Scenario-based land subsidence prediction maps of the Netherlands

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Abstract

We present updated land subsidence predication maps of the Netherlands for the period 2020-2050 for two distinct future scenarios in terms of climate changes and water-management decisions. The maps were produced using the time-efficient modelling tool Atlantis. The resulting maps show significant subsidence in the western and northern part of the Netherlands, but also demonstrate that mitigation measures such as water level fixation may help to reduce future subsidence.

Introduction

Large parts of the Dutch coastal zone subside at rates that range from 1-10 mm/year. Drainage in both rural and urban areas has led to compaction and oxidation of shallow peat(y) and clay soils (Erkens et al., 2016; Van Asselen et al., 2018), while extraction of natural resources such as oil, gas and salt caused significant deep-seated subsidence in specific parts of the Netherlands (Stouthamer et al., 2015). Land subsidence increases flood risk in already low-lying parts of the Netherlands and causes damage to infrastructure (roads, embankments, pipelines), buildings, public spaces (e.g. Erkens et al., 2015; Van den Born et al., 2016).

National predictive land subsidence maps can be used to quantify the impact of land subsidence on water-management and flood risk, supporting regional and national spatial-planning and policy-making. Moreover, these maps can help to increase attention to land subsidence issues and address potential mitigation measures. Since 1997, several attempts have been made to produce national subsidence prediction maps (e.g. Werkgroep Klimaat en Bodemdaling, 1997; Haasnoot et al., 1999; De Lange et al., 2011). However, these early maps often rely on relatively simple or inconsistent modelling concepts, and high computation times prevent scenario exploration. Deltares Research Institute developed a Python-based tool, Atlantis, for producing large scale (i.e. regional or national) predictive land subsidence maps in a consistent and time-efficient manner (Bootsma et al., 2020).

This paper reports on the first national prediction map of the Netherlands produced using Atlantis. Land subsidence is projected for two distinctive future scenarios in terms of climate change and water-management decisions. One scenario with conditions that promote subsidence, seen as the business as usual scenario and one scenario with conditions that limit or suppress subsidence, the alternative scenario. These scenarios are referred to as the 'business as usual' scenario and the 'alternative' scenario:

1. Business as usual: strong climate warming combined with continuation of current water-management practices: surface water levels are periodically lowered to maintain the drainage level and prevent waterlogging due to subsidence;

2. Alternative: limited climate warming combined with surface water level fixation to mitigate subsidence (thereby accepting developing waterlogged conditions).

The resulting scenario maps are not meant to predict the actual future nationwide. They are meant to elucidate spatial differences in the range of subsidence that can be anticipated and in the effectiveness of the potential mitigation measure of surface water level fixation. For instance, fixation is applied uniformly, as it is currently not yet clear to what extent and where such mitigation measures will be taken. The maps are also published on the Dutch Climate Impact Atlas.

Methods and model input

Figure 1 shows the main steps in the production of the prediction maps. Atlantis simulates one-dimensional (1D) shallow subsidence. It only considers land subsidence due to oxidation of peat and organic matter-rich soil layers, and mechanical land subsidence due to compaction of soft soil layers. Oxidation and compaction are simulated using the carbon-store and abc-Isotachen approach respectively. Bootsma et al. (2020) describe these concepts and implementation in Atlantis in greater detail. By varying the forcing mechanisms and parametrization, predictive maps for two different scenarios were simulated. Erkens et al. (2021) provide a more detailed technical description of the approach.

Predictions for Flevoland are based on an existing study (de Lange et al., 2012), because land subsidence is largely determined by processes initiated following its reclamation (e.g. ripening), which are currently not included in Atlantis. Estimated land subsidence due to deep oil, gas and salt extractions has been added separately based on reported subsidence projections in extraction plans of both active and inactive fields (*Kaart velden,* NLOG, n.d.).

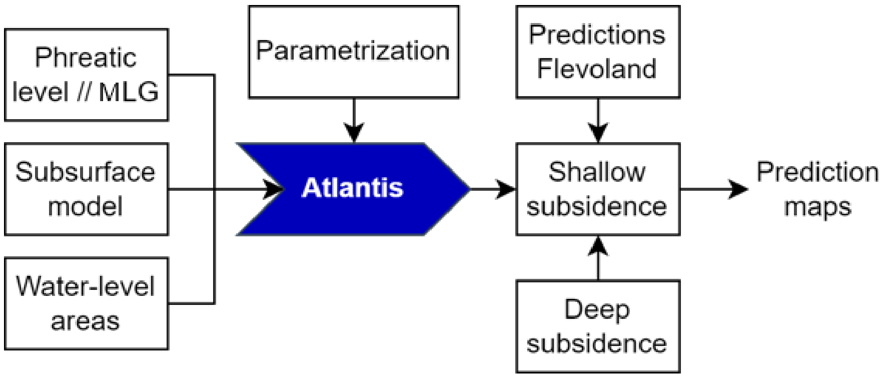

Figure 1 Schematic overview of stepwise approach

Figure 2 Example of merging GeoTop/NL3D (left), soil map (middle) and AHN3 (right) into a column (right) of the subsurface model. Percentages indicate organic carbon mass content. Colors indicate different lithologies.

