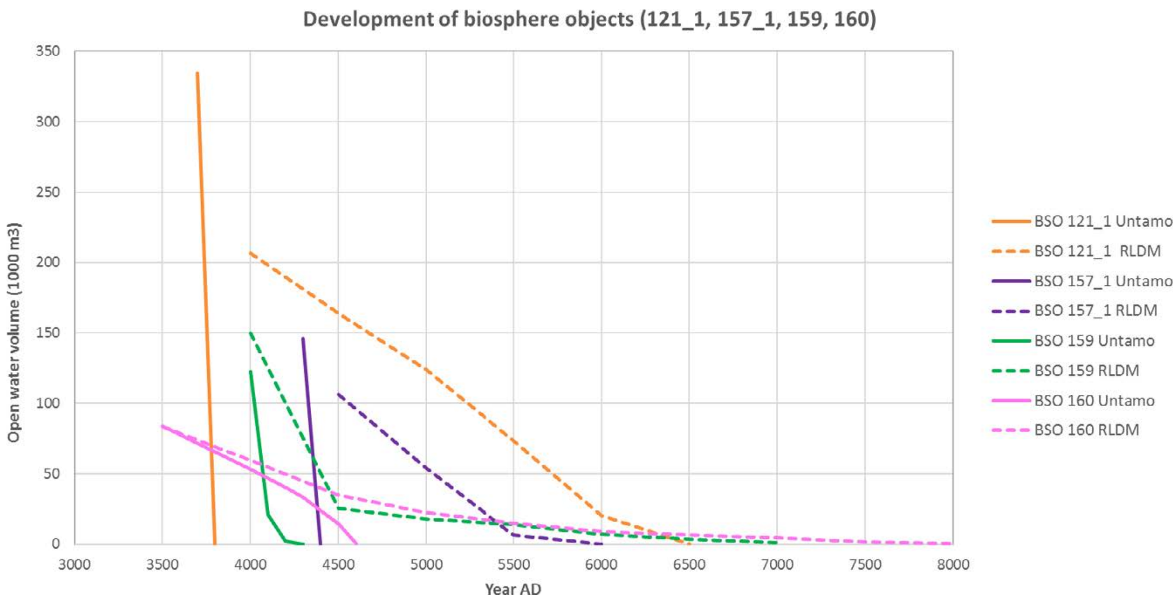

Figure 4-3. *Volume of the open-water parts of the biosphere objects 121_1, 157_1, 159 and 160 over time. Note: In RLDM these objects are lake basins and the graph shows their development from time of isolation from the sea to a mire. In Untamo, objects 121_1 and 157_1 are lacking the lake stage and the graph depicts the process of emergence from the sea.*

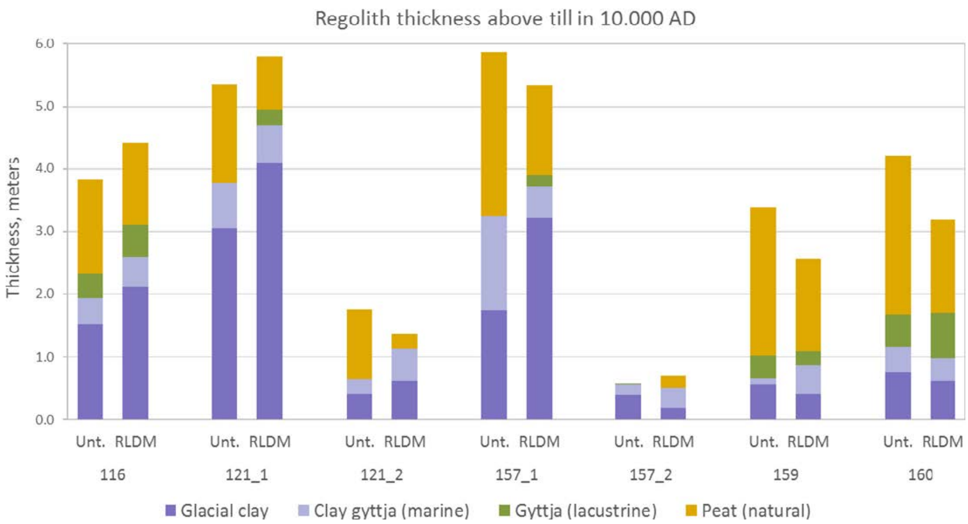

Figure 4-4. *Mean thickness of the upper regolith layers in year 10 000 AD for selected biosphere objects in Untamo and RLDM. The peat thickness shown here refers to uncompacted peat.*

The thickness of lacustrine deposits of gyttja between 2000 AD and 10.000 AD in the three lakes evolving in both models (objects 116, 159, 160) show only small differences which do not exceed 20 cm (Figure 4-5). The two basins 121_2 and 157_2 do not undergo a lake stage but stay connected to the sea in both models until the basin bottom reaches a height above sea level. Therefore, they do not accumulate gyttja in either of the models. However, in Untamo a very thin layer of gyttja is deposited in 157_2 resulting from reed growth in the sheltered coastal area. Objects 121_1 and 157_1 do not develop as lakes in Untamo and therefore do not accumulate any gyttja, while in the RLDM gyttja is deposited during lake stage.

A significant amount of natural uncompacted peat is forming in the Untamo model in all biosphere objects except for 157_2 where the development of peat is prevented by two streams draining the object (Figure 4-5). In the RLDM, peat soil can be seen in all biosphere objects. With the exception of object 157_2, the depth of the peat layer is thinner in the RLDM than in Untamo since the RLDM does not model raised bogs, i.e. in RLDM peat is only formed to the level of the lake threshold. The differences in peat thickness are largest for objects 157_1 and 160 where Untamo predicts over one meter more peat than the RLDM (Appendix 2). However, in the scenario of extensive agriculture the thickness of compacted peat is considerably larger in the RLDM results (Figure 4-6). This relates to the different way the sedimentation process in lakes is handled by the RLDM: While Untamo accumulates gyttja in all accumulation zones of a lake including those where vegetation grows, the RLDM accumulates peat in the shallow vegetated areas of a lake and treats them as a mire (see Section 2.5.1). In other words, up to their threshold the lakes are infilled with both gyttja and peat deposits in the RLDM, and only with gyttja deposits in Untamo. These deposits have, however, rather similar properties. Untamo starts accumulating peat only once a basin location does not fulfil the minimum water depth requirement anymore to be considered part of the lake (here 0.3 m) and therefore is treated as a mire (compare Section 2.5.1.1). Since mires are mostly converted into agricultural land as soon as the area fulfils the requirement on minimum soil thickness for cultivation, the peat layer stays very thin in the Untamo results for the scenario of extensive agriculture (Figure 4-6). However, a peat layer is forming in some parts of object 116 even in that scenario (Figure 4-6). These parts are not converted into cropland right after mire formation because the water level of the small lake persisting in the centre of the object would be higher than the compacted peat surface. Therefore the mire continues to grow for a few thousand years before it is turned into agricultural land.

Though the way in which lakes are infilled with sediment differs between both models, peat is the dominant sediment material that accumulates in both models by year 10000 AD (Figure 4-5). In the RLDM, this accumulated peat layer refers to the material that the model uses to infill the lake up to its threshold, and in Untamo the accumulated peat refers to the growing mire which develops on top of the infilled lake. Furthermore, the amount of accumulated gyttja in those lakes which show a lake stage in both models (116, 159, 160) is comparable between the two models, despite the different ways of lake infilling. These lakes are shallower and smaller in Untamo than in the RLDM. Therefore, even though Untamo fills the entire lake with gyttja, the accumulated amount stays similar to that what the RLDM deposits.

The process of lake infilling over time is shown in more detail with cross-sections for the different biosphere objects in the next section.

Detailed statistics showing the percentiles and mean values of water depth, water volume and thickness of regolith layers are provided in the appendix.

4.2.2 Isolation and infilling in figures

The sections below illustrate the development of the biosphere objects via maps and regolith profiles for both model results for selected years. All sediment cross-sections are based on the colour scheme shown in Figure 4-7. The locations of the cross-section lines are visible from Figure 4-1. The legend for the map figures in this section is given in Figure 4-8.

Please note that the criteria for selecting the streams shown on the maps in this section differ between RLDM and Untamo results. While the streams included in the Untamo figures shown here comply with a minimum width of 0.5 m, the RLDM-related figures show all streams with a mean run-off of at least 0.02 m^3/s.

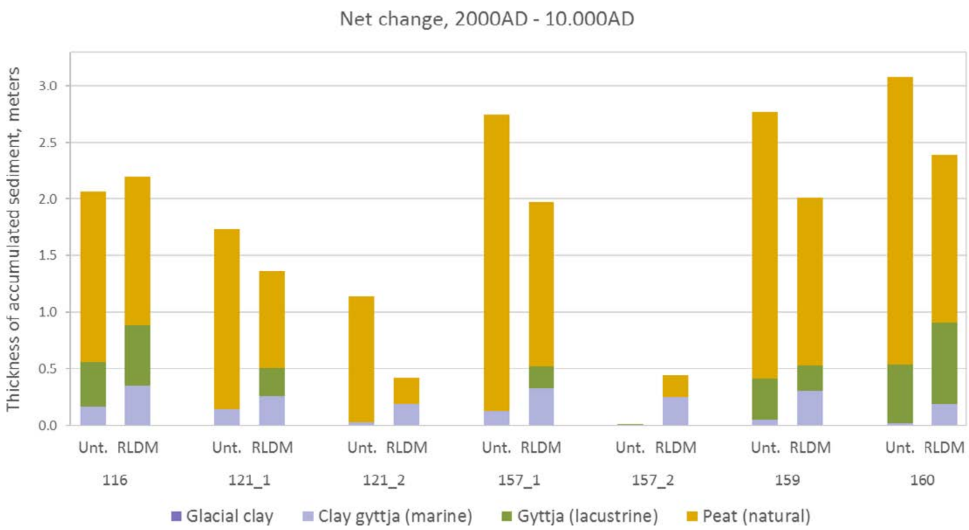

Figure 4-5. *Mean thickness of the sediment that has accumulated between 2 000 AD and 10 000 AD in Untamo and RLDM, for selected biosphere objects. The peat thickness shown here refers to uncompacted peat.*

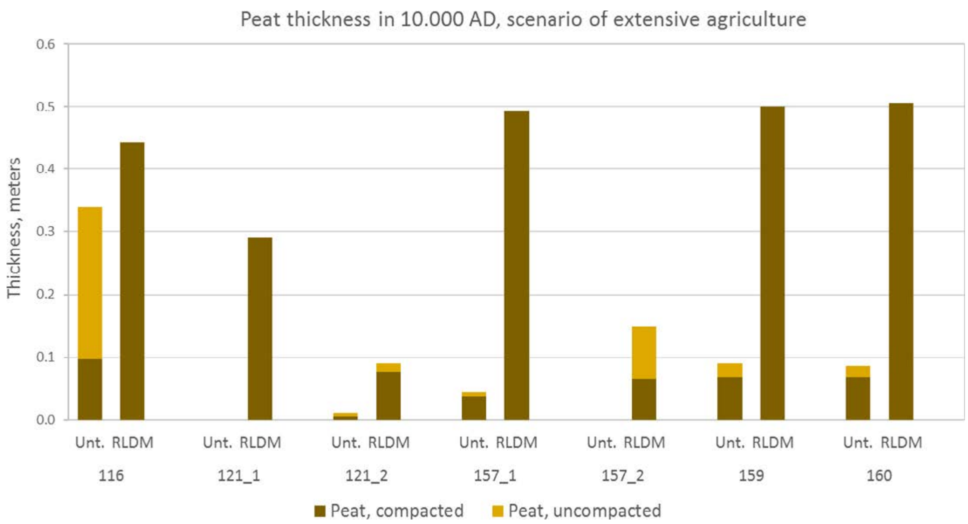

Figure 4-6. *Mean thickness of compacted and uncompacted peat in year 10.000 AD in the scenario of extensive agriculture in Untamo and RLDM, for selected biosphere objects.*

Figure 4-7. *Colour scheme of the regolith profiles shown in this report.*

Figure 4-8. *Legend applied in all maps shown in this section.*

Isolation and infilling of biosphere object 116

Biosphere object 116 gets isolated from the sea in year 4500 in RLDM and between 4500 and 4600 in Untamo (Figure 4-9). At the isolation time the lake is on average shallower in Untamo, and therefore infilling proceeds faster compared to the RLDM (Figure 4-10, Figure 4-11). Nevertheless, the central part of the original lake persists longer in Untamo, where the infilling is completed only in 11300, while the lake in the RLDM gets fully infilled by year 10000 (Figure 4-12). In both models the lake is fully covered with a peat layer after infilling, and in the agricultural scenario the entire BSO extent is turned into a cropland (Figure 4-12, Figure 4-13). In the scenario of natural development in Untamo, the mire keeps growing and by year 12 000 the thickness of the peat layer reaches in many places almost four metres (Figure 4-14). The different methods that were applied for accumulation of post-glacial clay gyttja by the models are visible from the profiles: While the layer of clay gyttja has an almost constant thickness in the RLDM results, the deposits are mainly accumulated in depressions by Untamo.

Results from the RLDM indicate the presence of a thin layer at the bottom of the lake, see Figures 4-9 and 4-10. Assumptions regarding landscape development suggest that the lake should fill with peat following the lake's isolation from the sea. However, the lake module in the RLDM fails to reproduce this assumption. Therefore, the missing peat was manually added for all time steps following the lakes isolation from the sea. This same procedure was also used for biosphere objects 121_1 (Figure 4-24) and 157_1 (Figure 4-16).

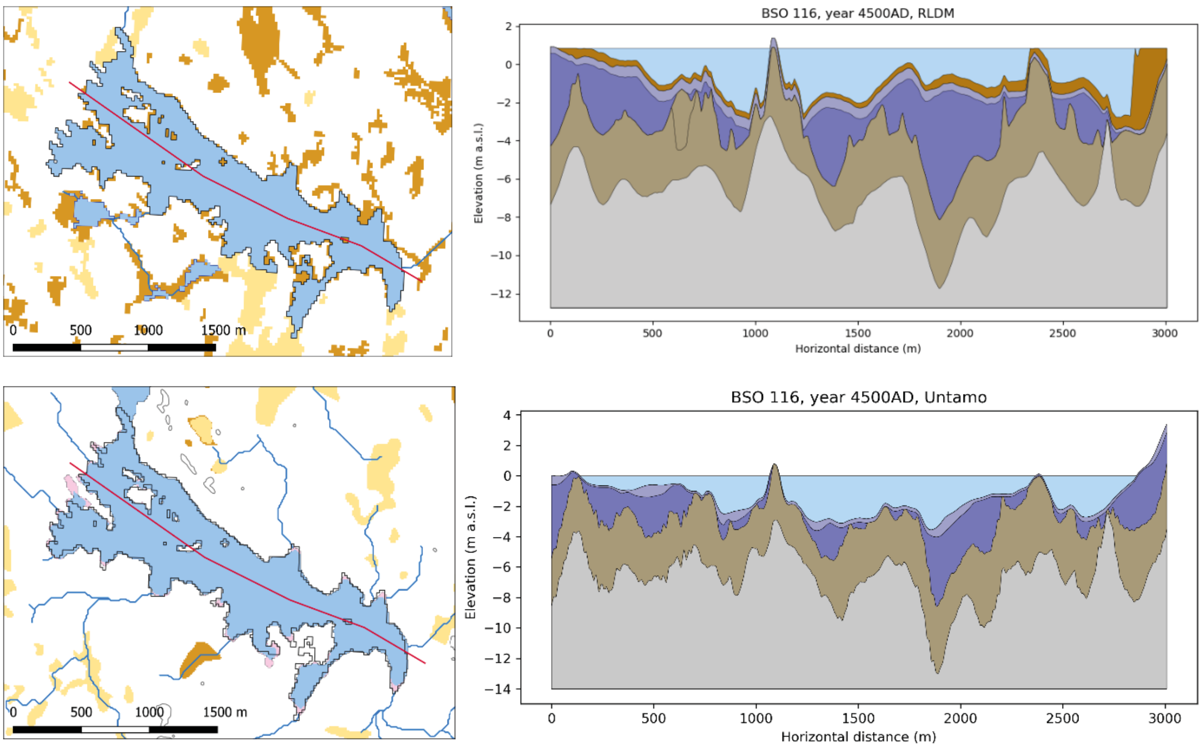

Figure 4-9. *BSO 116 in **year 4 500**: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

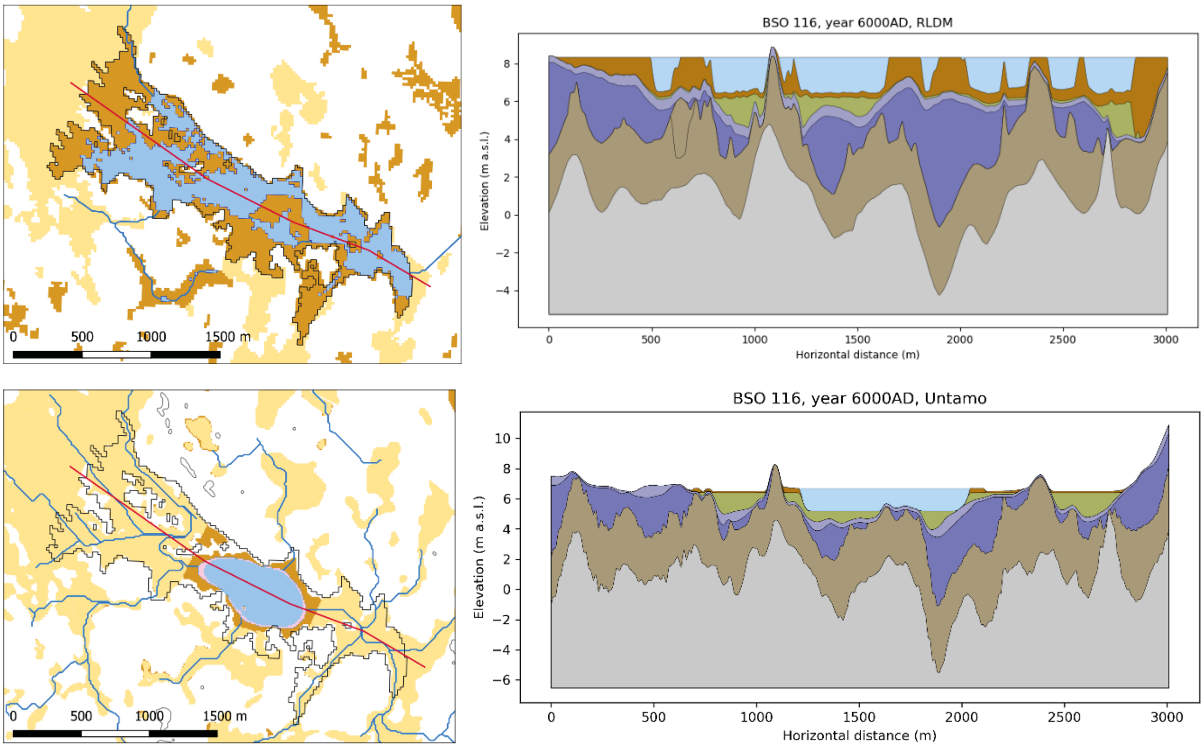

Figure 4-10. *BSO 116 in* ***year 6000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

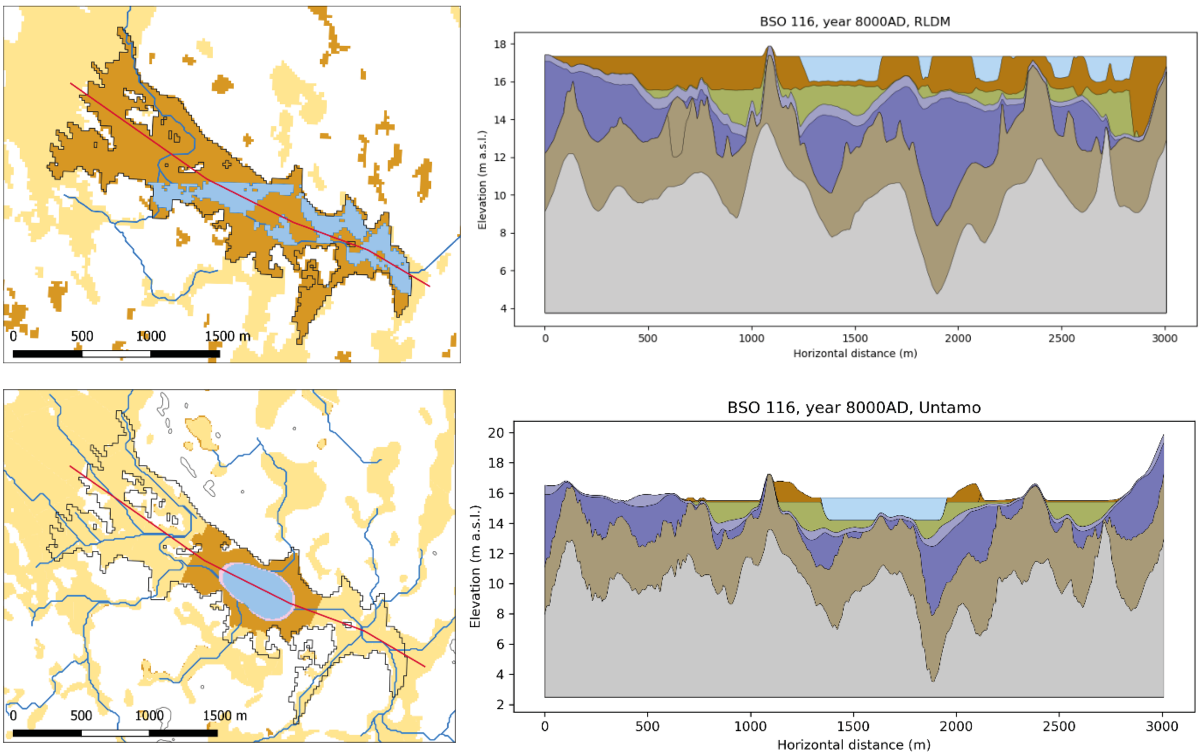

Figure 4-11. *BSO 116 in* ***year 8000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

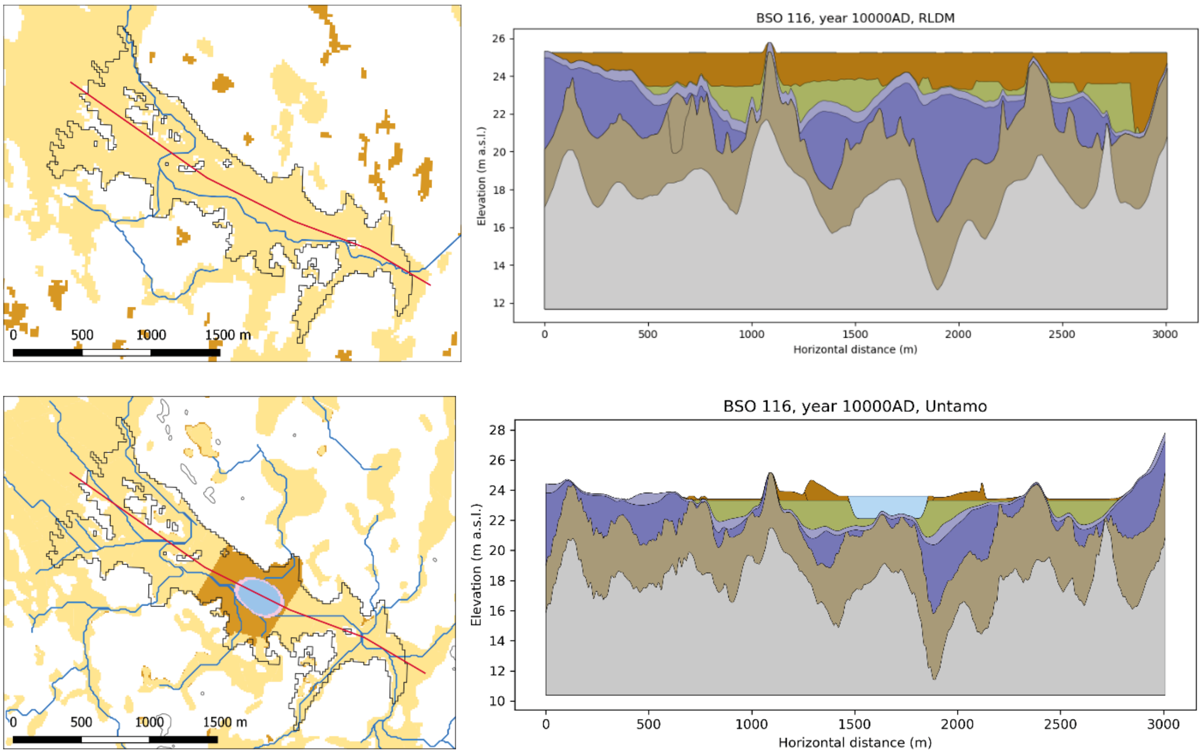

***Figure 4-12.** BSO 116 in **year 10 000**: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

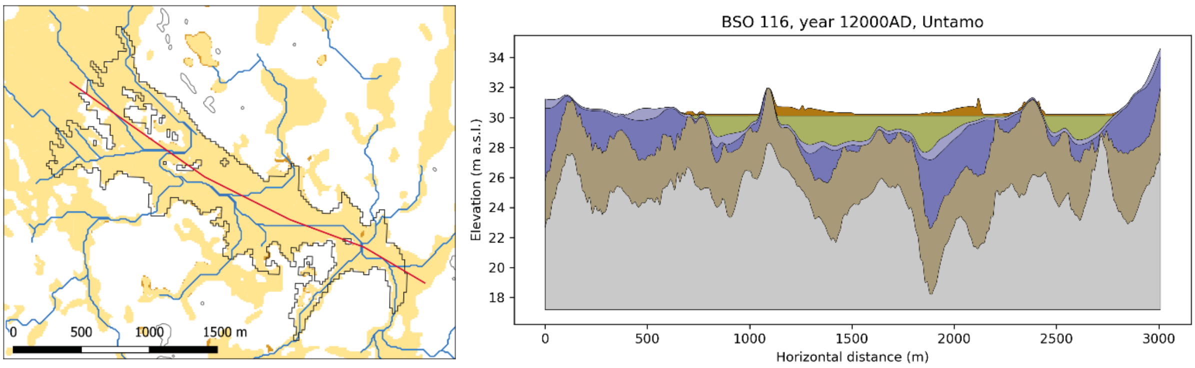

***Figure 4-13.** BSO 116 in **year 12 000**: Predicted development stage and regolith cross-section in Untamo. RLDM soil profile for this time step is identical to year 10 000, see previous figure.*

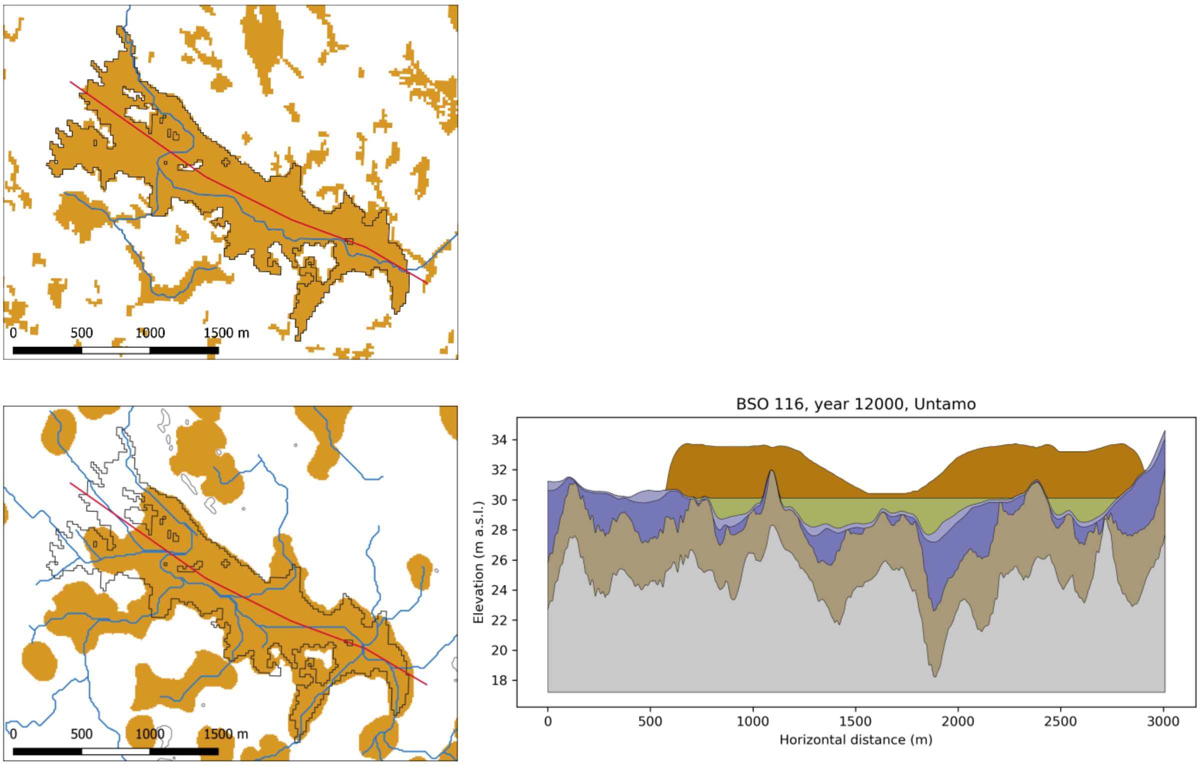

***Figure 4-14.** BSO 116 in **year 12 000,** scenario with **natural development** (no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 10 000, see Figure 4-12.*

Isolation and infilling of biosphere object 121_1

The shallow basin of biosphere object 121_1 gets isolated from the sea by year 3900 in the RLDM and forms a lake (Figure 4-16). In Untamo, however, it does not reach a lake stage and turns into land area between 3700 and 3800 as a result of terrain uplift. The object is drained by two joining streams, and due to channel erosion the object outlet is lower than the lake threshold. As a result, the mean water depth of the sink is below 0.8 m. Therefore, the object is classified as a land area in Untamo (Section 3.2.2). In the RLDM results the lake basin gets gradually overgrown by vegetation until it is fully infilled around year 6000 (Figure 4-17). The overgrown areas are considered as mire where peat is accumulated. In Untamo most of the basin is taken into agricultural use by year 4000 (Figure 4-16). Due to the missing lake stage, the topsoil consists mainly of marine post-glacial deposits (clay gyttja). After 4000 peat soil is forming in the Southern part of the basin but is soon drained for agriculture. In the RLDM, the mire gets converted into cropland by year 7000 when the lake is fully infilled. In the scenario of natural development, the basin remains a mire in both models, and in case of Untamo the peat reaches a thickness of nearly four meters by year 12 000 (Figure 4-18). There are clear differences in the shape of the developing mire between both models. In the RLDM, the mire extent is restricted to the lake basin and does not grow further. In Untamo the mires are of circular shape and grow wider.

The effects of the different accumulation methods used in the respective models are visible in the profile graphs. RLDM shows a constant layer of clay gyttja and Untamo has deposited the sediment mainly into deep depressions.

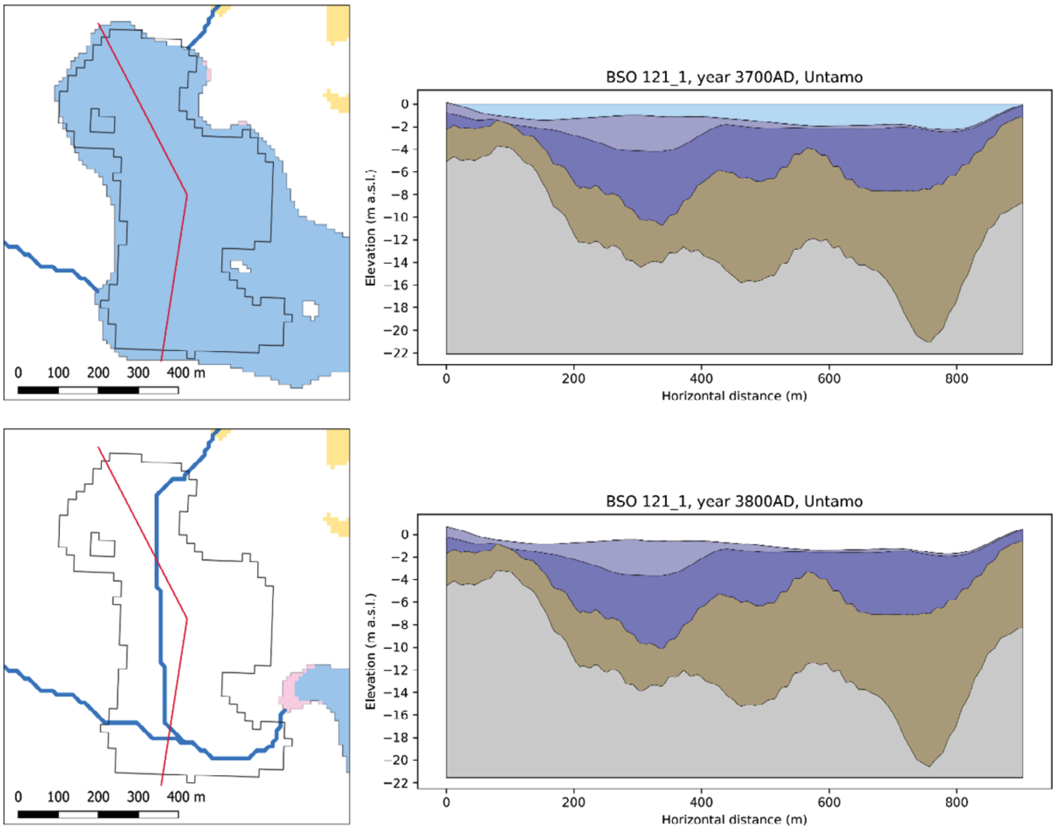

***Figure 4-15.** BSO 121_1 in **year 3700** (top) and **year 3800** (bottom): Predicted development stage and regolith cross-section in Untamo. No results available for RLDM.*

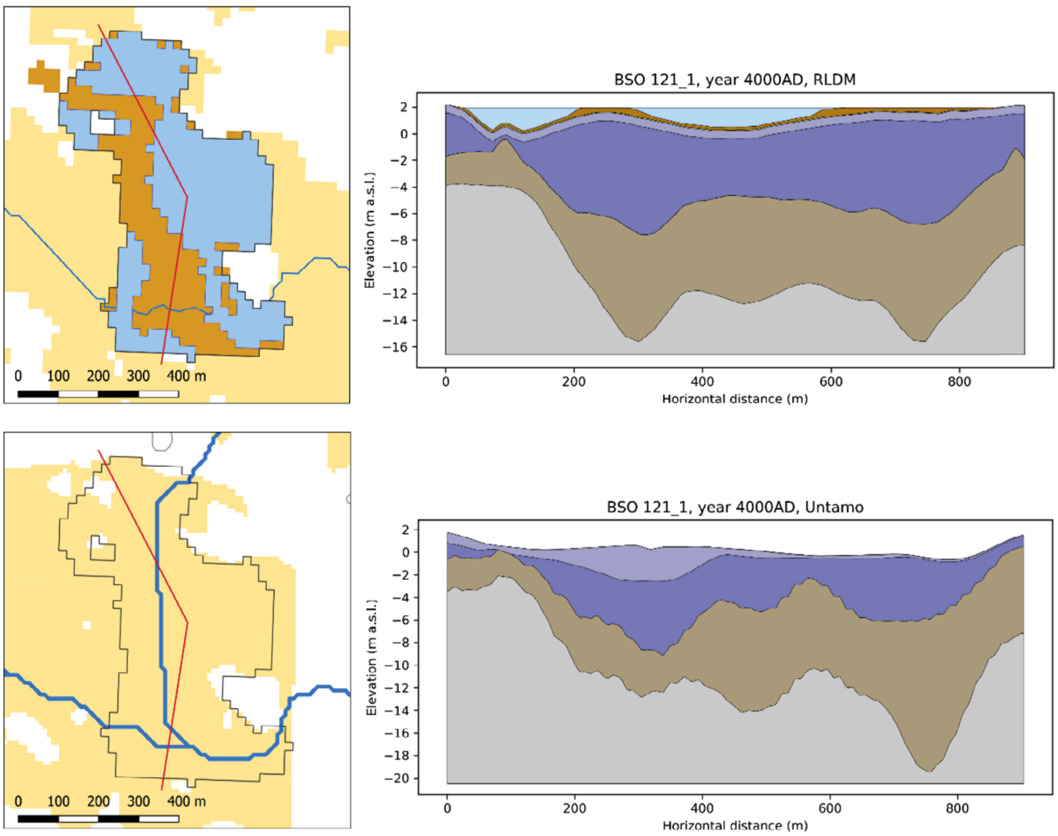

***Figure 4-16.** BSO 121_1 in **year 4000**: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

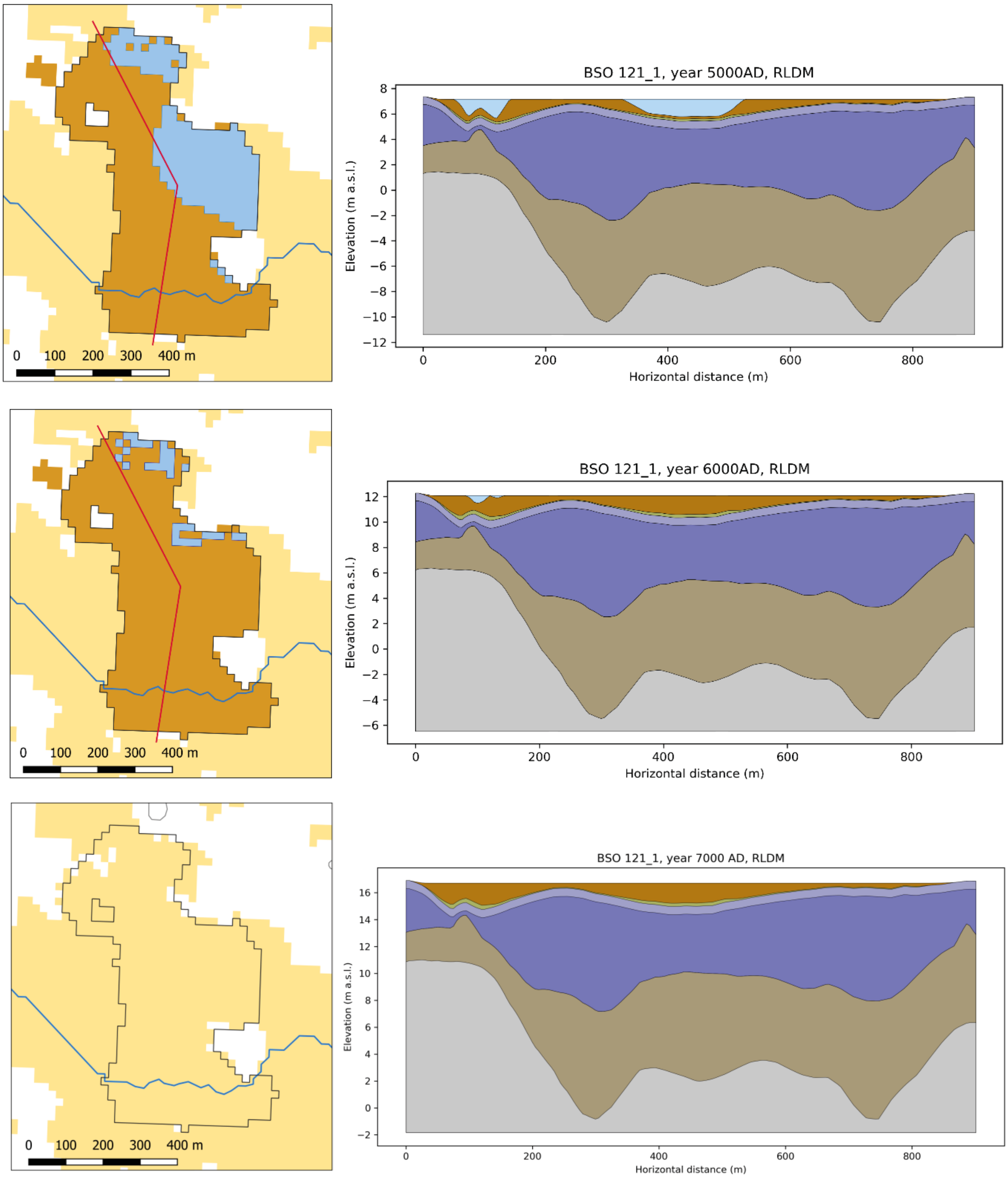

Figure 4-17. *BSO 121_1 in* ***year 5000*** *(top),* ***year 6000*** *(centre) and* ***year 7000*** *(bottom): Predicted development stage and regolith cross-section in the RLDM. Untamo results for these time steps are almost identical to year 4000, see previous figure.*

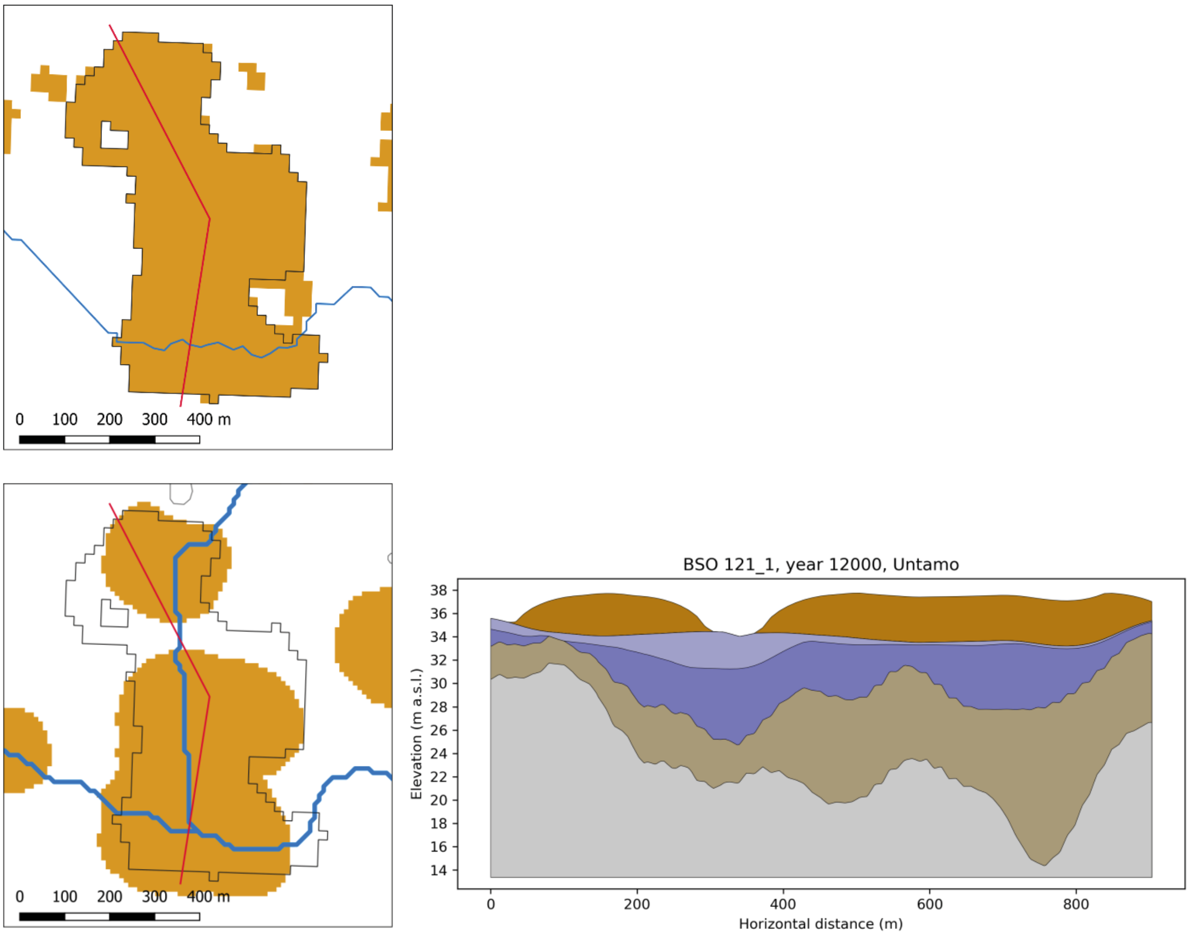

***Figure 4-18.** BSO 121_1 in **year 12 000,** scenario with **natural development** (no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 7000, see previous figure.*

Emergence of biosphere object 121_2

Biosphere object 121_2 does not reach a lake stage in neither the RLDM nor in the Untamo model. It stays connected to the sea until about year 3500 when the water has retreated due to land uplift (Figure 4-19, Figure 4-20). In the RLDM, the basin bottom shows deposits of clay gyttja, which are only partly present in the Untamo result. In both models some smaller mires are developing. In the RLDM they appear already in year 3 500, while in Untamo peat starts forming only around year 4500 in the Northern part of the object. The Southern part of the basin which has a sufficiently deep clay soil is taken into agricultural use in both models by year 4000. The scenario of natural development shows that in case of Untamo more than half of the basin has turned into a peatland with a thickness of about three meters (Figure 4-21). Similar to the biosphere objects described before, also for object 121_2 a circular shape of the developing mires is noticeable in the Untamo result.

The stream(s) crossing the object in the southern part follow a different route in the two models. This is caused by differences in the surface of the clay gyttja layer. In the RLDM, a constant layer of clay gyttja has accumulated since 8 500 BC which has resulted in a flat surface in the South of the object. Corresponding results from Untamo predict, a slightly undulating clay gyttja surface. The difference in modelled topography between the two models has an impact on the predicted flow routing.

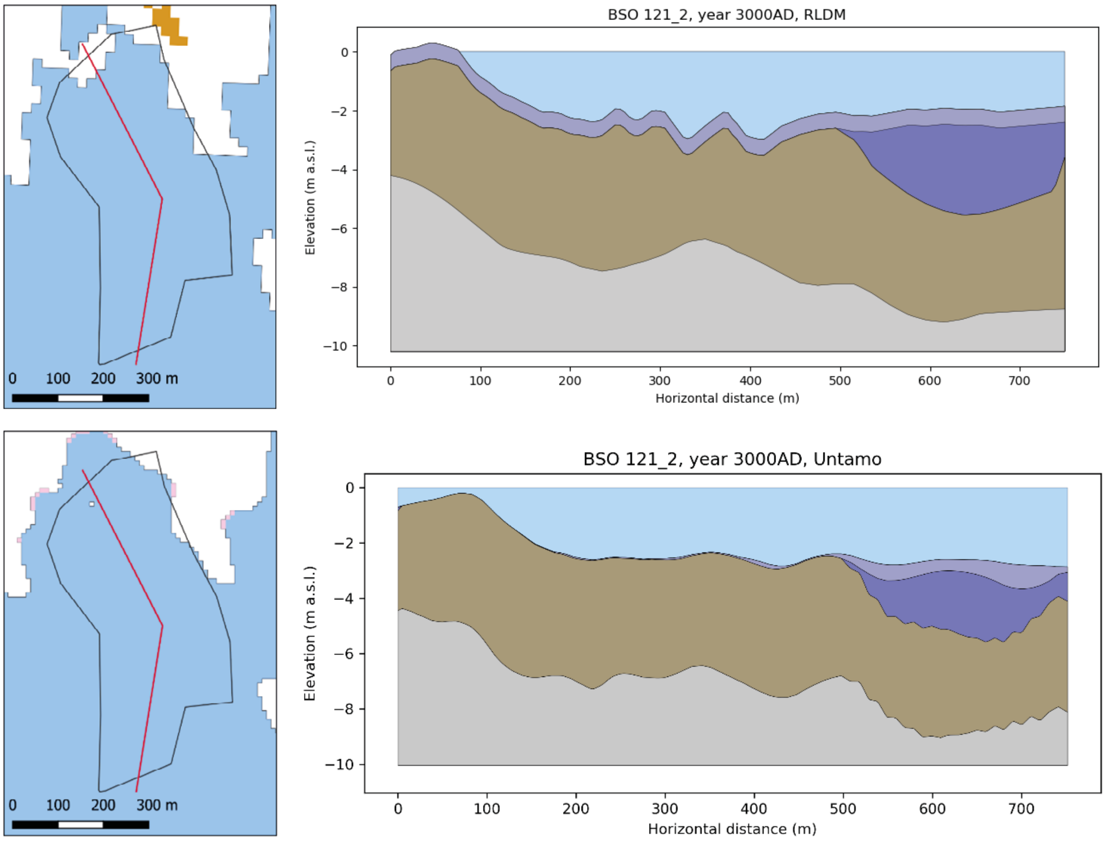

Figure 4-19. *BSO 121_2 in* ***year 3000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

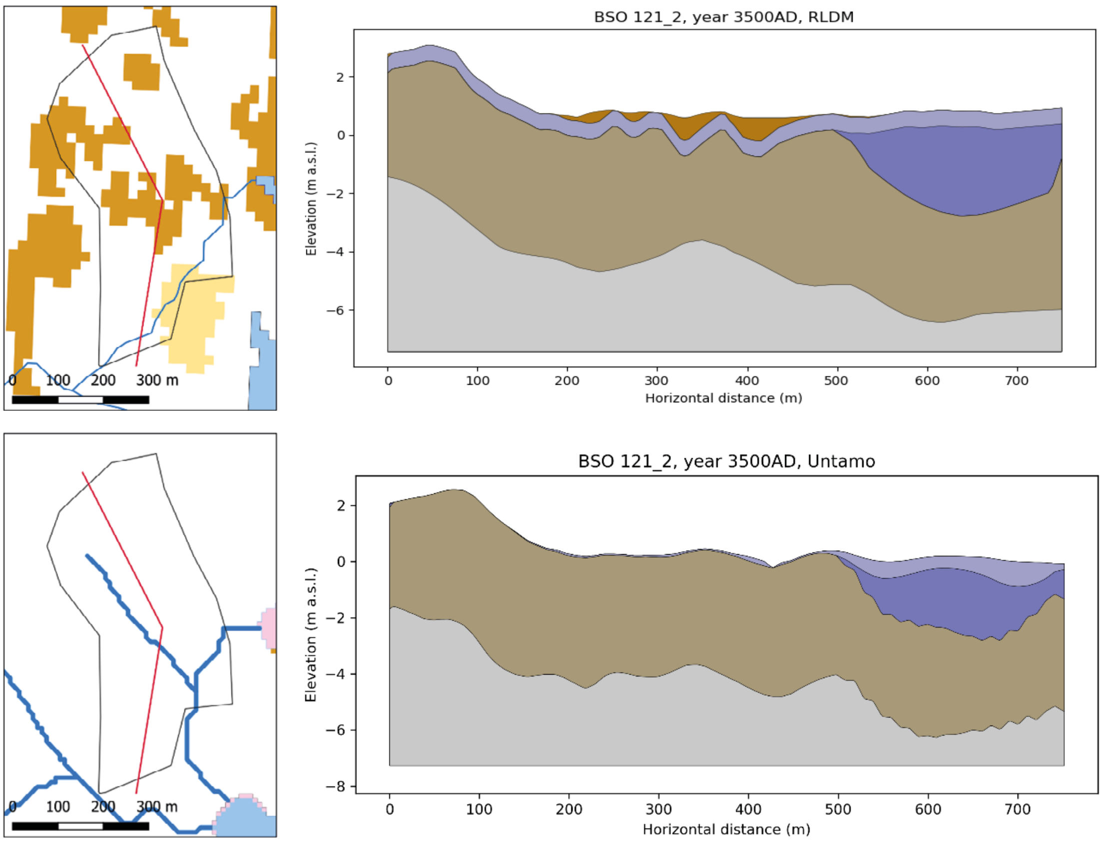

Figure 4-20. *BSO 121_2 in* ***year 3500****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

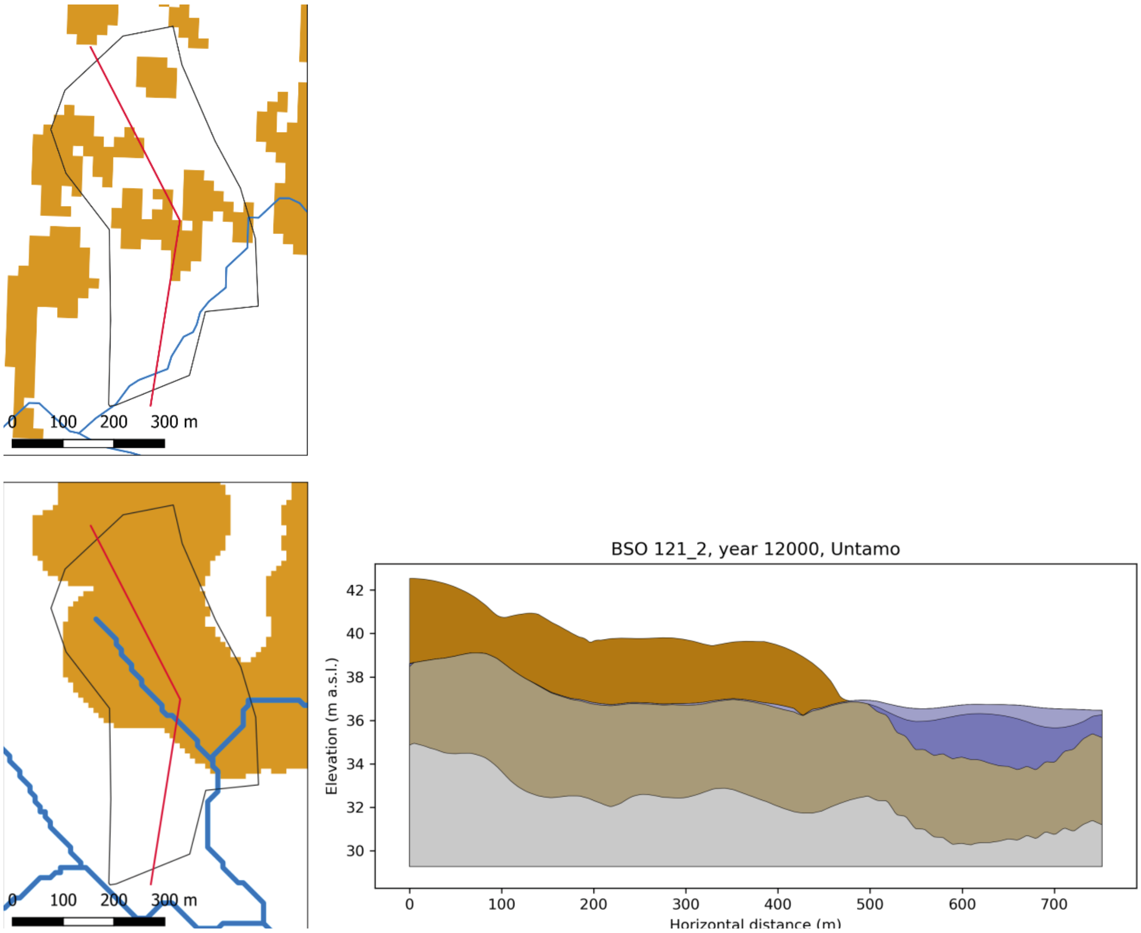

Figure 4-21. *BSO 121_2 in* ***year 12 000,*** *scenario with* ***natural development*** *(no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 3500, see previous figure.*

Isolation and infilling of biosphere object 157_1

Basin object 157_1 gets isolated as a lake around year 4400 in the RLDM model and is overgrown by vegetation until it is fully infilled with peat. In Untamo, the object does not form a lake but changes within 100 years from a sheltered coastal zone straight to terrestrial conditions (Figure 4-22). This is due to differences in how sedimentation dynamics are considered between the two models. In the RLDM the basin still has several open water areas in 5 000 (Figure 4-24). By year 5700 the basin gets completely infilled (Brydsten and Strömgren 2013). The accumulated sediment consists of gyttja and a thick layer of peat (Figure 4-24, Figure 4-25). In Untamo, peat soil starts forming around year 5000. In both models the entire basin is turned into a cropland, resulting in the compaction of the peat layer (see Figure 4-24 for Untamo and Figure 4-25 for RLDM). In the scenario of natural development, the peat layer reaches a thickness of about three meters by year 12 000 in Untamo (Figure 4-26) while it remains at about 1.5 m thickness on average in case of RLDM (Appendix 2).