Subsurface model

The subsurface model is composed of three different models (Figure 2): Basisregistratie Ondergrond (BRO) GeoTOP v1.4 (Stafleu, et al., 2020), Netherlands3D (NL3D; a low-resolution variant of GeoTOP) and the BRO Soil Map v2018 (de Vries et al., 2003) in combination with characteristic soil profiles (de Vries, 1999). GeoTOP is a voxel model providing a detailed three-dimensional view of the stratigraphy and lithology of the subsurface up to a maximum of 50 meter below Amsterdam Ordnance Datum (NAP). NL3D is the predecessor of GeoTOP and is only used where GeoTOP was not available (mainly eastern Netherlands). As GeoTOP and NL3D provide no information on organic matter content, the top 1.2 meter were replaced by characteristic soil profiles of the corresponding soil unit. This is about the maximum unsaturated zone of the soil and is considered the relevant zone for organic matter decomposition. Actueel Hoogtebestand Nederland v3 (AHN3) (Inwinning, AHN, n.d.) constitutes the reference surface level for the start of modelling (2020). Any discrepancy between GeoTOP/NL3D and AHN3 surface level was corrected for in the process of merging the soil profiles (illustrated in Figure 2). The resulting subsurface model has a horizontal resolution of 100 x 100 m and a vertical resolution of 0.5 m. In the top 1.2 m the vertical resolution is variable (ranging between 0.04 – 1.2 m), following the discretization of the soil horizons. The relevant soil properties and compaction parameters are assigned per lithology class (described in Erkens et al., (2021)).

Mean lowest groundwater level

Atlantis uses the mean lowest groundwater level (MLG) as 1D proxy for the (dynamic) phreatic groundwater regime. In the organic matter oxidation calculations, MLG defines the part of the soil in which oxidation occurs. In the compaction calculations, the MLG is used to determine porewater pressures and soil stresses. The initial MLG-map that describes the water levels in 2020 is composed out of two maps. In rural areas, the MLG 2020 is derived from an existing map (Groundwater regime based on Mappable Characteristics' by STOWA, 2010). This map provides a first order picture of the situation around 2010. However, validation shows that this MLG map deviates from measurements by up to 20 cm in peat areas (STOWA, 2010), but there is currently no alternative national MLG map available. We assume that this map represents the situation around 2020. For urban areas, the

National Hydrological Model v3.4 (LHM) (Hunink et al, 2019) was used (recommendation in Erkens et al. 2018).

Water level areas

Surface water levels are defined per water level area. Water level areas generally encompass several dozen individual parcels and have uniformly managed surface water levels. To prevent undesirable wet conditions due to subsidence, periodically water levels are lowered to restore the original drainage level. To mimic this water-management cycle in Atlantis, the groundwater level may be periodically adjusted per water level area. Within one water level area the surface water level is lowered by the median simulated subsidence within that area every 10 years. Atlantis assumes that any adjustment of the surface water level corresponds to an equal lowering of the MLG. Delineation of the water level areas was based on an inventory for the LHM.

Climate warming scenario's

Climate warming affects land subsidence by creating more favorable conditions for peat oxidation and affecting groundwater levels due to changes in weather patterns. Both aspects were included in the scenarios, as follows:

1) The oxidation rate increases due to higher soil temperatures: A structural increase in mean air temperature due to climate warming will be transferred to the soil and increase the rate of degradation. A correction factor to account for this was determined using: representative air temperature timeseries for downscaled climate warming scenarios (mild and strong) for the Netherlands (KNMI, 2015) and an empirical relationship between organic matter degradation rate and temperature in Dutch peat soils (Hendriks and Vermeulen, 1997).
2) The MLG changes due to changing precipitation and evaporation patterns. The simulated impact of climate change on the MLG by *Deltascenario's Warm* (scenario strong) and *Rust* (scenario mild) were used for this purpose (Wolters et al., 2018). These scenarios assume limited socio-economic development. The MLG changes were imposed stepwise per 10-year stress period assuming linear change.

Results and conclusions

Figure 3 shows the predicted amount of land subsidence in the Netherlands under two different future scenarios. Both maps show predominantly subsidence in the western and northern part of the Netherlands, but subsidence rates are up to 25% higher in areas peat soils for scenario *business as usual* (Table 1). In subsidence prone areas (> 3 cm cumulative subsidence in 30 years) land subsidence rates will range between 4.5 and 5.2 mm/yr on average (Table 1). To some extent both maps delineate the distribution of peat soils in the Netherlands, as here the largest subsidence levels appear (>10 cm). These soils feature oxidation in addition to compaction, which can be a persistent mechanism especially with low groundwater levels. Also clay soils show considerable subsidence due to mechanical compaction (Table 1).