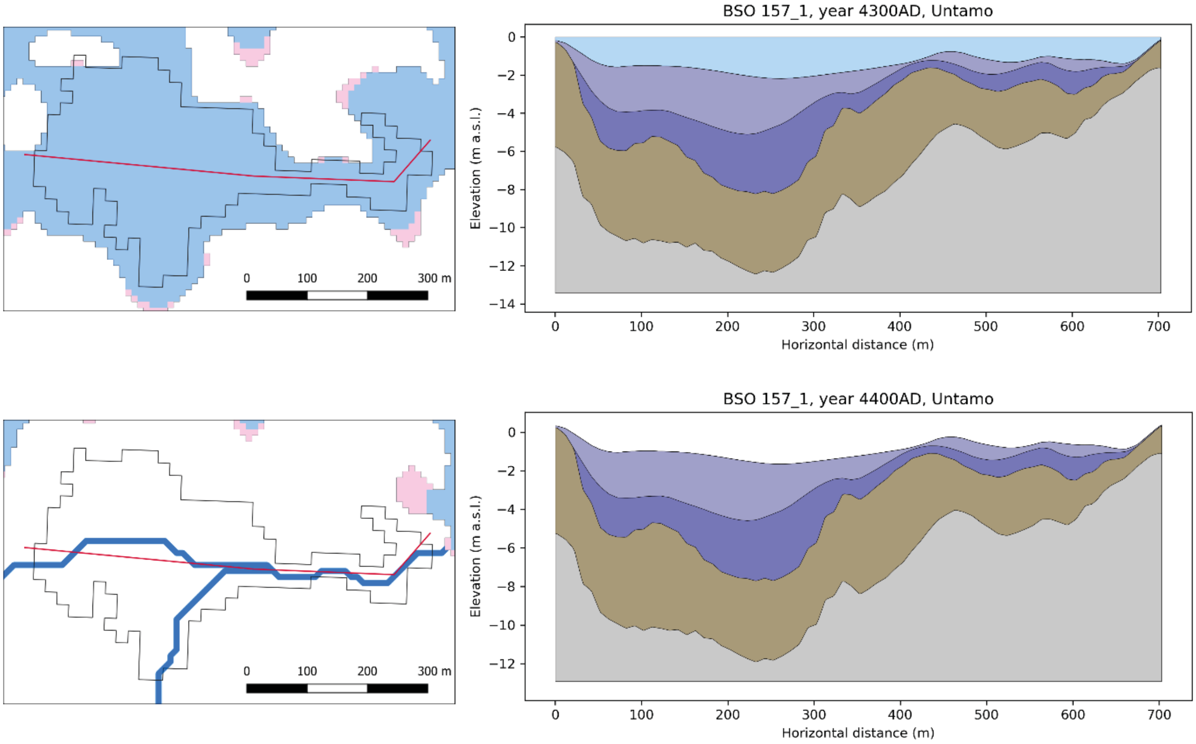

Figure 4-22. *BSO 157_1 in* ***year 4300*** *(top) and* ***year 4400*** *(bottom): Predicted development stage and regolith cross-section in Untamo. No results available for RLDM.*

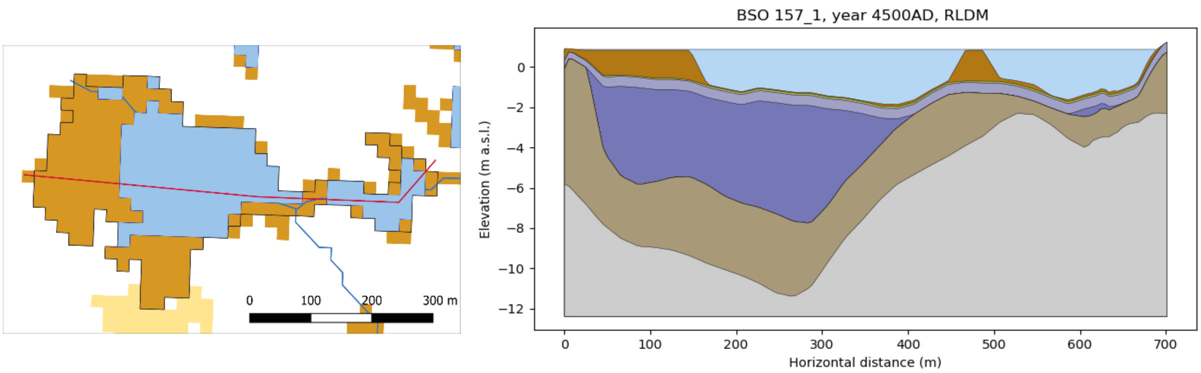

Figure 4-23. *BSO 157_1 in* ***year 4500****: Predicted development stage and regolith cross-section in the RLDM. Untamo result for this time step looks identical to year 4400 (see previous figure).*

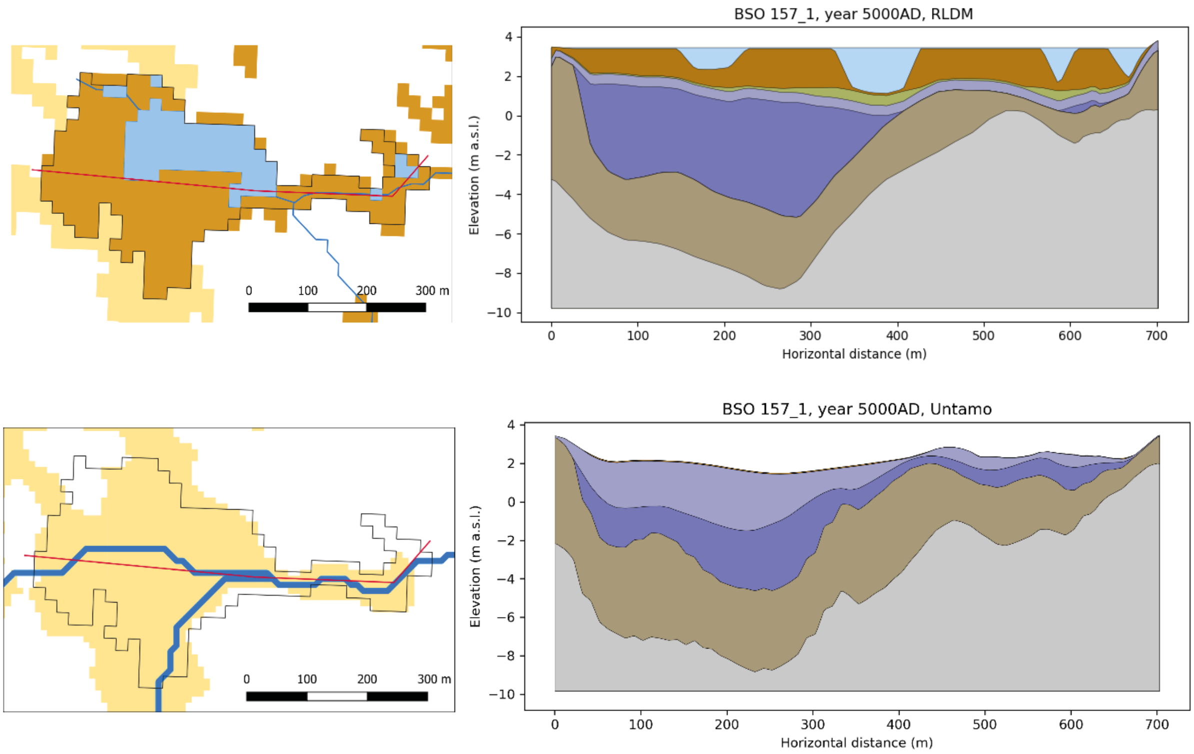

Figure 4-24. *BSO 157_1 in* ***year 5000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

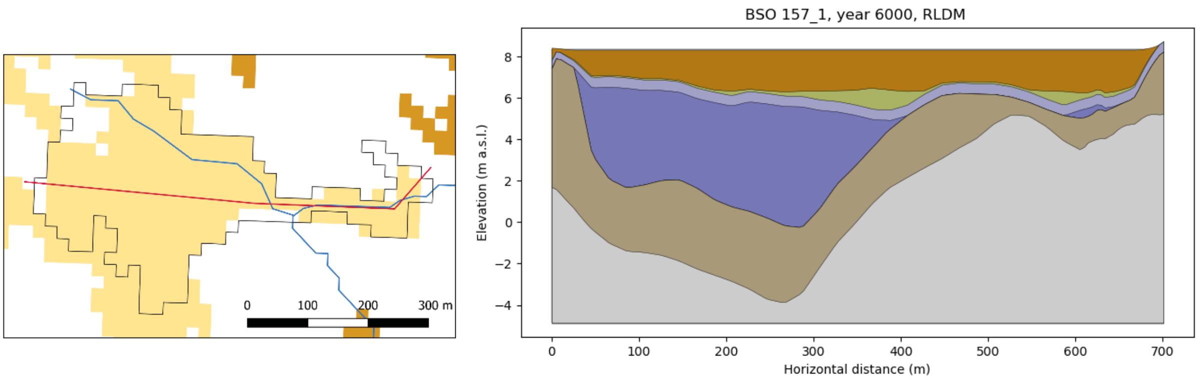

Figure 4-25. *BSO 157_1 in* ***year 6000****: Predicted development stage and regolith cross-section in the RLDM. Untamo result for this time step is identical to year 5000, see previous figure.*

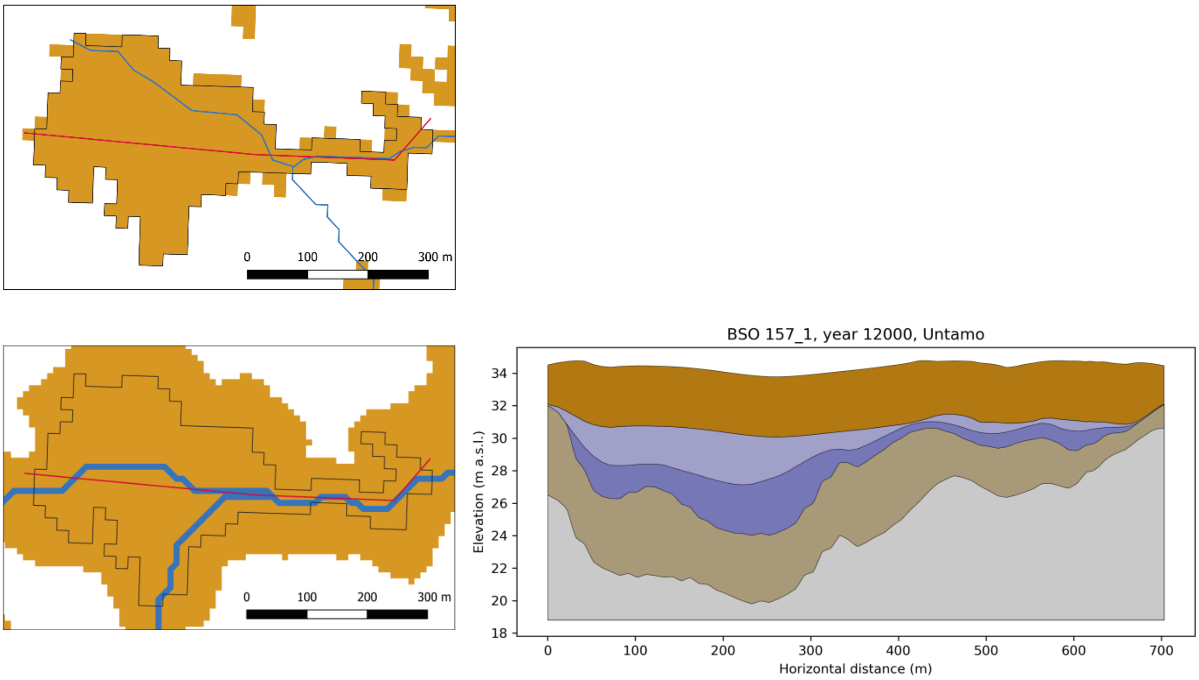

Figure 4-26. *BSO 157_1 in* ***year 12 000,*** *scenario with* ***natural development*** *(no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 6000, see previous figure.*

Emergence of biosphere object 157_2

In both model results biosphere object 157_2 does not get isolated as a lake but remains part of the sea until the water retreats due to land uplift. The regolith stratigraphy of the object shows differences in the profiles of bedrock and till between both models, which are non-modelled features. In both models the object is still fully below sea level in year 3000 (Figure 4-27) and then it gradually emerges from the sea (Figure 4-28, Figure 4-29). This process is slightly faster in Untamo since the regolith thickness above the bedrock is larger there, resulting in a lower water depth. Small mires are forming in the western and southern part of the object in the RLDM which do not appear in Untamo. The RLDM results however do show a terrain depression in the northern part which is not seen in the Untamo results. In Untamo this area is too flat to allow peat development. At the location of the two southern mires, Untamo identified streams within the object. Stream channel erosion has been applied over the entire stream network (Section 2.3), thereby creating outlets for the shallow hydrological depressions. This has prevented the formation of a mire in object 157_2 in Untamo. Parts of the object are in agricultural use in both models (Figure 4-30). In the scenario of natural development in Untamo, two larger mires are forming outside the biosphere object (Figure 4-31) which will extend into the object area in the long-term future.

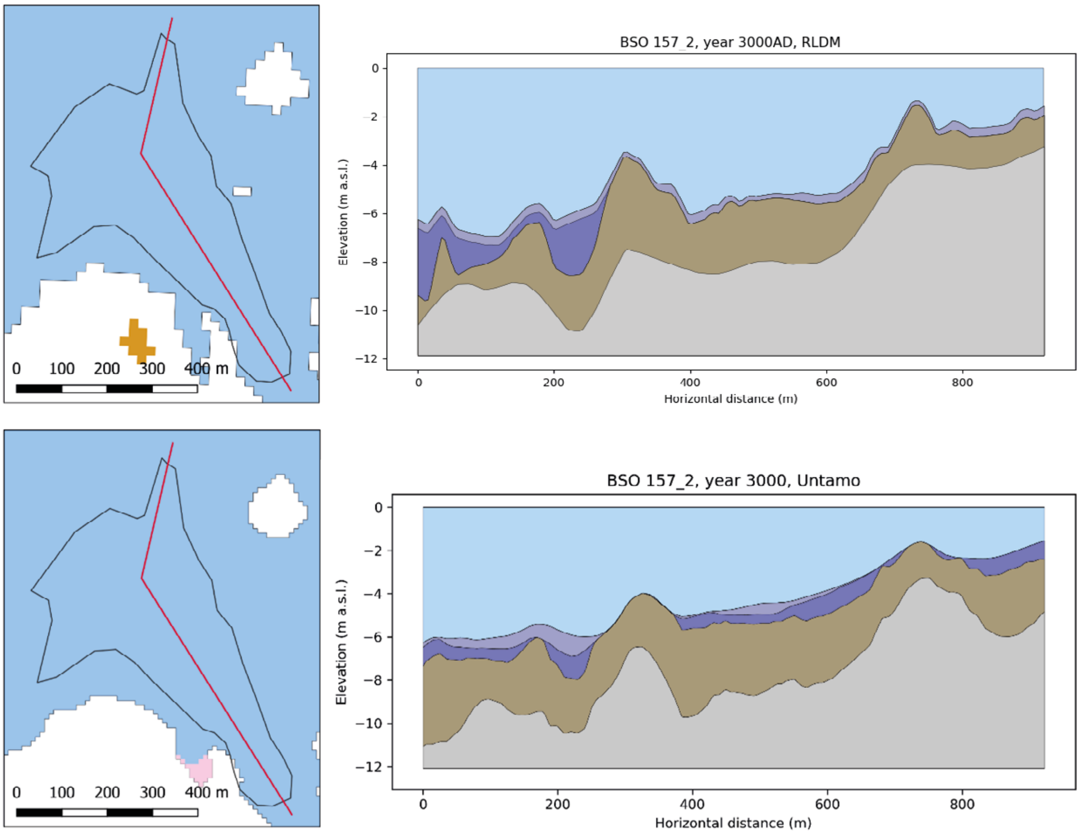

Figure 4-27. *BSO 157_2 in **year 3000**: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

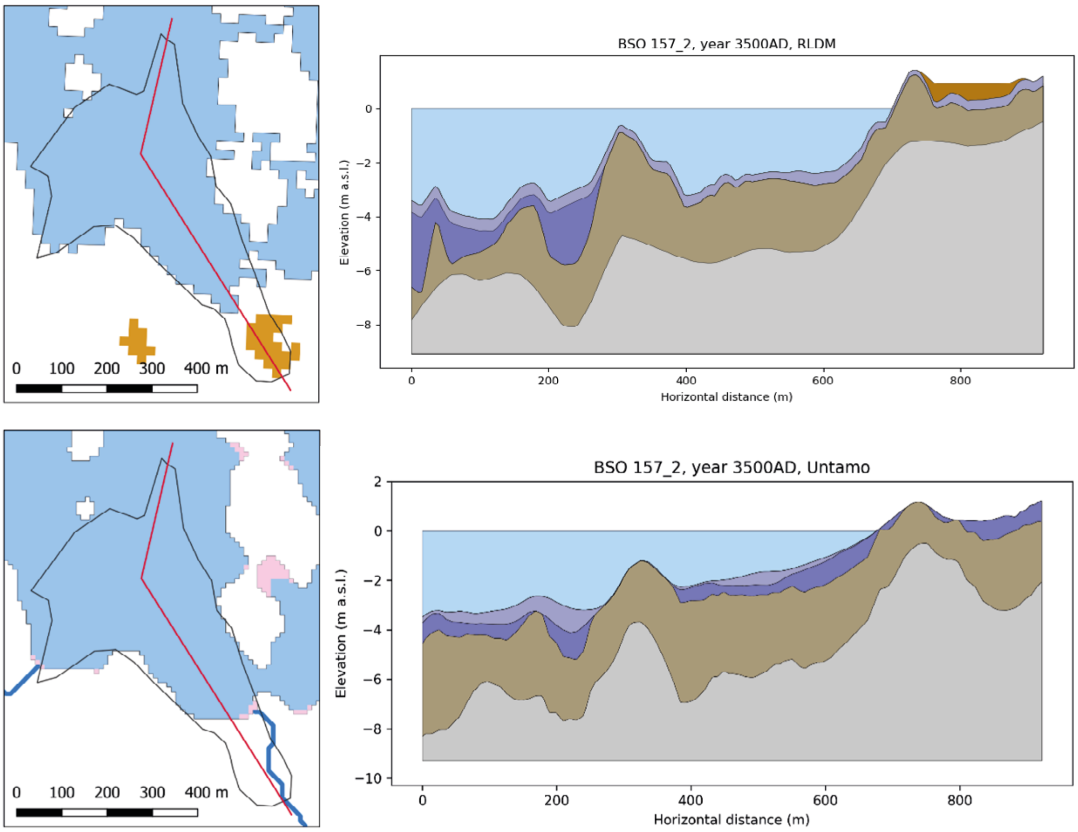

Figure 4-28. *BSO 157_2 in **year 3500**: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

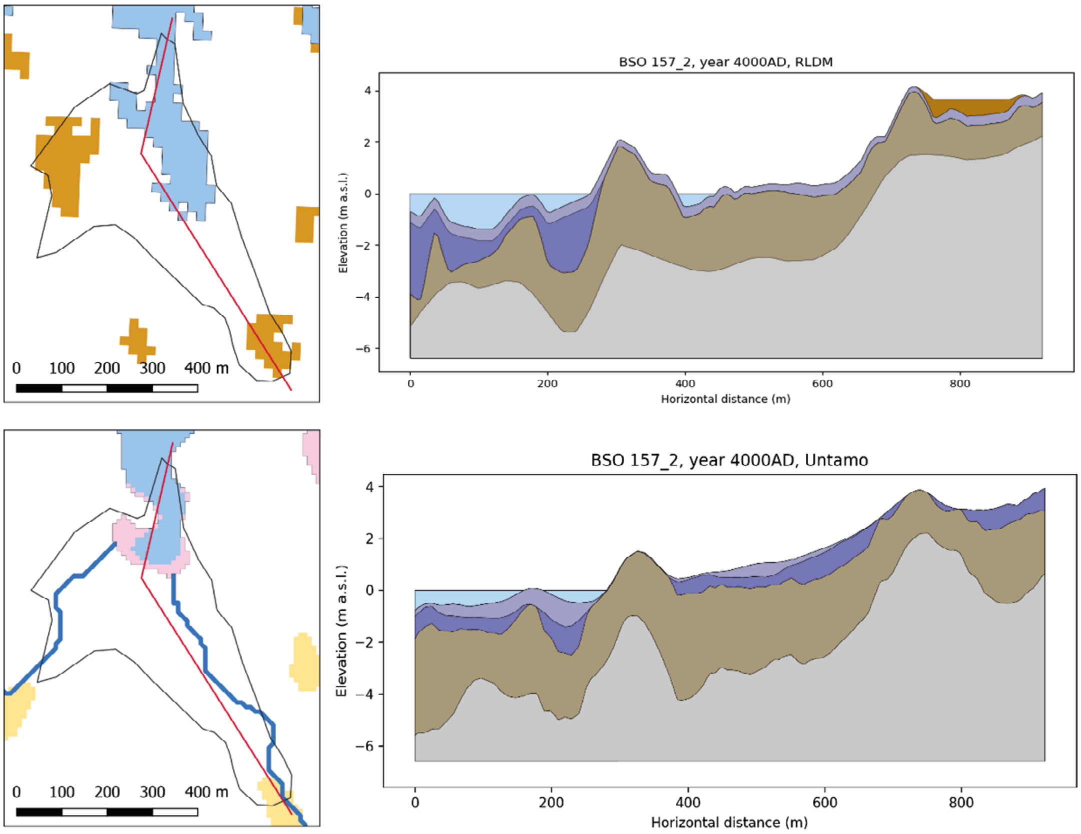

__Figure 4-29.__ BSO 157_2 in __year 4000__: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.

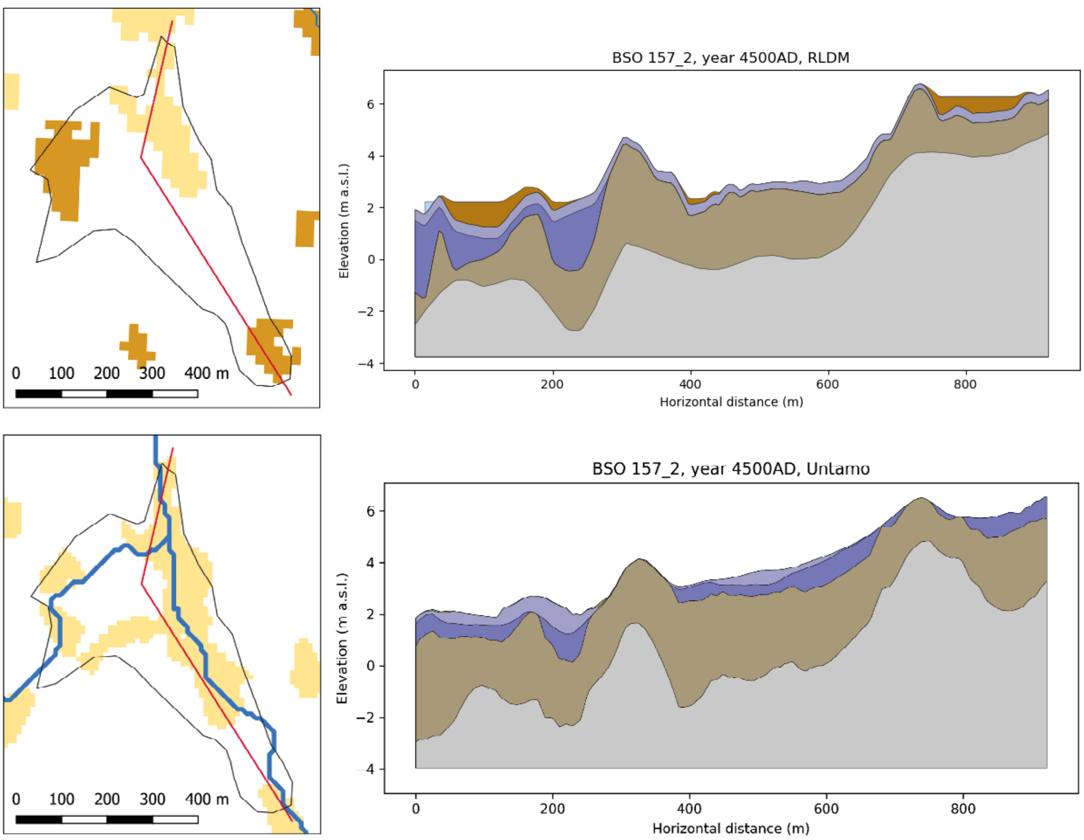

__Figure 4-30.__ BSO 157_2 in __year 4500__: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.

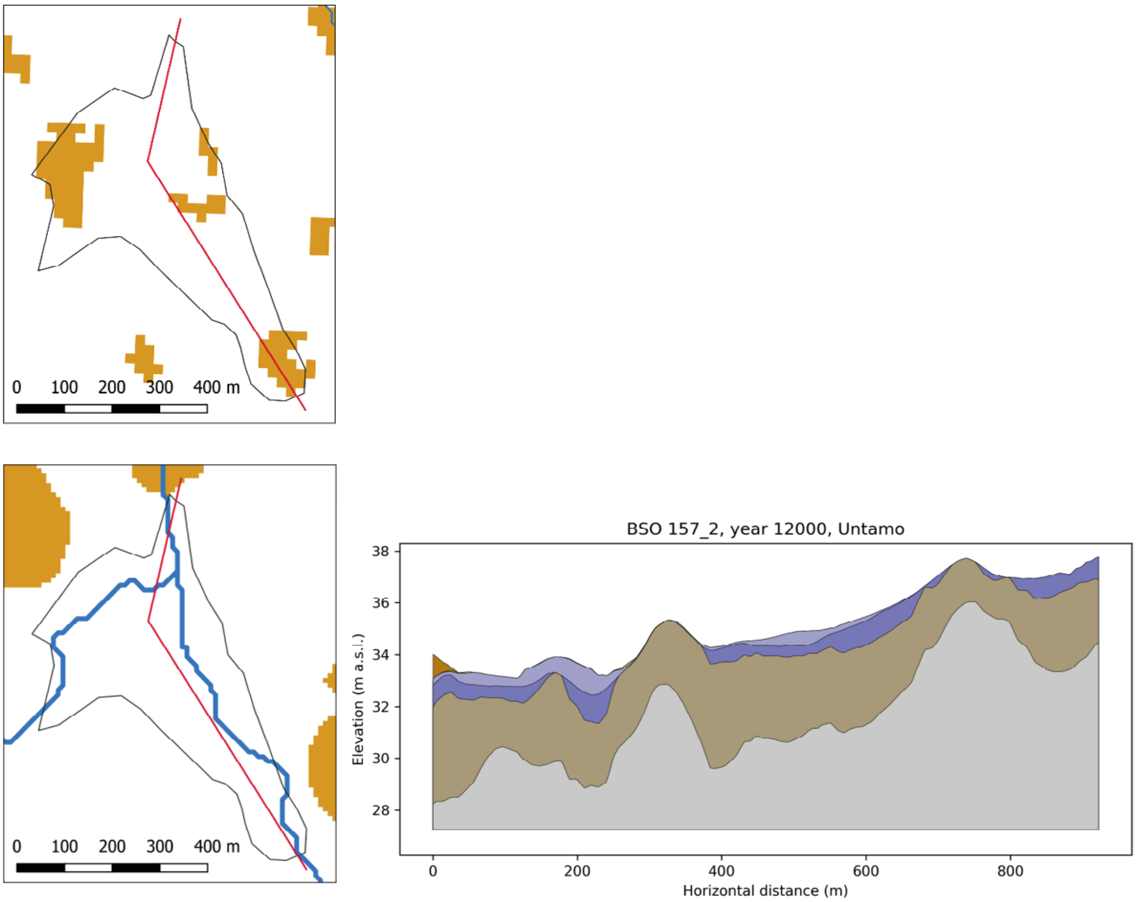

Figure 4-31. *BSO 157_2 in* ***year 12 000,*** *scenario with* ***natural development*** *(no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 4500, see previous figure.*

Isolation and infilling of biosphere object 159

The long and narrow biosphere object 159 is still connected to the sea in year 4000 and isolates as a lake by 4100 in both models (Figure 4-32, Figure 4-33). In Untamo, the north-western end of the biosphere object is overgrown by reed and a thin layer of gyttja accumulates. The lake evolves only in the eastern part of the basin while the north-western/central part of the object is drained by the connecting stream (Figure 4-33). This is also related to the fact that Untamo has applied channel erosion in this simulation which has lowered the threshold at the lake outlet and therefore the water level, so that the north-western/central part of the basin does not fulfil the criteria applied during lake delineation. Soon after isolation only a small open-water zone is left in the East and most of the remaining lake is covered by reedbeds (Figure 4-33). By 4500 the lake is fully infilled with gyttja and peat soil is forming at the surface (Figure 4-34). Thereafter it is turned into cropland for agricultural use (Figure 4-35). In the RLDM the centre part of the object is deeper than predicted by Untamo (Figure 4-32). In the RLDM, lakes are forming in both parts of the object. In 4500 the two lakes still cover a significant part of the basin, with a shallow part in the East and a small but deep part in the centre of the object (Figure 4-34). The remaining areas have filled up with gyttja and peat. In year 6000, a small part of the lake remains in the RLDM until around 7500 after which most of the area is turned into cropland (Figure 4-35, Figure 4-36). The accumulated peat layer is thicker in the RLDM result, while the Untamo model deposits mainly gyttja during the lake stage.

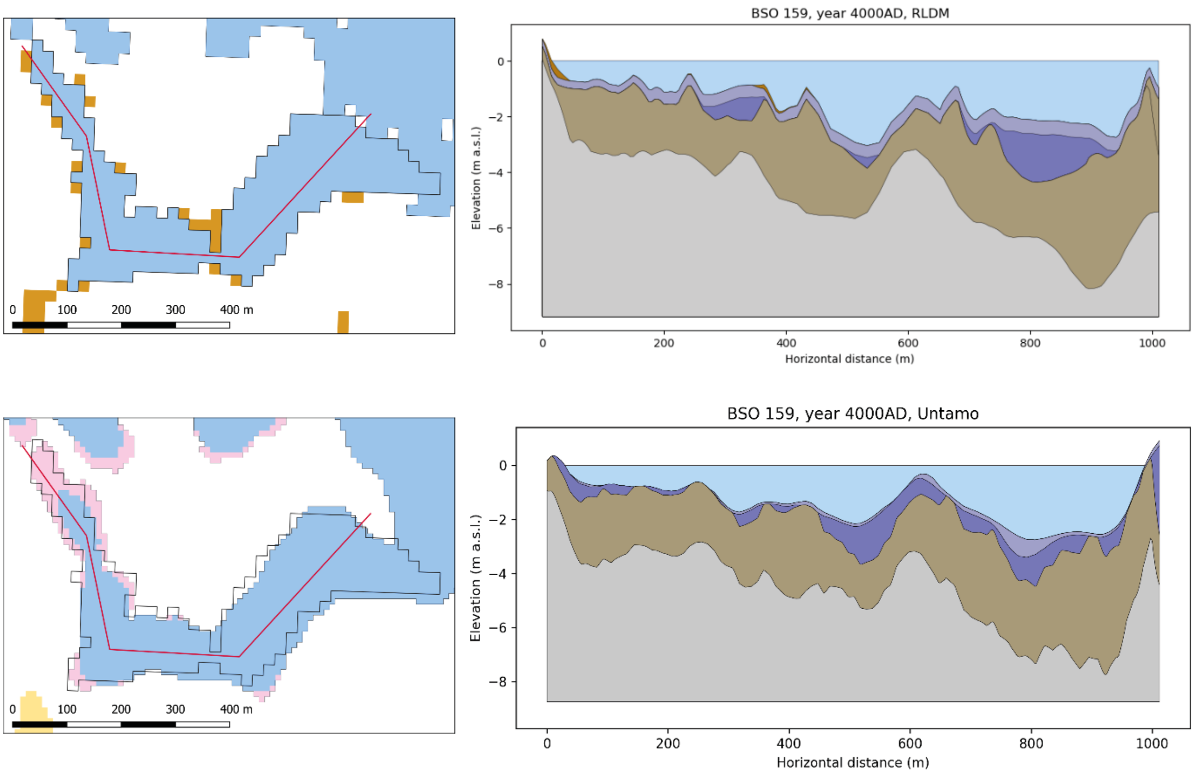

Figure 4-32. *BSO 159 in **year 4000**: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

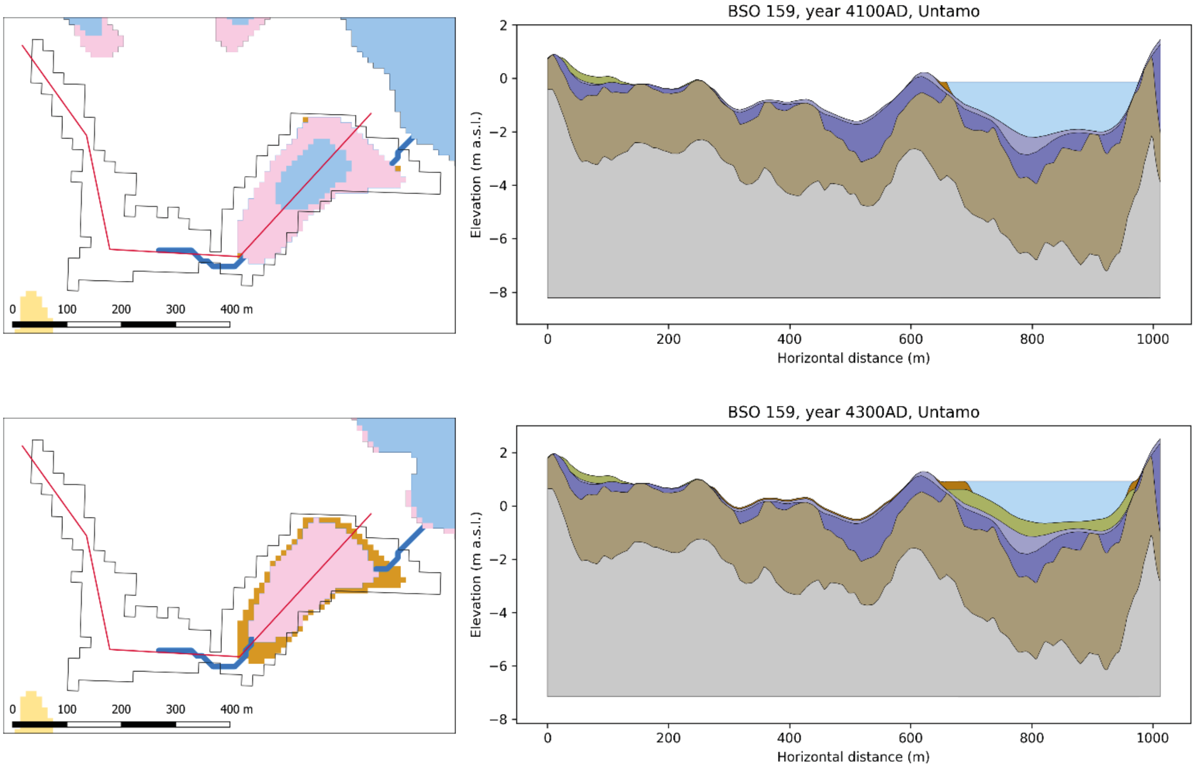

Figure 4-33. *BSO 159 in* ***year 4100*** *(top) and* ***year 4300*** *(bottom): Predicted development stage and regolith cross-section in Untamo. No results available for RLDM.*

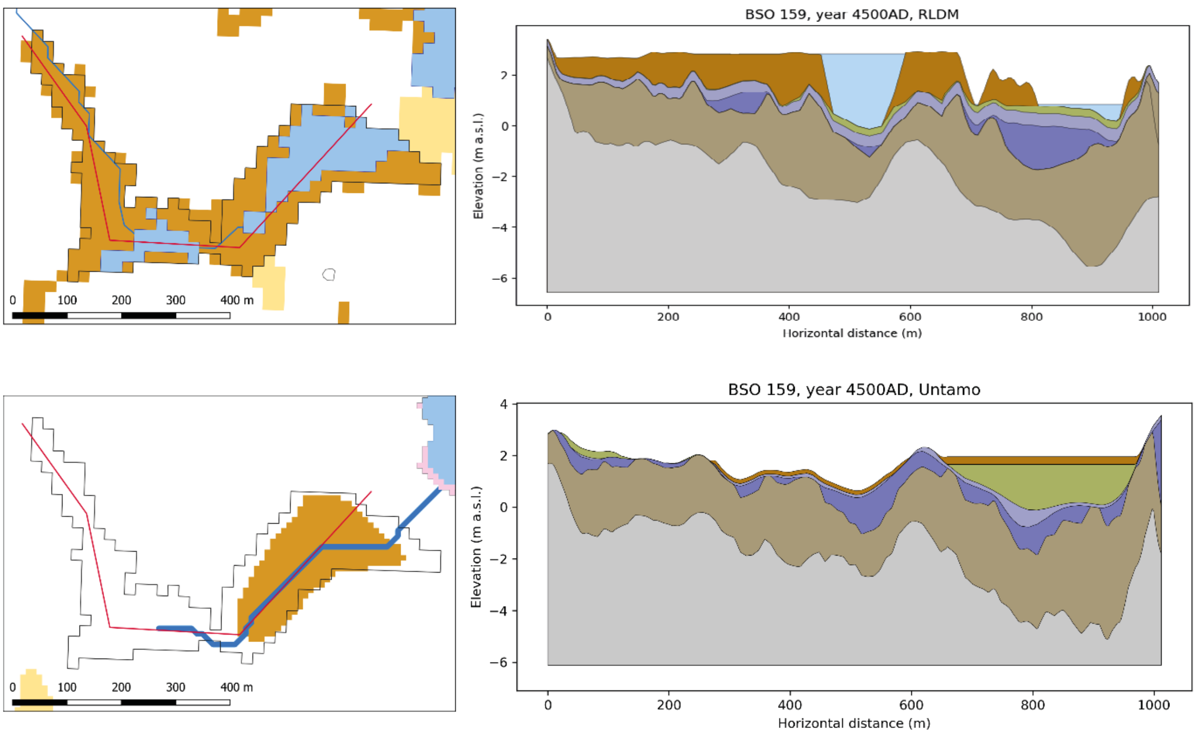

Figure 4-34. *BSO 159 in* ***year 4500****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

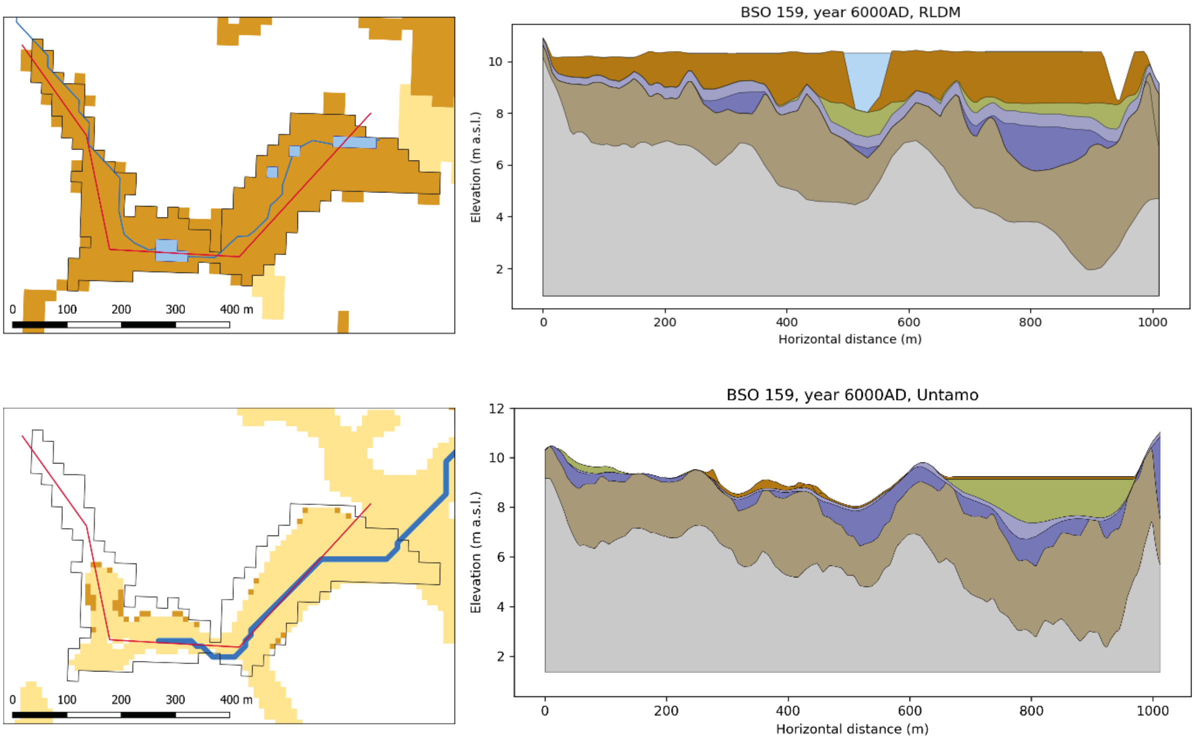

Figure 4-35. *BSO 159 in* ***year 6000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

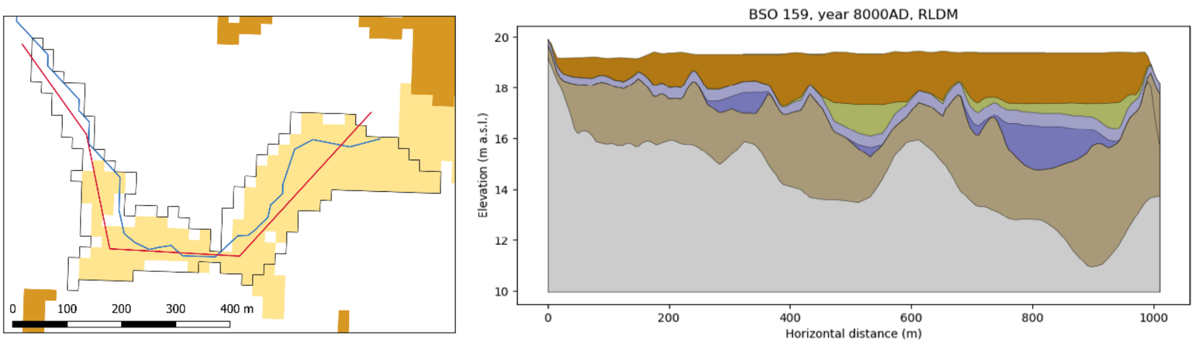

Figure 4-36. *BSO 159 in* ***year 8000****: Predicted development stage and regolith cross-section in the RLDM. Untamo result for this time step is identical to year 6000, see previous figure.*

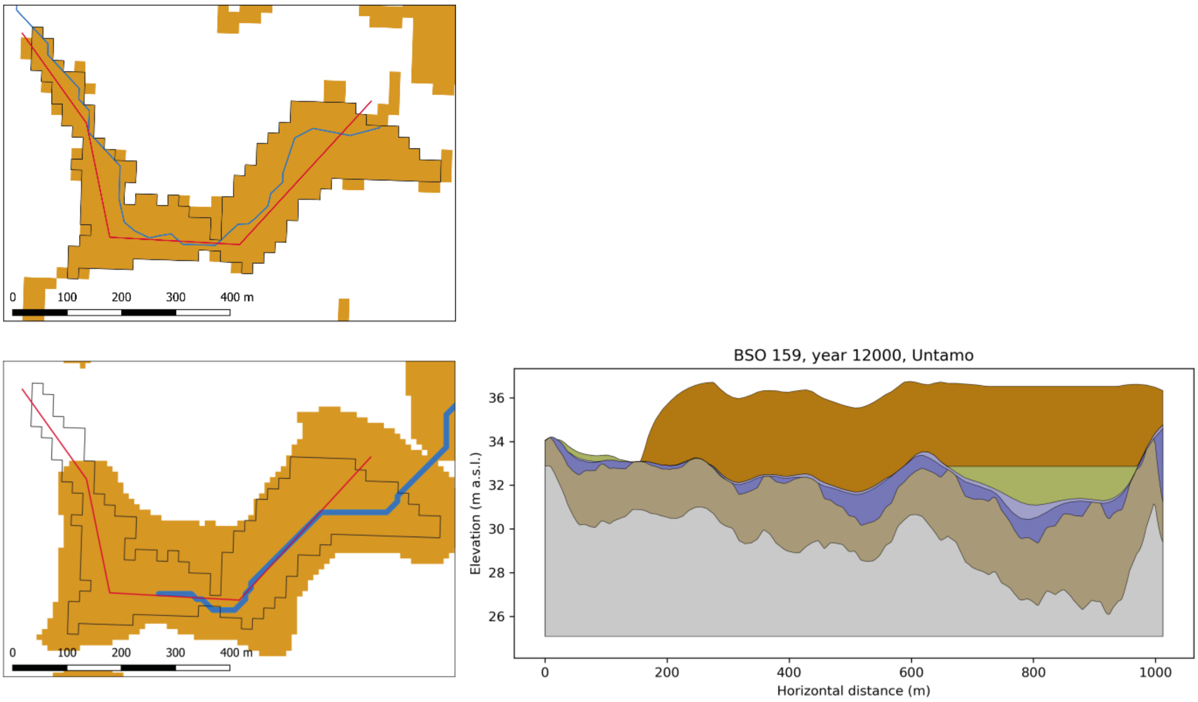

***Figure 4-37.** BSO 159 in **year 12 000,** scenario with **natural development** (no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 8000, see previous figure.*

Isolation and infilling of biosphere object 160

The lake stage of biosphere object 160 starts around 3500 in Untamo and later in the RLDM (Figure 4-38). The lake bottom is smoother and shallower in Untamo with a thick layer of post-glacial deposits. The principle of sediment distribution used in Untamo results in a smoother surface of the sea bottom (see Section 2.5.1.2), while the accumulation of a clay gyttja layer with constant thickness in the RLDM preserves the initial rugged terrain of the glacial deposits. Hence the profile of the RLDM result shows more variation in the basin depth, resulting in a more fragmented lake surface whereas in Untamo the lake has a very compact shape (Figure 4-38). In both models, mires are developing around the boundary of the basin and gyttja accumulates in the lake areas (Figure 4-39). By 4500, the lake is already very shallow in both model results (Figure 4-40). In case of Untamo, the basin is completely infilled with gyttja and covered by a peat layer in year 5000 (Figure 4-41). Due to agricultural usage, the peat is compacted. In the RLDM the central part of the original lake is still relatively large in year 5000, and the terrestrialization process continues until the basin is completely infilled and turned into a cropland around year 9000 (Figure 4-42). In the scenario of natural development, the basin is covered by peatland in both models, reaching a thickness of up to two and up to four meters in the RLDM and Untamo model, respectively, by year 12 000 (Figure 4-43).