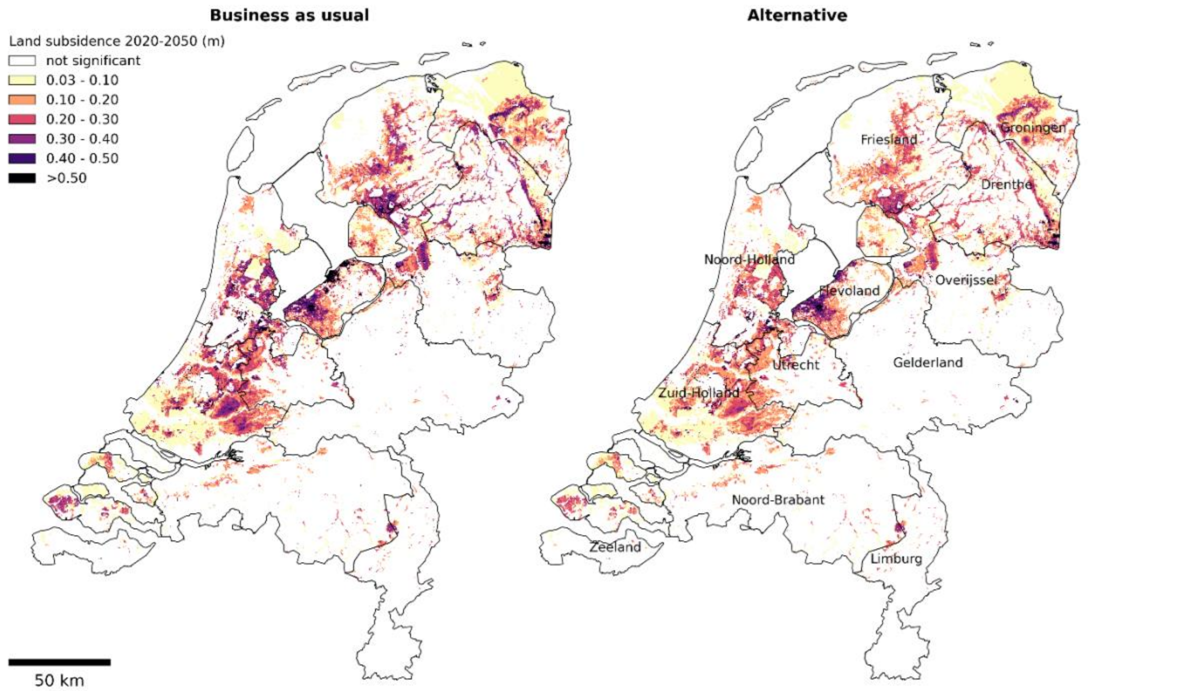

Figure 3 Predicted land subsidence (2020-2050) for two scenarios: business as usual (left) and alternative (right). Provinces are indicated in the right map. The maps can be downloaded in GIS format from the Dutch Climate Impact Atlas.

Comparing these maps demonstrate how water level management and climate warming may affect subsidence as combined processes. Scenario *business as usual* is effectively the continuation of the current practice, while the scenario *alternative* requires a serious transformation in water-management. The maps show that such a transformation may reduce land subsidence up to 40% locally. The difference between both scenarios in the peat areas in the province of Drenthe is less pronounced. Water flows here under a natural gradient due to subtle height differences, complicating strict water-management. Measures such as water level fixation may not be as affective here, if even practically feasible.

These maps also demonstrate that to halt land subsidence even more extreme measures than water level fixation are required, such as pressurized subsurface infiltration (Boonman et al., 2022). The importance of mitigation measures is becoming increasingly evident, especially in peatlands where oxidation is also responsible for significant greenhouse gas emissions. The spatial implementation of mitigation measures (where, how, and how much) are currently debated. Predication maps as presented here, can support the process of decision making.

Table 1: mean land subsidence rates (mm/yr) for different areas for two scenarios

	Business as usual	**alternative**
Mean subsidence in the Netherlands	1.30	1.11
Mean subsidence (areas > 3 cm in 30 years)	5.17	4.54
Mean subsidence peat soils	6.77	5.43
Mean subsidence clay soils	4.56	4.18

The subsidence prediction maps likely over- or underestimate subsidence, and a thorough understanding of the accuracy of the maps is still lacking. A lack of accurate land subsidence measurements hampers validation of the modelling concepts and parametrization based on simulations back in time. Sensitivity analyses will help to gain insights of the reliability of the subsidence and future work will focus on this.

This study demonstrates that with the Atlantis modelling framework we can make predictions of lands subsidence in a consistent manner using readily available datasets. Moreover, the significantly reduced computational times support consistent nationwide scenario exploration (hours instead of weeks). The maps will be updated in the future in consultation with potential users and with improved datasets and insights.

Acknowledgements

We thank Jan Stafleu from the TNO – Dutch Geological Survey, and Jan van den Akker and Guido Bakema from Wageningen Environmental Research, for their cooperation. We also thank Climate Adaptation Services for funding this project.

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