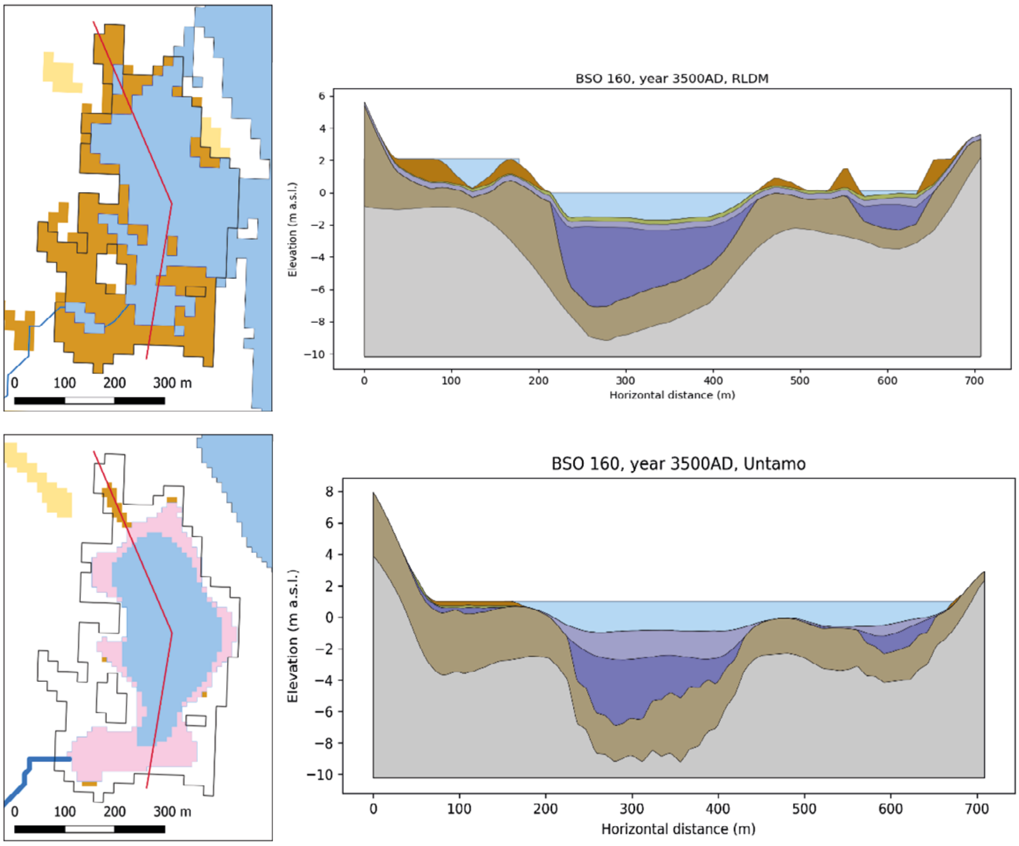

Figure 4-38. *BSO 160 in* ***year 3500****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

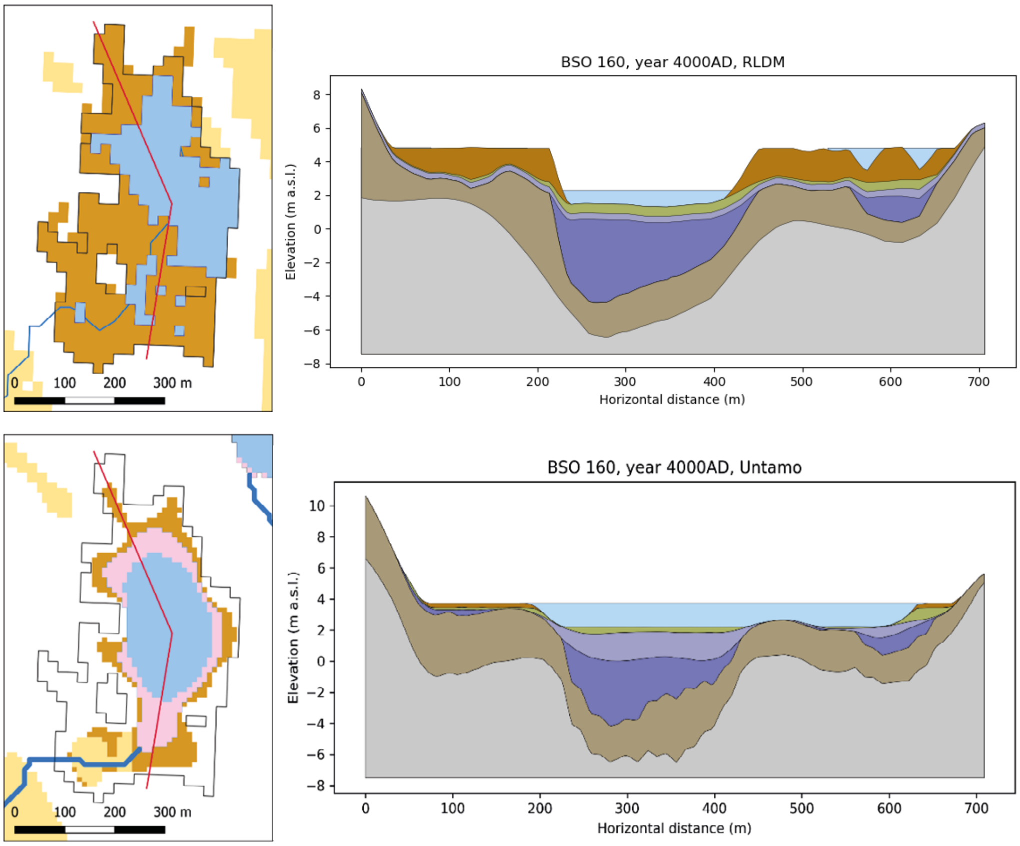

Figure 4-39. *BSO 160 in* ***year 4000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

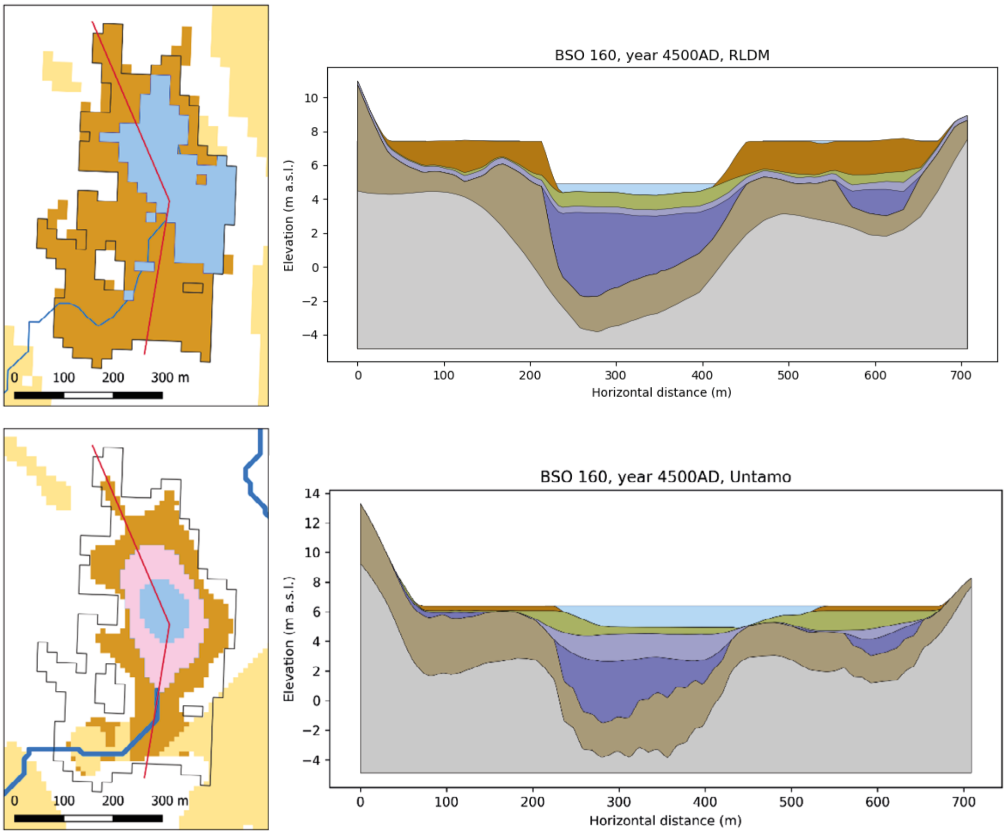

Figure 4-40. *BSO 160 in* ***year 4500****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

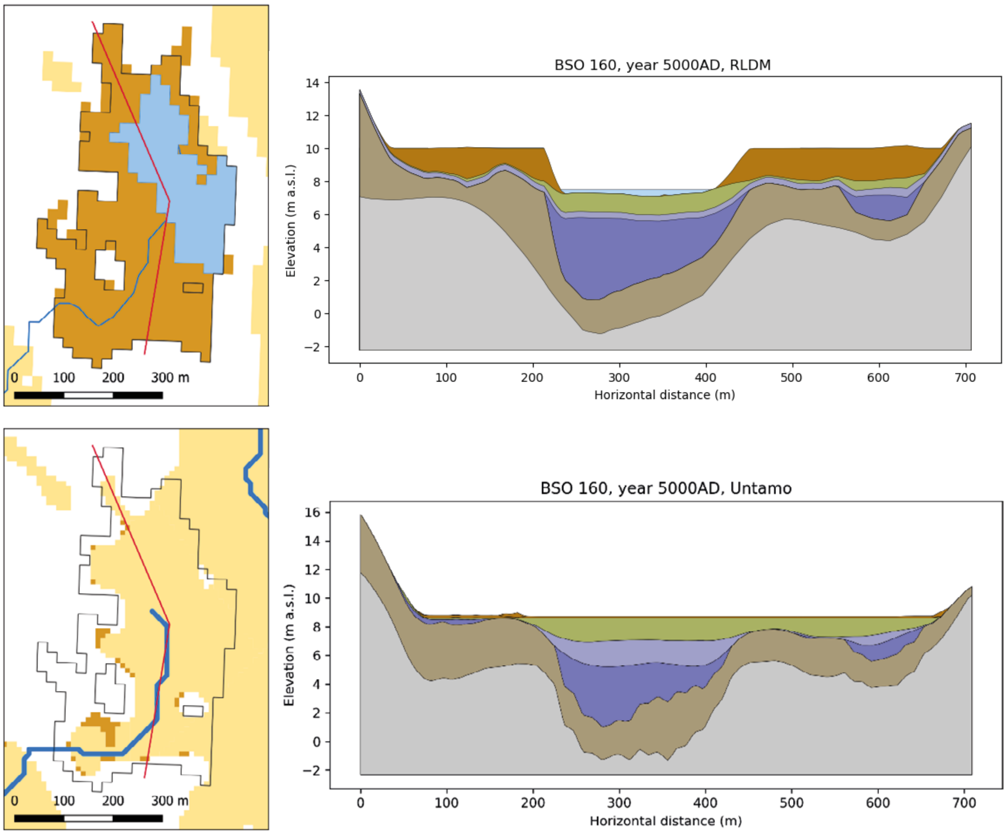

Figure 4-41. *BSO 160 in* ***year 5000****: Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo.*

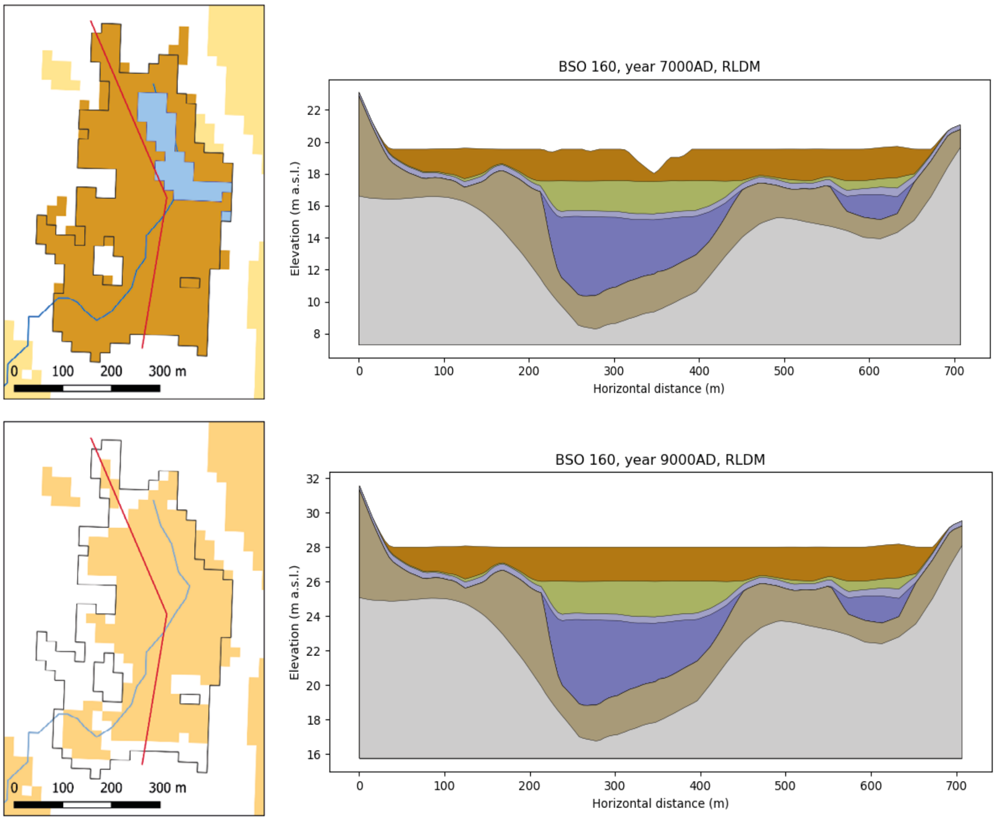

Figure 4-42. *BSO 160 in* ***year 7000*** *(top) and* ***year 9000*** *(bottom): Predicted development stage and regolith cross-section in the RLDM. Untamo result for this time step is almost identical to year 5000, see previous figure.*

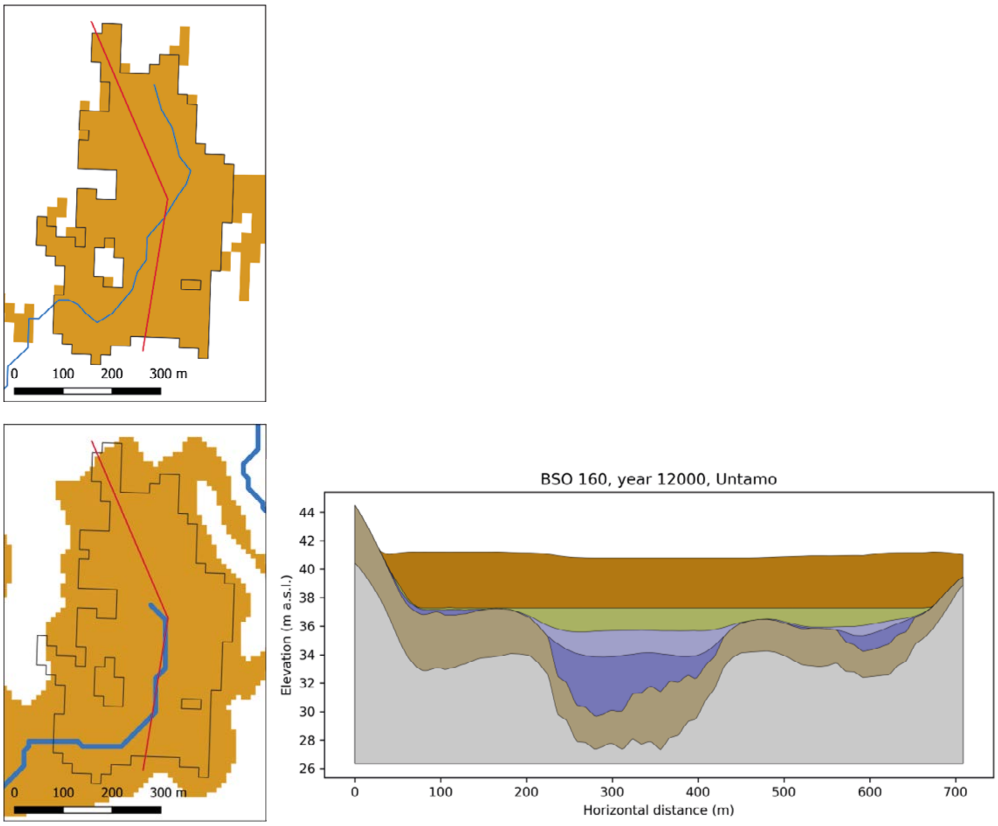

Figure 4-43. *BSO 160 in* ***year 12 000,*** *scenario with* ***natural development*** *(no agriculture): Predicted development stage and regolith cross-section. Top: RLDM, bottom: Untamo. RLDM regolith profile for this time step is identical to year 9000, see previous figure.*

4.3 Development at landscape level

For both models, results were derived for the entire study area, considering the scenario of extensive agriculture without erosion during marine stage, and the scenario of natural development (Section 4.1) All map figures follow the same common legend as provided in figure below.

Please note that the criteria for showing streams on the maps differ between RLDM and Untamo results. While the streams included in the Untamo overview maps comply with a minimum width of 1.5 m, the RLDM-related map figures show all streams with a mean run-off of at least 0.02 m^3/s.

4.3.1 Scenario considering agricultural usage

The figures in this section show the simulated landscape development for the coming 10 000 years under a scenario that assumes agricultural practices comparable to the present time. Erosion of glacial clay and post-glacial clay-gyttja during marine stage is not considered in these results. The impact of erosion is considered separately in Section 4.4 .

Overall, the landscape development in both models is comparable, though most lakes are infilling faster in the RLDM results, resulting in a slightly smaller total lake area at landscape level (Figure 4-45). By year 12 000 the large lake that evolves in the North-East of the model area has infilled with peat nearly completely in the RLDM while it has kept most of its original extent in Untamo. The total area of mires is significantly larger in the RLDM/LDM due to the faster infilling of lakes with peat and because in Untamo most peat soils are converted into cropland. Furthermore, the map figures only show peat soils with at least 0.3 m thickness for the Untamo results. Both models show large amounts of potential cropland in the new areas arising from the sea.

In the Untamo results, the large amount of croplands is directly linked to the fact that the simulations did not account for erosion. The layers of glacial clay and post-glacial clay-gyttja that are present at the sea bottom at the initial condition do not change over time in the no-erosion model variant. They emerge unchanged from the sea and are classified as croplands since they fulfil the soil requirements for agricultural use. The variant including erosion shows significantly less croplands on the new land (see Section 4.4). An important difference between the two models is that Untamo allows cultivation of wetlands bordering lakes while the RLDM/LDM only allow cultivation once the entire lake basin is filled with sediment and peat.

Figure 4-44. *Legend applied in all maps shown in Section 4.3 .*

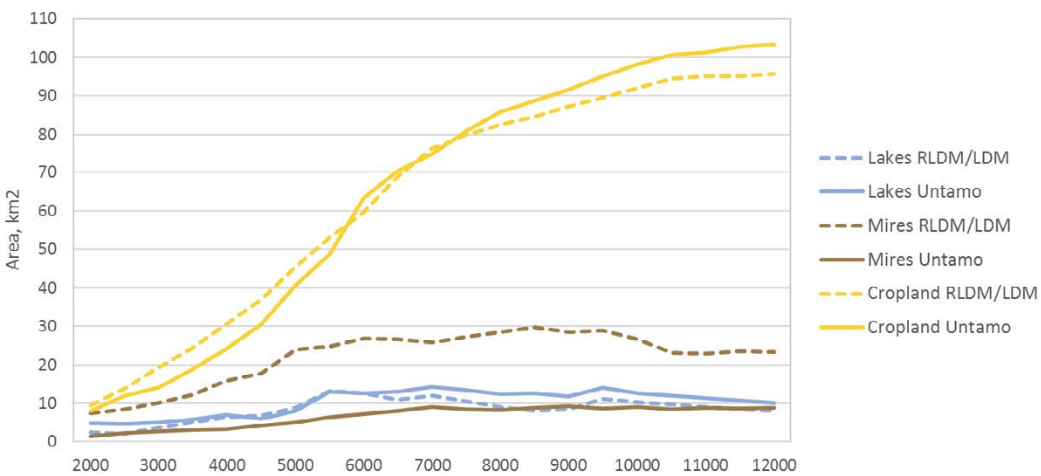

Figure 4-45. *Total area of lakes, mires and croplands within the model area over time in the scenario of extensive agriculture.*

In the RLDM/LDM, the large amount of cropland areas is caused by the fact that clayey till soil is considered suitable for agriculture, unlike in Untamo. The regolith depth model which was used in this study as input for Untamo does not distinguish clayey till as a separate soil type. In Untamo, till was considered unsuitable for agricultural use. Therefore, some areas of clayey till which are cultivated at present are not delineated as croplands in the Untamo results. The croplands shown in the RLDM-related figures shown in this section were taken from SKB's Landscape Development Model (LDM) which does consider presently cultivated land. An example is the large clayey-till area in the East of lake Fiskarfjärden which is shown as cropland in the RLDM-related map figures but not in Untamo.

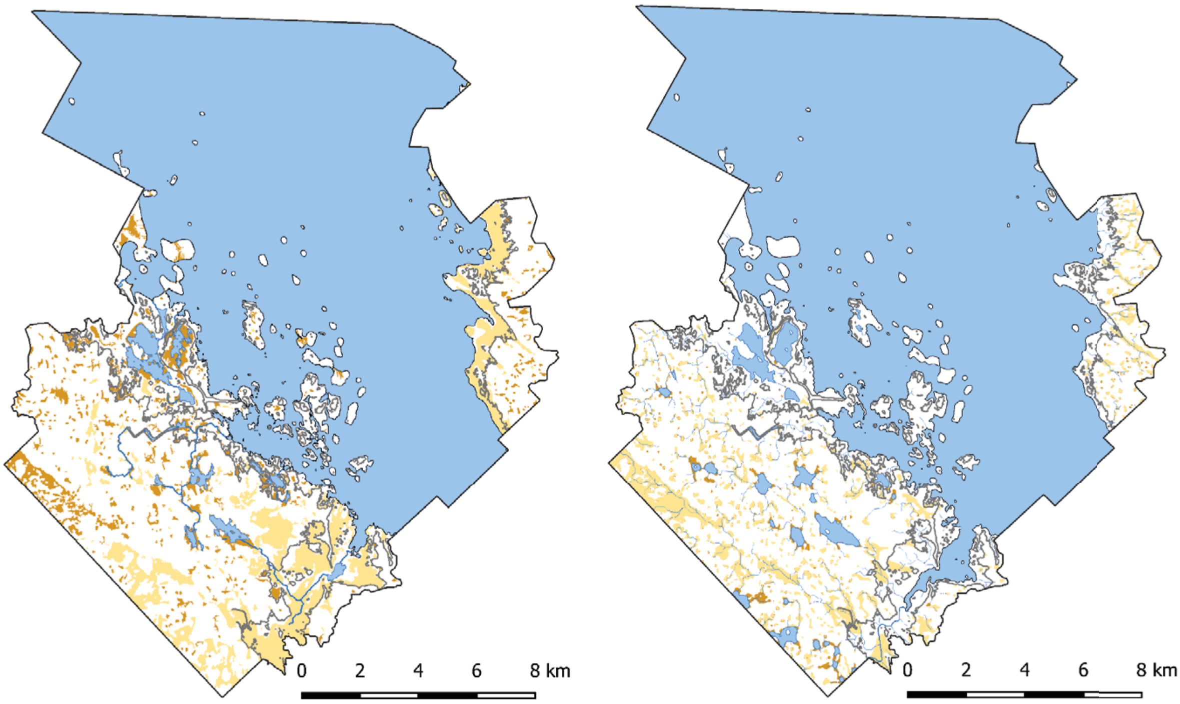

***Figure 4-46.** Model results for year **3000 AD**, scenario of extensive agriculture. Left: RLDM/LDM, right: Untamo.*

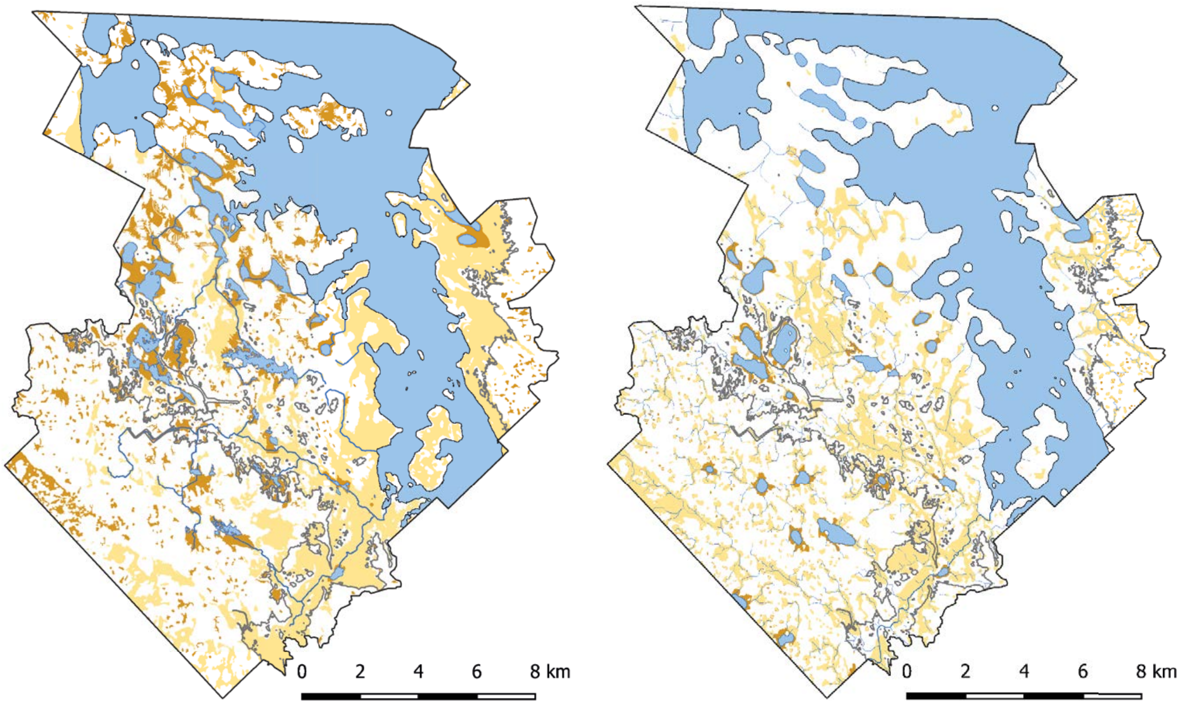

***Figure 4-47.** Model results for year **5000 AD**, scenario of extensive agriculture. Left: RLDM/LDM, right: Untamo.*

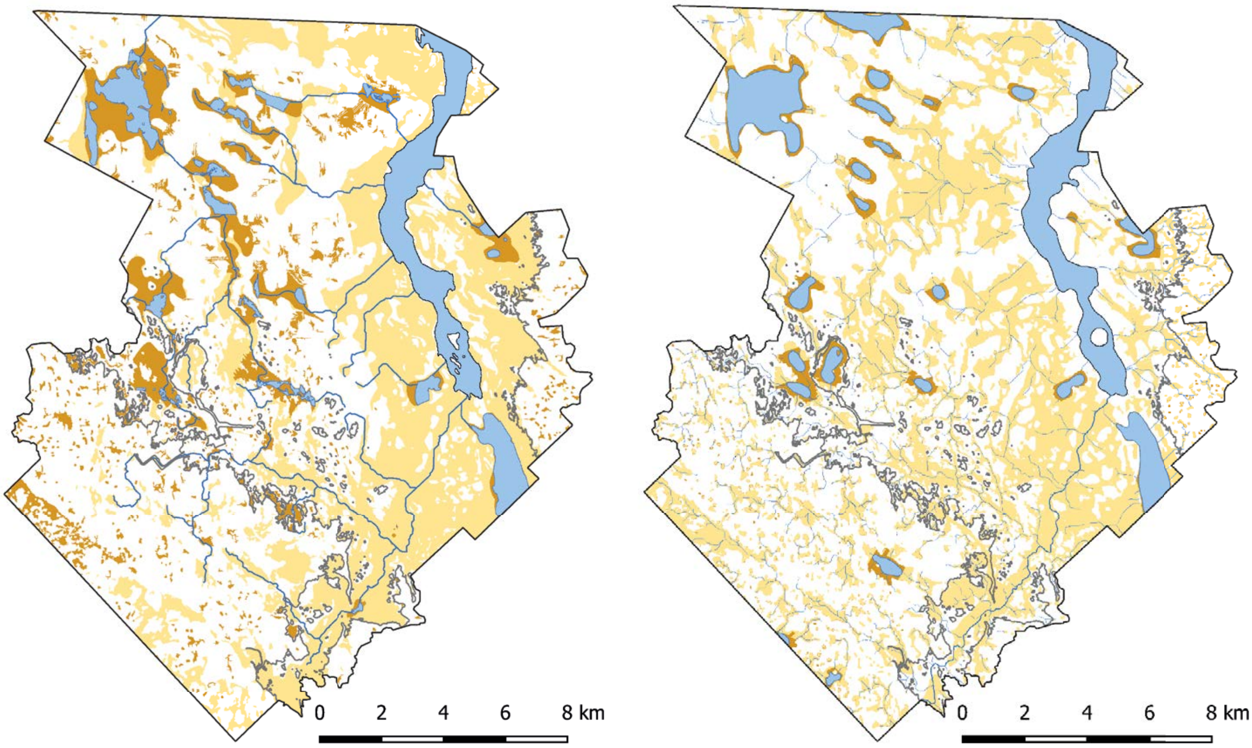

Figure 4-48. *Model results for year **8000 AD**, scenario of extensive agriculture. Left: RLDM/LDM, right: Untamo.*

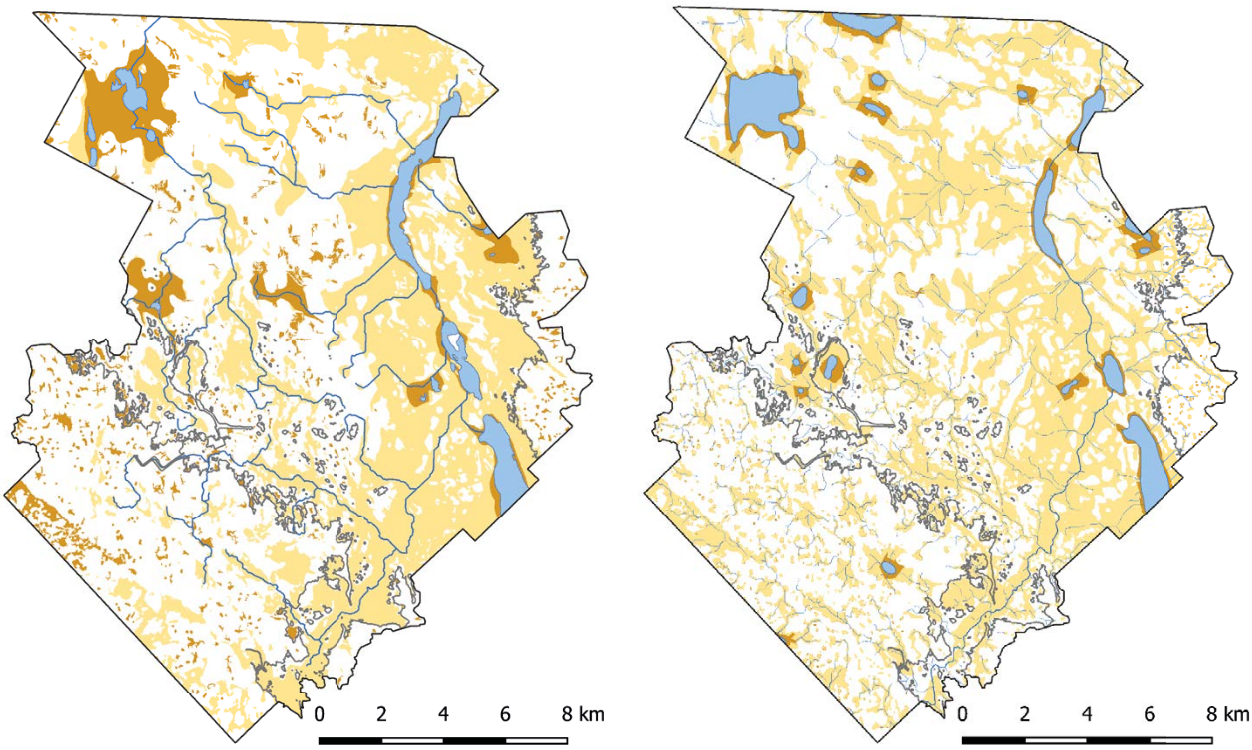

Figure 4-49. *Model results for year **12 000 AD**, scenario of extensive agriculture. Left: RLDM/LDM, right: Untamo.*

4.3.2 Natural scenario without human interference

The map figures in this section show the simulated landscape development for selected time steps up to year 12 000 under a scenario of natural development without human impact. The difference to the scenario considering agricultural usage is therefore only related to land use and growth of mires. Erosion of glacial clay and post-glacial clay gyttja during marine stage is not considered in these results. The LDM result maps for the natural development scenario were only available for years 3 000, 5 000 and 20 000. Therefore, the RLDM/LDM results shown in the comparison figures for year 12 000 (Figure 4-50, Figure 4-53) were constructed from the lake data of year 12 000 from the agriculture scenario and the mire data of year 20 000 from the natural development scenario under the assumption that mires, once classified, do not change over time in the RLDM/LDM.

In the RLDM, all lakes eventually transform into mires which keep their extent over time. In Untamo lakes are changing into mires as well, though the infilling is on average slower than in the RLDM (see Section 4.3.1) and the large lake evolving in the North-Western part of the model area is still existing in Untamo in year 12 000 (Figure 4-53). The amount of new mires developing on the emerging land areas is initially smaller in Untamo compared to the RLDM/LDM (Figure 4-52). However, the extent of peatlands is larger in the Untamo result for later time-steps since the model applies a peat growth algorithm which considers the lateral expansion of the peatlands, while the delineated mire areas in the RLDM/LDM do not change their extent over time. By year 12 000 the area covered by peatland in Untamo is larger than that in the RLDM/LDM results. Figure 4-50 depicts the increase in total mire area over time.

While mires in the RLDM/LDM keep the shape of the basin where they originate from, mires in Untamo tend to have a circular shape. The model of Clymo (Section 2.6) which is used in Untamo considers a theoretical mire originating from a single point on a flat plane. It lets the mire extend equally to all sides if the topography allows. As a result, in relatively flat terrain the mires grow in a circular shape.

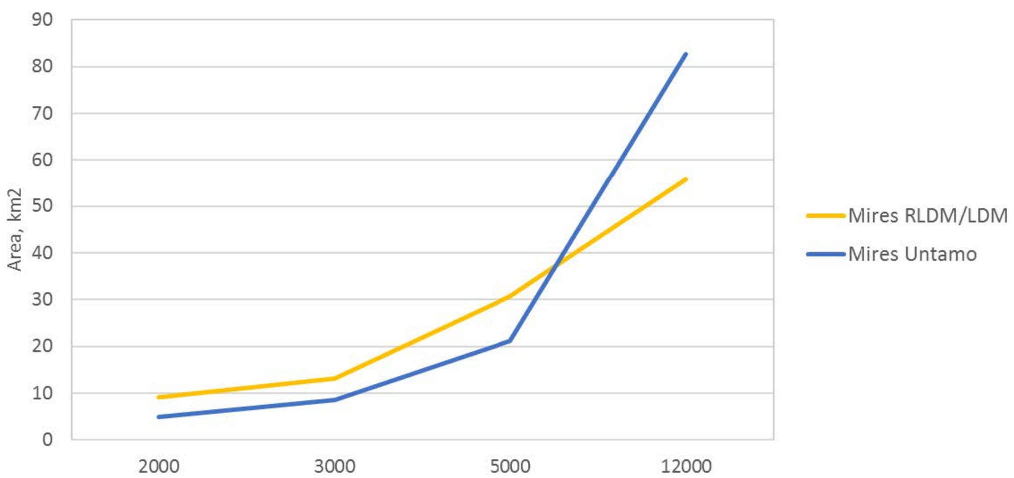

Figure 4-50. *Total area of mires within the model area over time in the scenario of natural development. RLDM/LDM mire area in year 12 000 was derived from the mire data of year 20000 after removing those areas that are still covered by lakes in 12 000.*

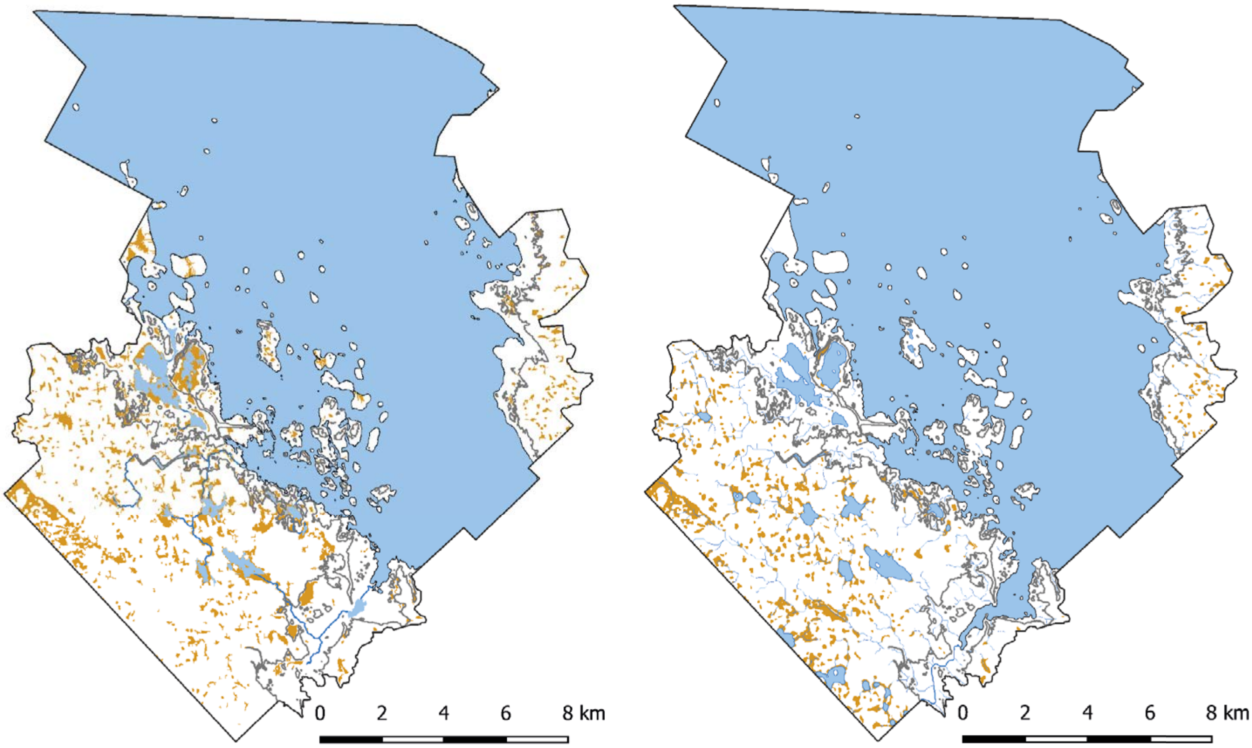

***Figure 4-51.** Model results for year **3000 AD**, natural development scenario. Left: RLDM/LDM, right: Untamo.*

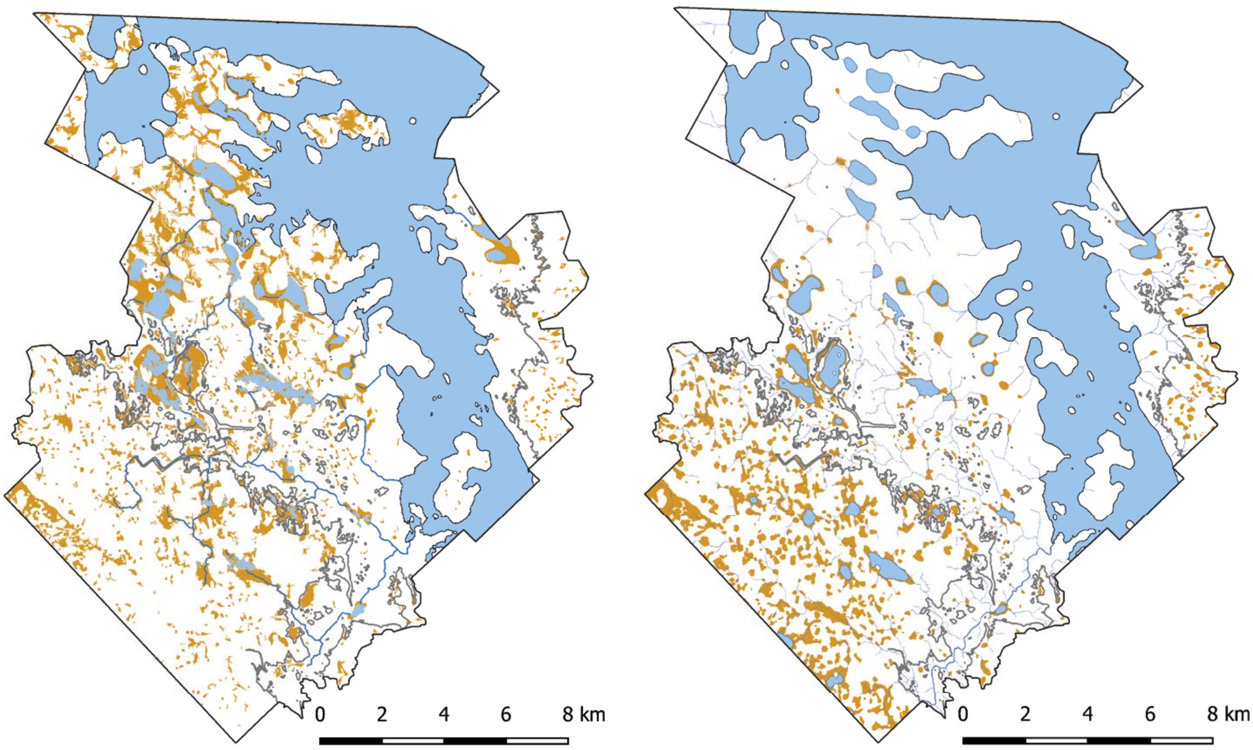

***Figure 4-52.** Model results for year **5000 AD**, natural development scenario. Left: RLDM/LDM, right: Untamo.*

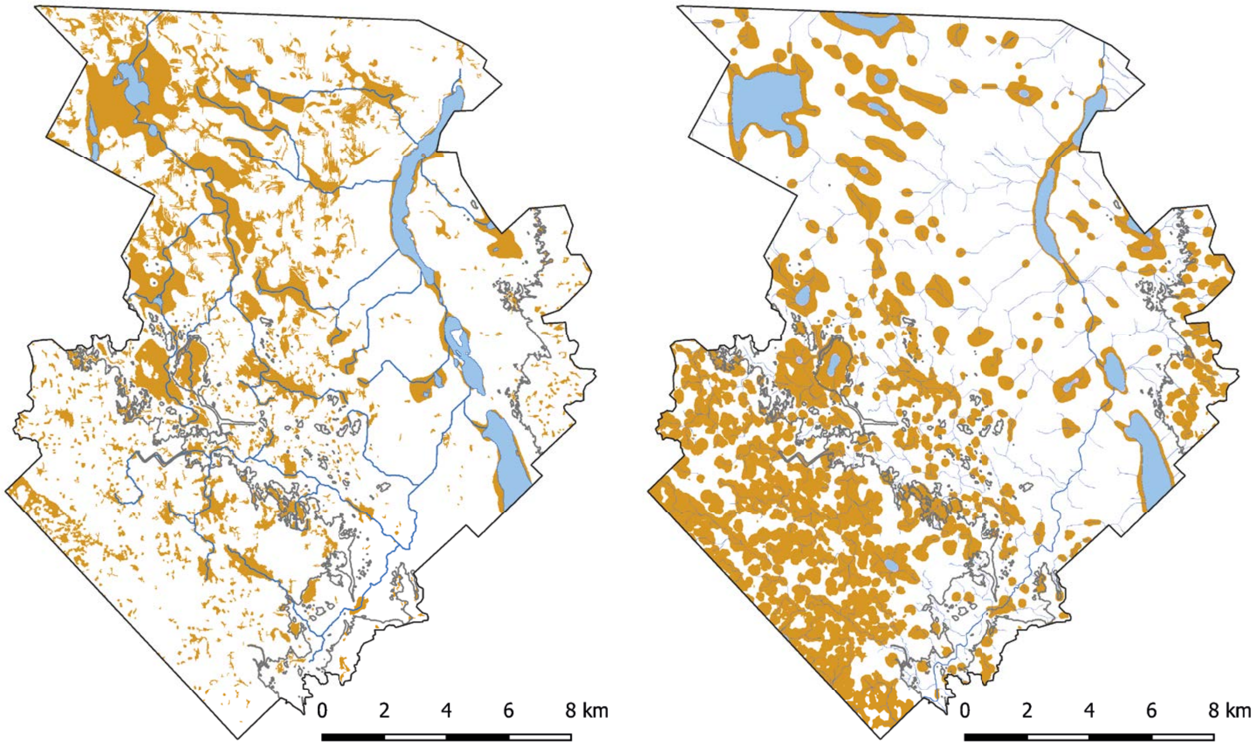

***Figure 4-53.** Model results for year **12 000 AD**, natural development scenario. Left: RLDM/LDM, right: Untamo.*

4.4 Impact of erosion

4.4.1 Erosion effects at landscape level

An additional simulation variant was calculated in Untamo which applies an erosion rate of 0.96 mm/year for glacial clay during marine stage in areas classified as erosion bottom. This rate had been estimated based on the present-day thickness of glacial clay in erosion and non-erosion environments (see Section 3.2.4.1). All other parameter values were identical to those of the scenario of extensive agriculture. At landscape level, the most significant change compared to the results which neglect erosion rate is the reduced amount of cropland on the new land areas emerging from the sea. Erosion along the seashore results in a somewhat altered coastline. The erosion effects mainly those terrain features on the sea floor that are elevated and therefore are most exposed to waves. Areas that would possibly form future lake thresholds may get eroded if the impact of wave-induced shear stress on the sea floor is strong enough (Section 2.5.1.2). As a result, some basins stay longer connected to the sea before they get isolated as lakes, while other basins do not reach a lake stage at all if the threshold is too low after the erosion impact. The number of lakes is therefore reduced when erosion is considered. Results for model runs with and without erosion are presented in Figure 4-54 through Figure 4-56. The maps follow the same legend as shown in Figure 4-44.

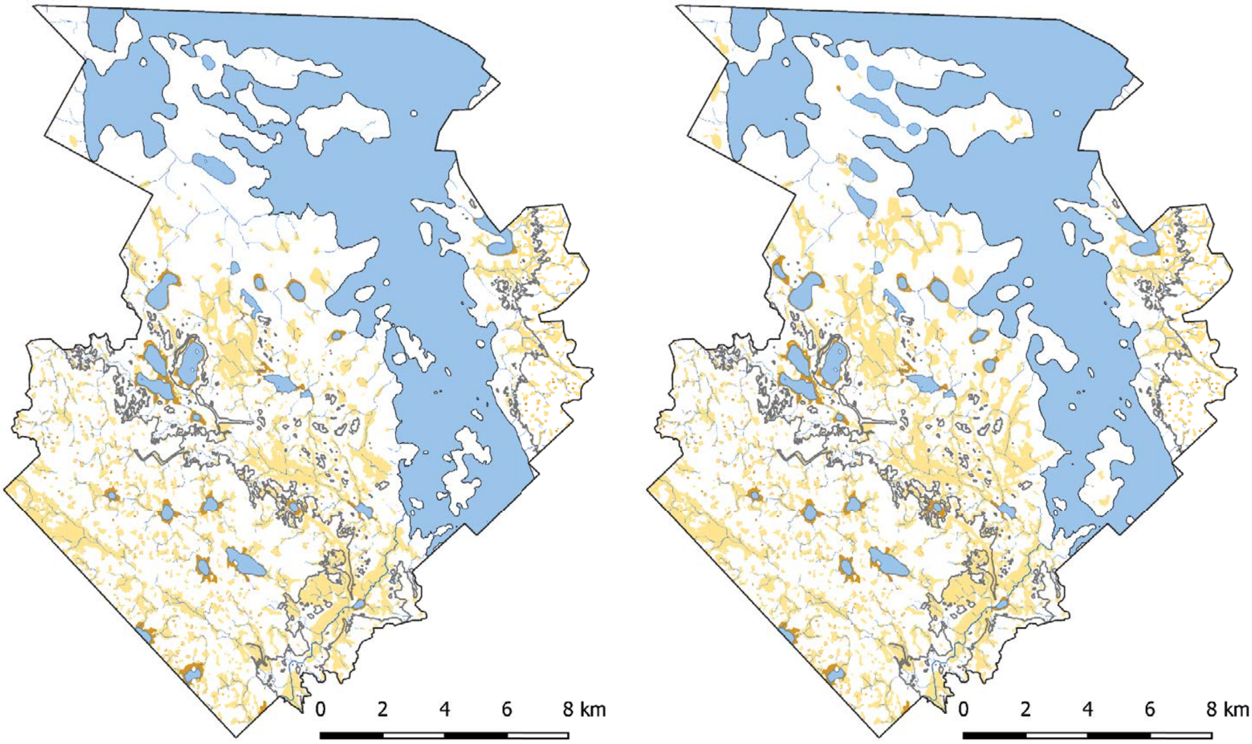

Figure 4-54. *Model results for year* ***5000 AD*** *for the scenario including erosion (left) in comparison to results without erosion (right).*

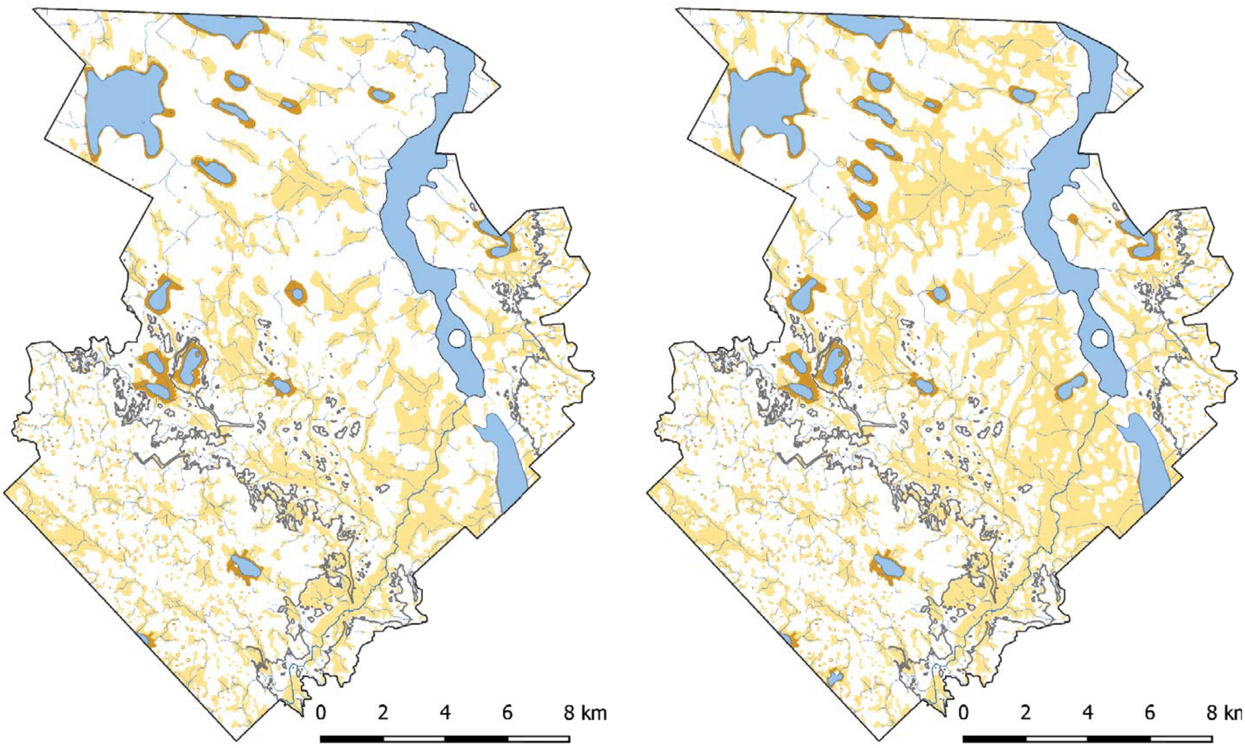

Figure 4-55. *Model results for year* ***8000 AD*** *for the scenario including erosion (left) in comparison to results without erosion (right).*

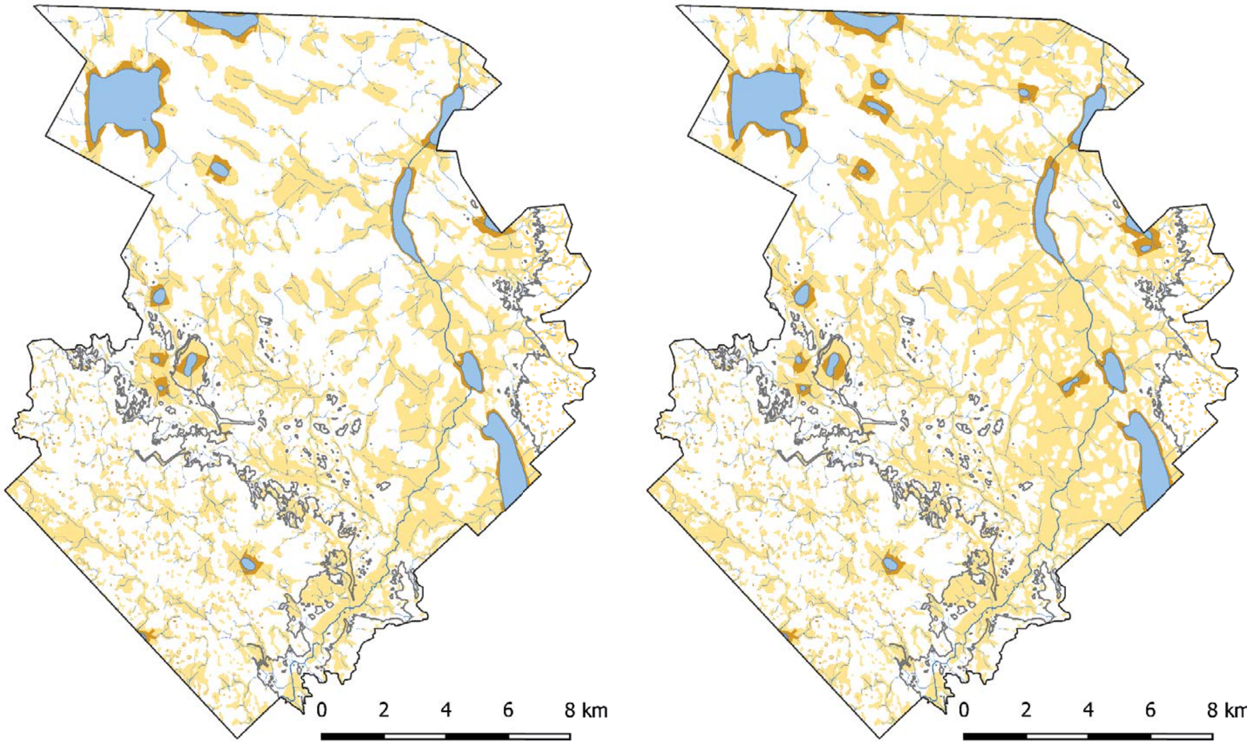

Figure 4-56. *Model results for year* ***12 000 AD*** *for the scenario including erosion (left) in comparison to results without erosion (right).*

4.4.2 Erosion effects on biosphere objects

For the biosphere objects of interest, erosion effects are only visible for objects 157_2, 159 and 160 (see Figure 4-57 through Figure 4-66). The presented regolith cross-sections and object-level maps are based on the colour schemes provided in Figure 4-7 and Figure 4-8, respectively.

The cross-section through basin 157_2 shows how glacial clay gets eroded at the seashore (Figure 4-57). Due to land uplift, erosion takes place only for about 800 years. Since the object does not get isolated as a lake in Untamo, the effect of the erosion on the future landscape features is only marginal. The stream which is crossing the object takes a slightly altered route (Figure 4-58).

Biosphere object 159 isolates later in the erosion variant because the seashore threshold is eroded (Figure 4-59, Figure 4-60). When the lake isolates, its water depth is relatively low and thus it infills faster than in the variant without erosion (Figure 4-61). The erosion effects and the differences in water depth are also visible from the basin cross-sections (Figure 4-62). However, the eroded structure is an esker-like formation consisting of glaciofluvial sediment. The regolith stratigraphy which served as input to Untamo is a simplified version of the Forsmark RDM with the aim of reducing the amount of regolith layers through aggregation to those regolith types which are important for the modelled sedimentation processes. As part of this simplification, all glaciofluvial sediment had been aggregated with the glacial clay layer and was treated as such. Therefore, the erosion of this structure might be unrealistic. It is nevertheless shown here to demonstrate how erosion functions in Untamo.

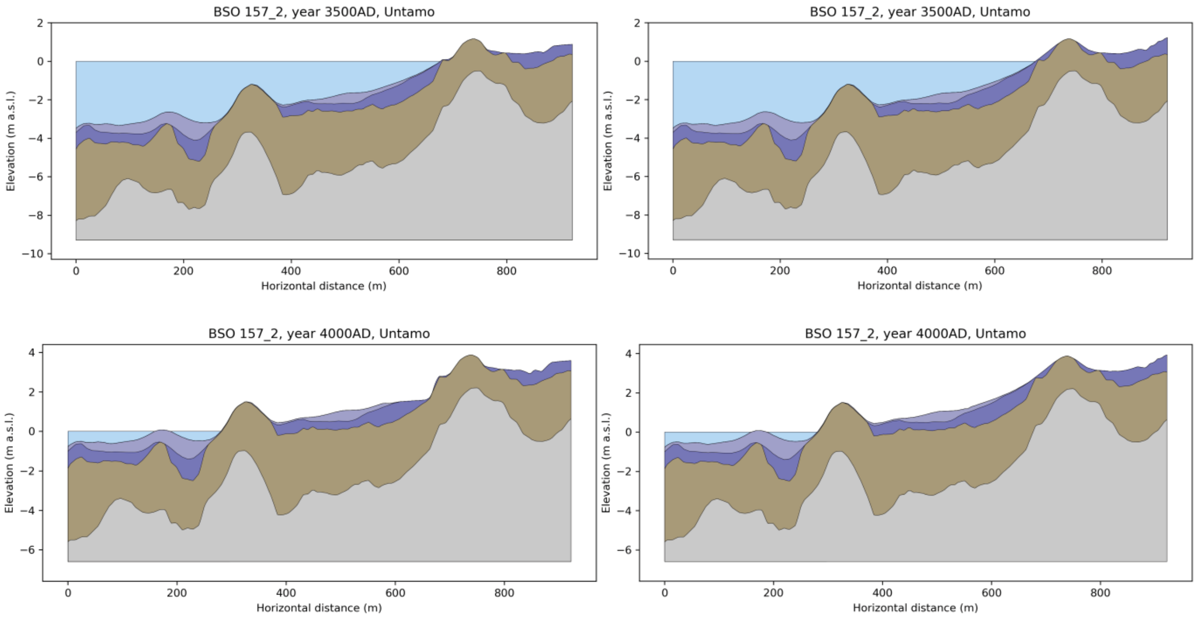

Figure 4-57. *Shoreline erosion effects on biosphere object 157_2 by year 3500 and 4000 in the simulation variant considering erosion (left) in comparison to the variant neglecting erosion (right). The profile line can be seen from Figure 4-58.*

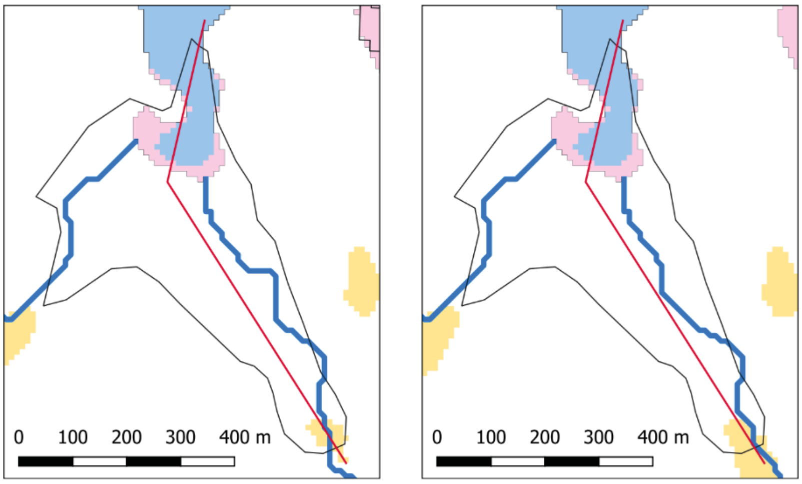

Figure 4-58. *Erosion effect on biosphere object 157_2 by year 4000: Slightly altered river flow in the result considering erosion (left) when compared to the result neglecting erosion (right).*

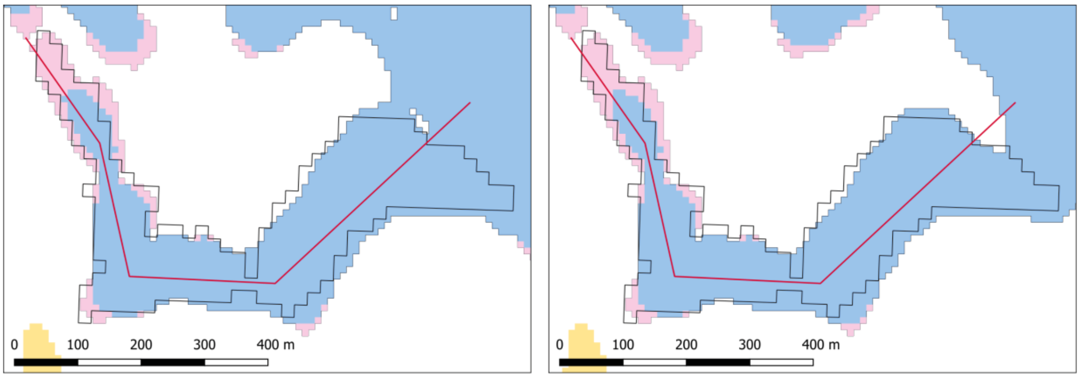

Figure 4-59. *Erosion effect on biosphere object 159 by year 4000: Lowered bank elevation due to erosion (left) compared to the result neglecting erosion (right).*

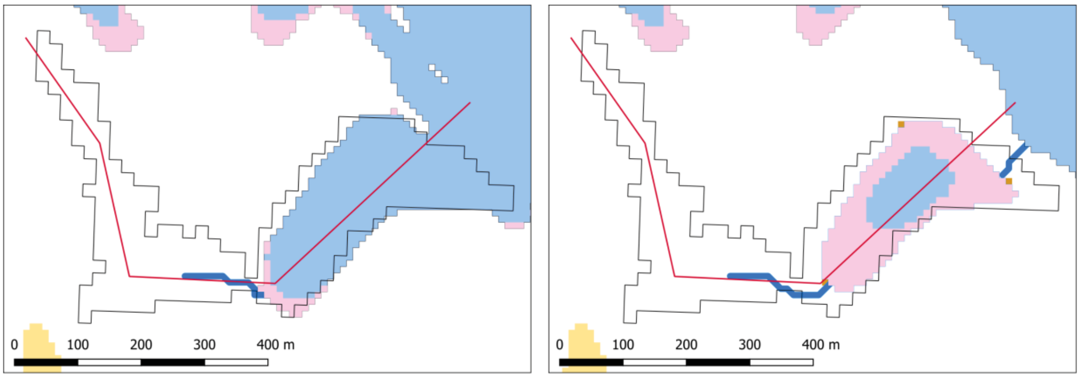

Figure 4-60. *Erosion effect on biosphere object 159 by year 4100: Remaining connection to the sea in the result considering erosion (left) compared to the result neglecting erosion (right).*

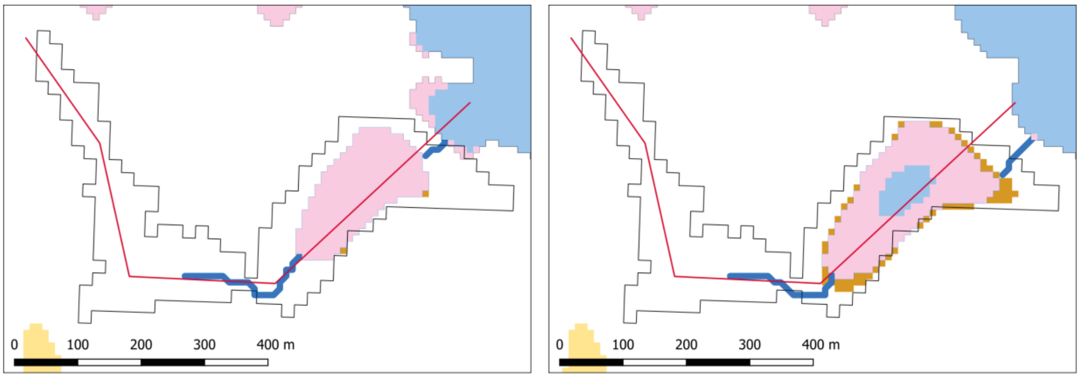

Figure 4-61. *Erosion effect on biosphere object 159 by year 4200: Faster infilling of the lake in the result considering erosion (left) compared to the result neglecting erosion (right).*

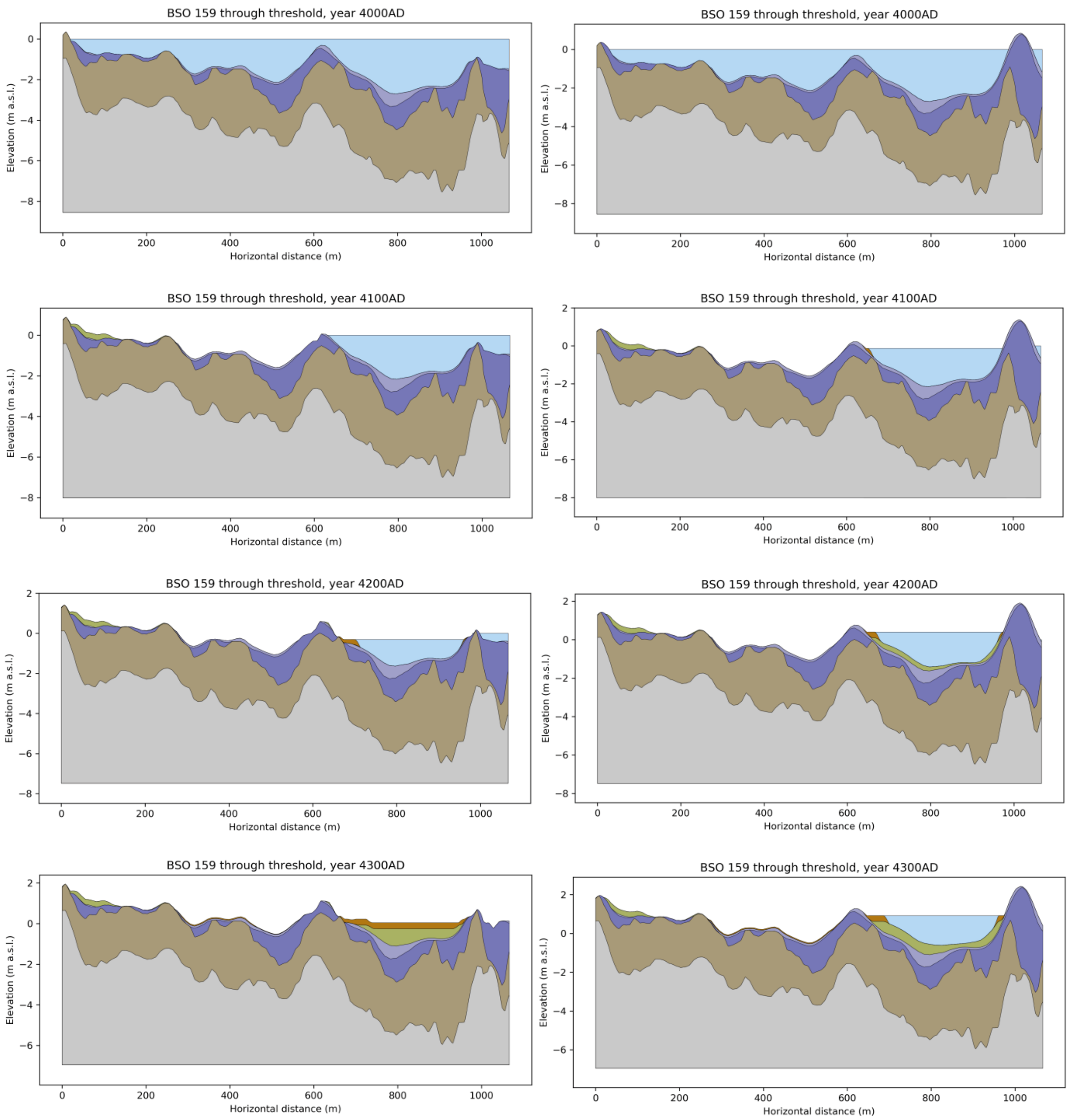

Figure 4-62. *Development of the basin cross-section of biosphere object 159 between year 4000 and 4300. Left: results considering erosion; right: result neglecting erosion. The profile line can be seen from Figure 4-59. Note: The esker-like formation in the profiles on the right consists of glaciofluvial sediment, but for reasons of simplification was treated as glacial clay in Untamo.*

Similarly, for biosphere object 160 the banks of the basin are eroded during the marine littoral stage. Therefore, the water surface height of the basin corresponds to the sea level and the object does not reach a lake stage but forms a bay around year 3 500 (Figure 4-63). The shallow Southern part of the bay is overgrown by reed and gets infilled with gyttja. Already by year 3 600 the entire basin has turned into a land area which is used for agricultural purposes soon after, while in the non-erosion variant a lake is formed that exists over 1 000 years, from 3 500 to 4 700 (Figure 4-64 and Figure 4-65). The erosion of the bank has also altered the drainage direction: In the simulation variant considering erosion the object is drained by a river towards North, discharging into object 116. In the non-erosion variant, the basin is discharging towards South into objects 121_2 and 121_1 (Figure 4-65). However, similarly as for object 159, bank is an esker-like formation consisting of glaciofluvial sediment in the Forsmark RDM. Due to the simplification of the RDM as input to Untamo, the structure was treated as glacial clay. Therefore, also in this case the full erosion is not realistic.

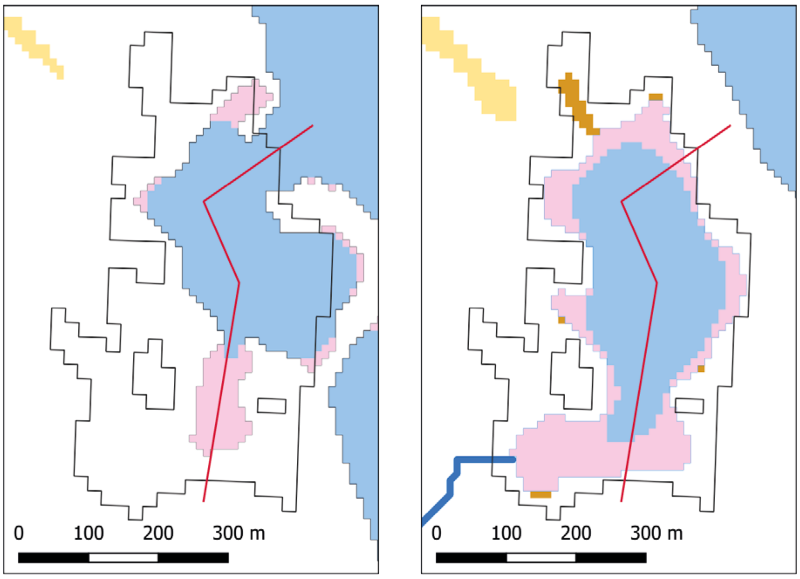

Figure 4-63. *Biosphere object 160 in year 3500: Erosion of the basin threshold results in the formation of a bay instead of a lake. Left: Simulation variant considering erosion; right: simulation variant neglecting erosion.*

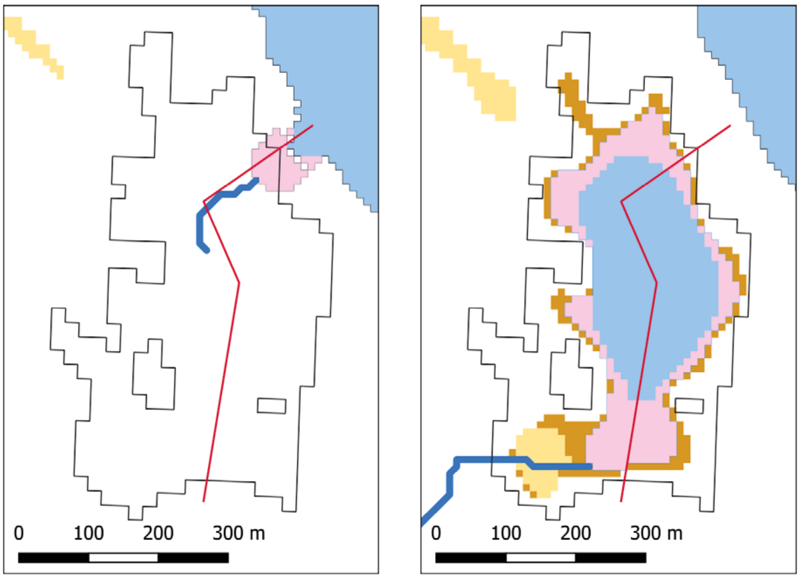

Figure 4-64. *By year 3600 the biosphere object 160 has turned into a land area in the simulation variant considering erosion (left), while a lake is slowly infilling in the variant without erosion (right).*

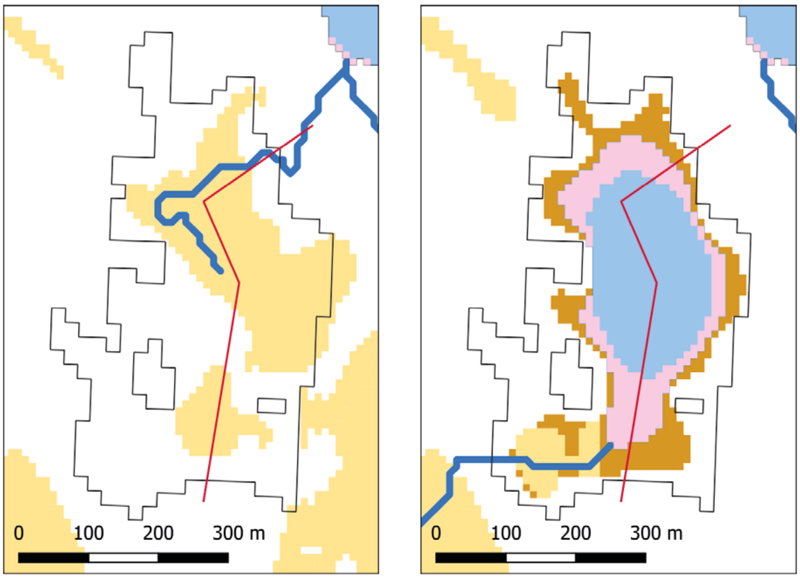

Figure 4-65. *Biosphere object 160 in year 4000: Drainage towards North in the simulation variant considering erosion (left), while the basin discharges towards South in the non-erosion variant (right).*

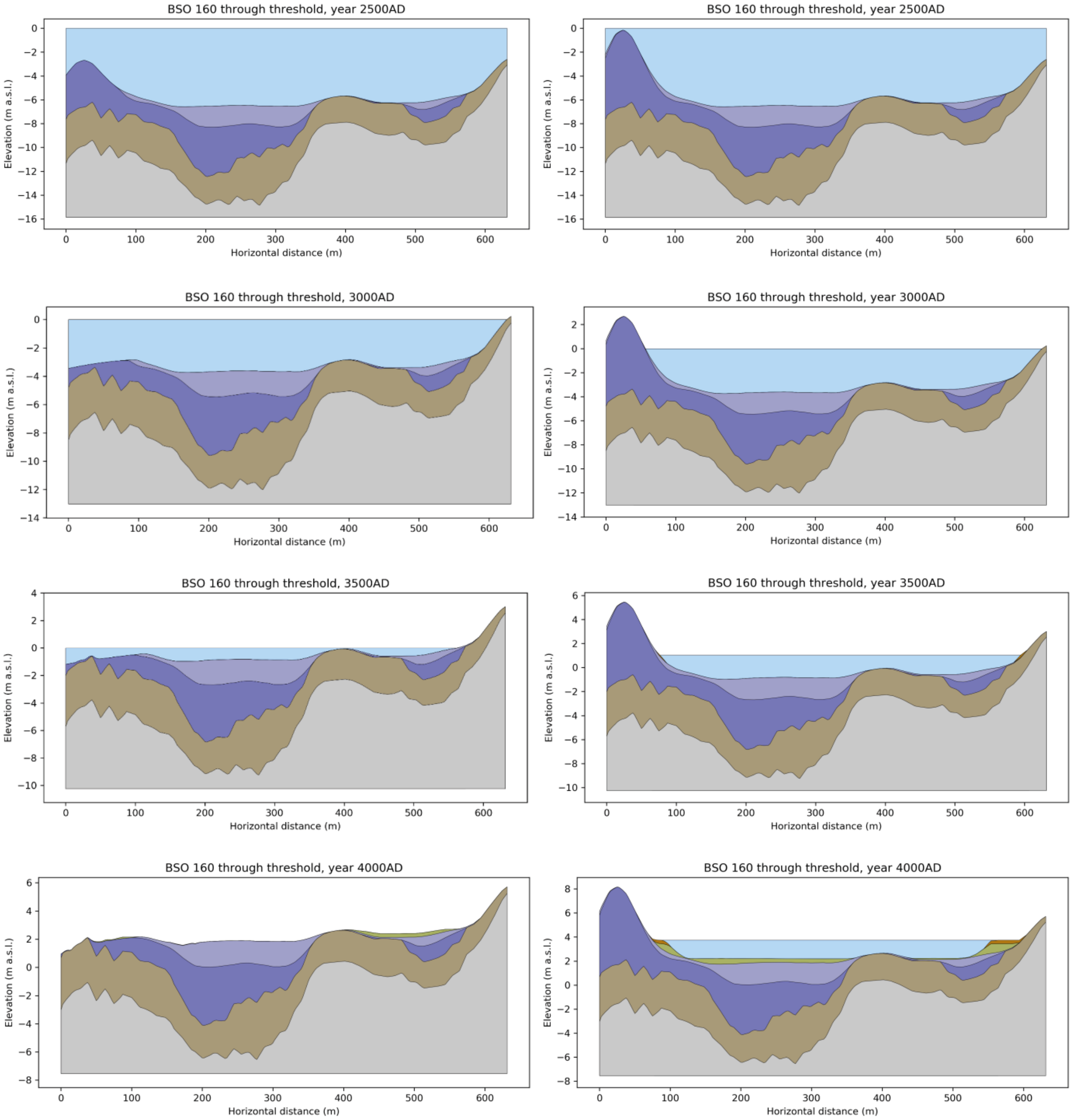

***Figure 4-66.** Development of the basin cross-section of biosphere object 160 between 2 500 and 4 000. Left: results considering erosion; right: result neglecting erosion. The profile line can be seen from Figure 4-59. Note: The esker-like formation in the profiles on the right consists of glaciofluvial sediment, but for reasons of simplification was treated as glacial clay in Untamo.*

4.5 Untamo simulation starting post-glaciation until present

As part of the sedimentation rate calibration for marine and lacustrine environments, the Untamo model was applied for the period 8 500 BC until the present time, see Section 3.2.4 . The DEM and regolith stratigraphy representing the conditions in 8 500 BC were prepared in a similar way as was done for the RLDM simulations, but based on the RDM version 2 018, see Sections 3.1.1 and 3.1.2

This section compares the year 2 000 landscape-level results of that simulation with the present-day situation. The simulation results are presented below in comparison to topographic reference data at three different scales: At the regional scale showing the overall landscape pattern (Figure 4-67), at the scale of the model area with focus on the present-day land (Figure 4-68), and at more detailed scale for those lakes that had been included in the calibration of the gyttja sedimentation rate (Figure 4-69).

The overall pattern of the landscape in the Untamo simulation results is comparable to the present-day landscape. The density of lakes is similar, however, there are some differences in the amount and size of mires (Figure 4-67). Also, some modelled lakes in Untamo have already turned into mires in reality, while some mires modelled by Untamo are still lakes at present (Figure 4-67). There is a larger mire area missing in the Untamo simulation results which is at present located west of the model area as a result of a man-made dam (lake Bruksdammen). Another reason for the differences in mire areas is related to the different ways of mire delineation: In Untamo, mires are defined as areas with peat, while the Swedish National Land Survey applies a definition based on wet areas. That explains for example why many coastal areas are shown as mires in the topographic reference data and not in the Untamo results, since the time for peat formation has been too short.

When keeping in mind how the input data for 8 500 BC were constructed and that there is no accurate reference data for that time available, the simulation results are not too far off from the actual present-day situation. Moreover, the applied sedimentation rates are calibrated based on a limited number of relatively young reference lakes (Figure 4-69). When looking only at this calibration zone, the modelling result fits relatively well with the present-day situation.

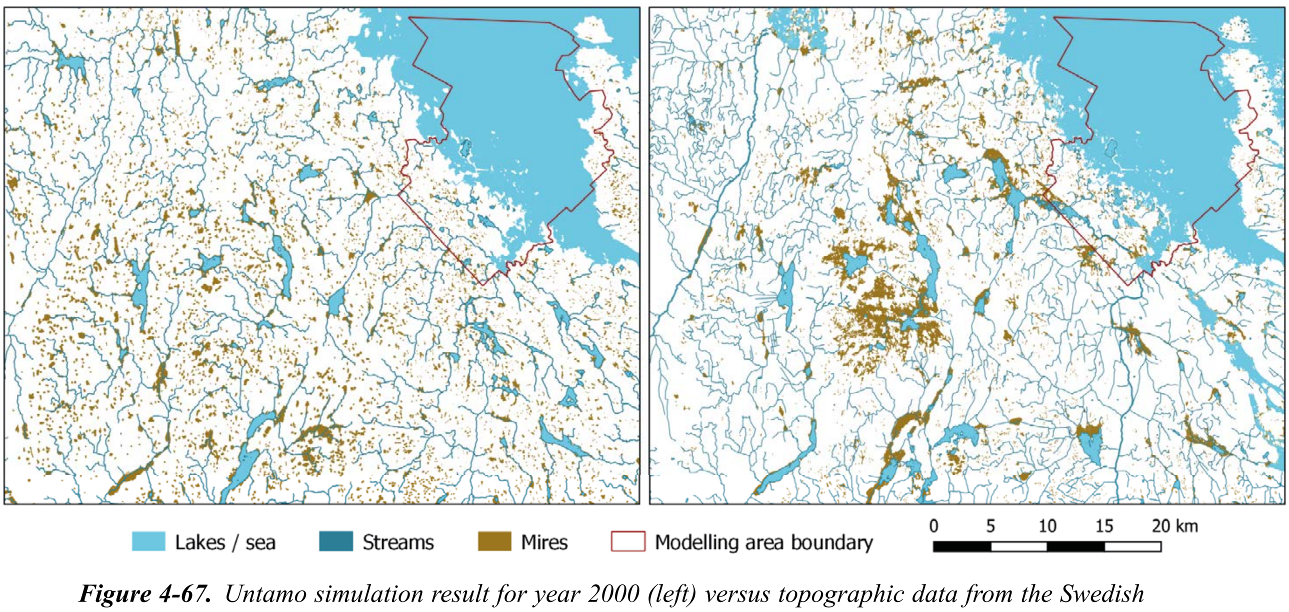

Figure 4-67. *Untamo simulation result for year 2000 (left) versus topographic data from the Swedish National Land Survey (right) at regional scale.*

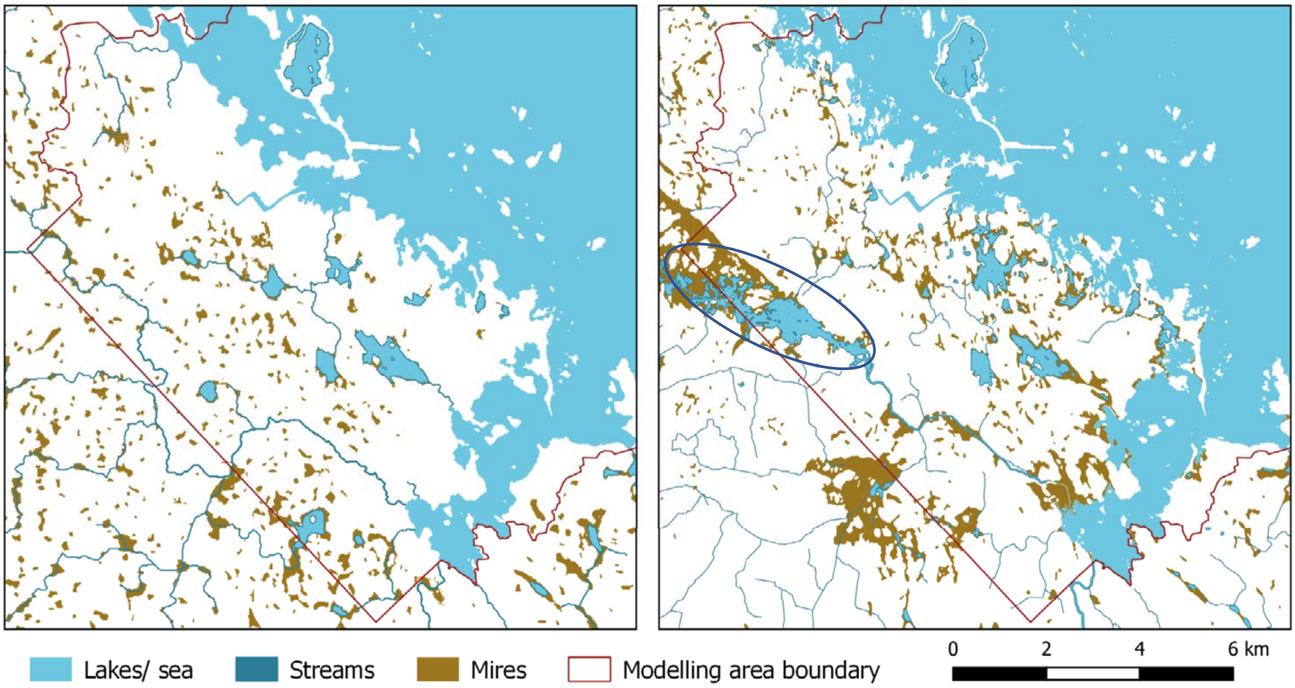

***Figure 4-68.** Untamo simulation result for year 2000 (left) versus topographic data from the Swedish National Land Survey (right) in the South-Western part of the model area. The large circumscribed water and mire area in the right map shows a man-made dam lake (lake Bruksdammen).*

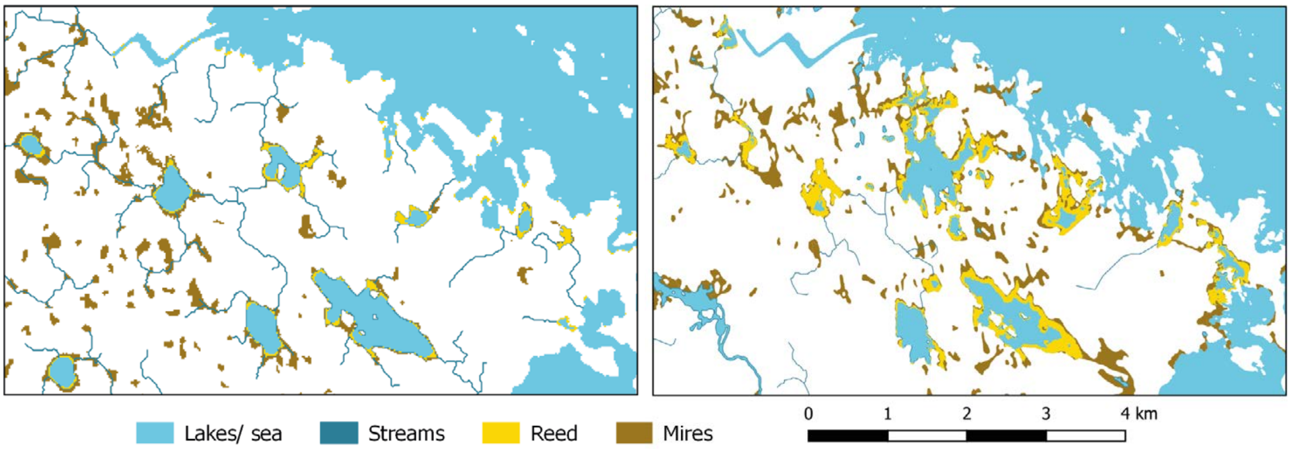

***Figure 4-69.** Lakes included in the calibration of the gyttja sedimentation rate: Untamo simulation result for year 2000 (left) versus reference lake basins digitized from figures in Andersson (2010) (right).*

5 Discussion and conclusions

Overall, results are comparable between both models when looking at the result maps at the landscape level. A large part of the differences visible from the simulated regolith profiles may be related to the fact that two different versions of the regolith depth model for Forsmark were used as input. However, the analyses presented in this report are not capable of fully discerning how much of the demonstrated differences are attributed to the different versions of the regolith depth model. Other differences between the modelling methods which have an impact on the model results as well as specific characteristics of the Untamo model are summarized below.

Notable difference between both models regarding the infilling of lakes is the sediment type that both models accumulate in lakes. While the RLDM fills lake basins partly with gyttja and partly with peat, Untamo accumulates only gyttja during lake stage and peat growth starts only after the lake is fully infilled (this is however only a matter of model parametrization and can be changed in future model runs). Generally, larger lakes tend to infill slower in Untamo than in the RLDM. One characteristic of the Untamo model is the tendency to generate roundish-looking lakes as a result of infilling. Small bays and shallow lake fragments are overgrown by reed and fill up very fast, leaving a roundish open-water zone. Due to the roundish shape the lake shore does not fulfill the criteria for reed growth anymore until the lake diameter is smaller than the limiting fetch distance. Therefore, infilling proceeds slower once the round shape is established. Furthermore, shallow parts of a lake below a certain depth limit (1.5 m in this work) are considered transport bottoms and do not accumulate sediment unless they are colonized by reed vegetation. As a result, shallow roundish lakes might persist for a very long time if they are large enough, i.e. if the diameter is above the limiting fetch distance for reed growth. This is a feature of the model and may not be realistic. It can be improved in future simulations by adjusting the methodology used for reed delineation so that reed colonies are mapped more realistic and infilling of larger lakes proceeds faster while avoiding the convergence towards round shapes.

The calibration of the gyttja sedimentation rate for lakes was based on reference data (regolith depth model) from relatively young lakes close to the present coastline. As the speed of lake infilling is sensitive to the sedimentation rate, calibration of the sedimentation rate could be improved by including older lakes, for which measurement data of gyttja thickness are available, in the calibration of the sedimentation rate. However, these lakes tend to be located further inland and are therefore outside of the currently modeled area.

The distribution of sediment at the lake or sea bottom differs between the two models. In Untamo, sediment deposits are not accumulated in a uniform/constant layer like in the RLDM but accumulate faster in deeper parts of the basin. This difference can be clearly seen from the regolith profiles of the simulation outputs.

Current model iterations (both Untamo and the RLDM) do not explicitly account for upstream sediment loads. In future modelling efforts, sediment transport by rivers should be included explicitly. This could be of particular importance for Olandsån with a catchment area of approximately 880 km^2 (Thoms-Hjärpe et al. 2002).

Isolation of lakes and their subsequent development is also subject to the applied model settings for channel erosion and removal of soft sediment from lake outlets. These settings have a direct impact on the lake water level and will therefore affect the water volume and consequently whether a basin is classified as lake or not. Both Untamo and RLDM were set up to remove soft sediment (peat and gyttja) from lake outlets. Untamo, however, also erodes any hard sediment below the soft layers down to the depth of the streamflow channel, derived from the outlet discharge. It may be worthwhile to calculate an alternative variant where only soft sediment is eroded by Untamo in order to evaluate the effect of the different approaches.

With the current Untamo version, peat soils can be drained and compacted for agriculture or forestry, but this option is at the moment not available for other soft sediment such as gyttja and clay. In RLDM, gyttja is compacted to 25% of its original volume for agriculture. This has an impact on the allocation of croplands in Untamo because gyttja soils keep their original thickness instead of being compacted, thus overestimating potential agriculture land when there is a thin layer of soft sediments other than peat.

In contrast to RLDM, mires accumulate peat over time and expand vertically and horizontally in Untamo. Due to the lack of site-specific data needed for the peat accumulation model, data from the Biosphere Assessment Programme of Posiva Oy has been used instead (Posiva 2013). We acknowledge that these parameter values lead to an unrealistically high asymptotic limit for peat thickness, approximately 30 meters after 200 000 years, while at the same time underestimating peat thickness in younger mires. If peat accumulation under the bog phase of wetlands is to be modelled, it would be advisable to derive a site-specific peat accumulation curve, reflecting local conditions. The mires in Untamo tend to have a circular shape which is caused by the lateral expansion applied by the Clymo model (Section 2.6). However, the aim of the Clymo model is to estimate the thickness of the peat rather than the exact shape of it.

Regolith bulk density used by Untamo can be adjusted to values used by SKB. At the moment the sedimentation model applies only the density values of peat, gyttja, clay gyttja and glacial clay. Changing these parameter values will require recalibration of the sedimentation rates, so that the thickness of accumulated material stays in line with what is observed from reference data.

The regolith depth model for Forsmark has been a direct input to the Untamo simulations. However, it was reduced to six regolith layers to comply with a regolith profile structure suitable for the model. During this generalization, glaciofluvial sediment was aggregated with glacial clay. Since glacial clay was considered an erodible layer, some glaciofluvial structures have been altered by the erosion module. This has for example affected esker-like structures close to the biosphere objects of interest (see Section 4.4.2). It is therefore important for upcoming modelling work to improve the generalized regolith stratigraphic input for Untamo by aggregating glaciofluvial sediment with a sediment layer that is unable to be eroded on the time-scales considered such as till.

Uncertainties arising from the parameters and models applied by Untamo will be addressed in a separate study where model sensitivity and parameter uncertainty are analysed in detail.

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Appendix 1

Water depth and water volume of selected biosphere objects over time

The statistics presented in this section consider only the **open water** areas of the water body.

Object 116

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m) Q1	Q2	Q3	max.	Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)	Development stage	Water depth quartiles (m) Q1	Q2	Q3	Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)
4 500	sea	0.56	1.04	1.88	3.95	1 408 900	1.30	1 831 570	lake	0.70	1.55	2.13	1 491 600	1.50	2 237 862
5 000	lake	1.33	1.65	1.70	1.76	342 800	1.47	504 602	lake	1.60	1.91	2.07	905 600	1.94	1 753 775
5 500	lake	1.45	1.54	1.54	1.54	273 100	1.44	392 445	lake	1.71	1.90	1.96	809 600	1.84	1 492 569
6 000	lake	1.47	1.51	1.51	1.51	236 600	1.43	339 048	lake	1.70	1.83	1.89	713 600	1.78	1 267 927
6 500	lake	1.48	1.50	1.50	1.50	208 200	1.43	298 142	lake	1.62	1.70	1.74	617 600	1.66	1 026 185
7 000	lake	1.47	1.50	1.50	1.50	183 800	1.43	263 569	lake	1.52	1.57	1.60	521 600	1.54	802 991
7 500	lake	1.45	1.50	1.50	1.50	162 300	1.43	231 602	lake	1.38	1.43	1.47	425 600	1.40	596 556
8 000	lake	1.44	1.50	1.50	1.50	138 900	1.42	197 794	lake	1.25	1.30	1.34	329 600	1.28	422 099
8 500	lake	1.41	1.50	1.50	1.50	118 600	1.42	167 819	lake	1.14	1.19	1.22	233 600	1.18	274 879
9 000	lake	1.36	1.50	1.50	1.50	98 300	1.40	137 915	lake	1.06	1.09	1.12	137 600	1.09	149 906
9 500	lake	1.31	1.50	1.50	1.50	78 700	1.39	109 000	lake	1.01	1.03	1.04	41 600	1.03	42 666
10 000	lake	1.27	1.48	1.50	1.50	58 300	1.37	79 696							
10 500	lake	1.25	1.46	1.50	1.50	36 800	1.37	50 232							
11 000	lake	1.22	1.39	1.50	1.50	13 500	1.34	18 117							
11 100	lake	1.22	1.40	1.50	1.50	4 800	1.35	6 461							
11 200	lake overgrown by reed	0	0	0	0	0	0	0							

Object 121_1

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m)				Open water surface (m²)	Mean water depth (m)	Water volume (m³)	Development stage	Water depth quartiles (m)			Open water surface (m²)	Mean water depth (m)	Water volume (m³)
		Q1	Q2	Q3	max.					Q1	Q2	Q3			
3700	sea	0.85	1.16	1.55	2.64	269300	1.24	334471							
3800	terrestrial	0	0	0	0	0	0	0							
4000									lake	0.83	1.32	1.94	141200	1.46	206500
4500									lake	1.23	1.60	1.93	109200	1.50	164034
5000									lake	1.40	1.71	1.84	77200	1.61	124096
5500									lake	1.62	1.68	1.71	45200	1.63	73509
6000									lake	1.53	1.55	1.57	13200	1.55	20444

Object 121_2

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m)				Open water surface (m²)	Mean water depth (m)	Water volume (m³)	Development stage	Water depth quartiles (m)			Open water surface (m²)	Mean water depth (m)	Water volume (m³)
		Q1	Q2	Q3	max.					Q1	Q2	Q3			
2500	sea	4.55	5.38	5.64	6.36	177000	5.06	895443	sea	4.37	4.95	5.43	178000	4.81	855774
3000	sea	1.81	2.55	2.79	3.50	173800	2.25	391745	sea	3.49	4.57	5.56	167200	4.47	747771
3500	terrestrial	0	0	0	0	0	0	0	terrestrial	0	0	0	0	0	0

Object 157_1

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m)				Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)	Development stage	Water depth quartiles (m)			Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)
		Q1	Q2	Q3	max.					Q1	Q2	Q3			
4300	sea	0.99	1.34	1.72	2.21	103900	1.40	145876							
4500	terrestrial	0	0	0	0	0	0	0	lake	1.77	2.04	2.28	52000	2.05	106441
5000									lake	1.83	1.94	1.99	28000	1.93	54094
5500									lake	1.59	1.64	1.72	4000	1.66	6636

Object 157_2

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m)				Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)	Development stage	Water depth quartiles (m)			Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)
		Q1	Q2	Q3	max.					Q1	Q2	Q3			
3000	sea	3.25	4.12	4.94	6.77	165700	4.08	675890	sea	1.62	2.06	2.54	168400	2.02	340203
3500	sea	1.00	1.64	2.30	3.98	139200	1.69	234830	sea	1.17	2.12	2.94	140400	2.11	296426
4000	sea	0.28	0.39	0.46	1.25	13900	0.38	5296	sea	0.42	0.76	1.20	36000	0.85	30586
4500	terrestrial	0	0	0	0	0	0	0	terrestrial	0	0	0	0	0	0

Object 159

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m)				Open water surface (m²)	Mean water depth (m)	Water volume (m³)	Development stage	Water depth quartiles (m)			Open water surface (m²)	Mean water depth (m)	Water volume (m³)
		Q1	Q2	Q3	max.					Q1	Q2	Q3			
4000	sea	0.77	1.24	1.80	2.79	90500	1.36	122809	sea	0.79	1.55	2.16	103200	1.45	150108
4100	lake	1.67	1.85	1.98	2.11	11500	1.81	20815							
4200	lake	1.67	1.76	1.80	1.86	1200	1.74	2086							
4300	reed lake	0	0	0	0	0	0	0							
4400															
4500									lake	0.22	0.39	2.09	27200	0.94	25599
5000									lake	0.11	0.43	2.10	17600	1.02	18030
5500									lake	0.29	2.08	2.30	8800	1.60	14050
6000									lake	0.65	2.12	2.23	4400	1.58	6950
6500									lake	2.06	2.08	2.20	1600	2.15	3444
7000									lake	2.12	2.12	2.12	400	2.12	849

Object 160

Year (AD)	UNTAMO								RLDM						
	Development stage	Water depth quartiles (m)				Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)	Development stage	Water depth quartiles (m)			Open water surface (m^2)	Mean water depth (m)	Water volume (m^3)
		Q1	Q2	Q3	max.					Q1	Q2	Q3			
3500	lake	1.08	1.44	1.77	2.08	59100	1.42	83686	sea	0.44	0.98	1.40	87200	0.95	83239
4000	lake	1.16	1.49	1.54	1.56	39300	1.36	53291	lake	0.55	0.88	1.36	60800	0.98	59608
4300	lake	1.38	1.42	1.43	1.50	24700	1.36	33543							
4500	lake	1.42	1.42	1.43	1.49	10100	1.43	14403	lake	0.39	0.59	0.94	51200	0.68	34951
4600	lake	1.42	1.42	1.43	1.43	500	1.42	712							
4700	reed lake	0	0	0	0	0	0	0							
5000									lake	0.22	0.48	0.73	46000	0.48	22162
5500									lake	0.19	0.33	0.57	40000	0.37	14706
6000									lake	0.13	0.27	0.41	33200	0.27	8816
6500									lake	0.14	0.29	0.39	24000	0.27	6566
7000									lake	0.14	0.29	0.39	16400	0.27	4487
7500									lake	0.08	0.15	0.20	9600	0.16	1511
8000									lake	0.06	0.08	0.12	4000	0.09	378

Appendix 2

Regolith thickness in year 10 000 AD by regolith types

Glacial clay

Object	UNTAMO						RLDM					
	Water depth percentiles (m)					Mean thickness (m)	Water depth percentiles (m)					Mean thickness (m)
	P5	P25	P50	P75	P95		P5	P25	P50	P75	P95	
116	0.00	0.00	0.89	2.27	5.13	1.52	0.00	0.09	1.70	3.17	6.58	2.11
121_1	0.00	1.29	2.81	4.33	6.74	3.05	0.00	2.45	4.40	5.93	7.18	4.09
121_2	0.00	0.00	0.00	0.58	2.17	0.41	0.00	0.00	0.00	0.99	2.86	0.61
157_1	0.00	0.55	1.53	2.80	3.74	1.73	0.30	0.41	3.91	4.99	5.86	3.20
157_2	0.00	0.00	0.26	0.63	1.44	0.41	0.00	0.00	0.00	0.00	1.55	0.19
159	0.00	0.00	0.24	0.72	2.36	0.56	0.00	0.00	0.00	0.74	1.87	0.42
160	0.00	0.00	0.08	1.20	3.23	0.75	0.00	0.00	0.00	0.78	3.38	0.61

Post-glacial clay gyttja (marine)

Object	UNTAMO						RLDM					
	Water depth percentiles (m)					Mean thickness (m)	Water depth percentiles (m)					Mean thickness (m)
	P5	P25	P50	P75	P95		P5	P25	P50	P75	P95	
116	0.09	0.15	0.24	0.51	1.11	0.41	0.27	0.33	0.56	0.56	0.56	0.47
121_1	0.12	0.21	0.57	0.81	2.56	0.73	0.61	0.61	0.61	0.61	0.61	0.61
121_2	0.00	0.01	0.12	0.41	0.78	0.24	0.37	0.54	0.54	0.54	0.54	0.53
157_1	0.09	0.36	1.33	2.49	3.04	1.51	0.50	0.50	0.50	0.50	0.50	0.50
157_2	0.00	0.00	0.03	0.22	0.64	0.15	0.20	0.27	0.27	0.37	0.44	0.31
159	0.00	0.00	0.07	0.12	0.34	0.10	0.27	0.44	0.50	0.50	0.50	0.44
160	0.00	0.00	0.13	0.52	1.67	0.40	0.29	0.37	0.37	0.37	0.54	0.37

Gyttja (lacustrine)

Object	UNTAMO						RLDM					
	Water depth percentiles (m)					Mean thickness (m)	Water depth percentiles (m)					Mean thickness (m)
	P5	P25	P50	P75	P95		P5	P25	P50	P75	P95	
116	0.00	0.00	0.00	0.54	1.77	0.39	0.00	0.02	0.12	0.94	1.90	0.53
121_1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.08	0.23	1.22	0.24
121_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
157_1	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.06	0.10	0.20	0.71	0.19
157_2	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00
159	0.00	0.00	0.00	0.46	1.60	0.36	0.01	0.01	0.06	0.43	0.95	0.23
160	0.00	0.00	0.19	0.87	1.61	0.52	0.06	0.06	0.11	1.44	2.41	0.72

Peat (uncompacted, natural development scenario)

Object	UNTAMO						RLDM					
	Water depth percentiles (m)					Mean thickness (m)	Water depth percentiles (m)					Mean thickness (m)
	P5	P25	P50	P75	P95		P5	P25	P50	P75	P95	
116	0.00	0.00	1.86	2.47	2.62	1.50	0.00	1.06	1.51	1.70	1.79	1.30
121_1	0.00	0.00	1.78	2.88	2.95	1.58	0.00	0.32	0.78	1.36	1.75	0.85
121_2	0.00	0.00	0.81	2.17	2.96	1.11	0.00	0.00	0.00	0.38	1.00	0.23
157_1	1.75	2.50	2.76	2.76	2.76	2.62	0.30	1.21	1.58	1.95	2.05	1.45
157_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	1.05	0.19
159	0.00	2.02	2.71	2.81	2.90	2.36	0.38	0.99	1.75	1.97	1.99	1.47
160	0.92	2.37	2.69	2.93	2.95	2.54	0.28	1.05	1.91	1.98	2.00	1.49