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GEOTOP: A STANDARD IN 3D LAND SUBSIDENCE STUDIES IN THE NETHERLANDS

Introduction

The Geological Survey of the Netherlands (TNO-GDN) has developed a suite of 3D geological subsurface models. In this contribution we address the protocol used for developing one of these models: GeoTOP. We show its applied value in recent subsidence studies, focusing on the coastal plain of the Netherlands, and provide a perspective on its future use by governmental decision makers and other users under the newly implemented Key Register of the Subsurface.

GeoTOP

GeoTOP is a high-resolution voxel model that covers the subsurface down to 50 m below mean sea level (Figure 1). Each voxel is a volumetric cell in a regular, rectangular grid bounded laterally by

regionally delimited model boundaries. GeoTOP has a grid resolution of 100 x 100 x 0.5 m, and its millions of cells are attributed with lithostratigraphy, lithology, and associated probabilities (Stafleu et al., 2011; 2020). It is based on approximately 455,000 coded borehole descriptions from the national subsurface database DINO, operated by TNO, complemented with 125,000 borehole logs from Utrecht University. At present, GeoTOP consists of eight model areas, covering most the subsiding lowlands.

Drivers of subsidence

Prime subsidence-governing processes in the shallow subsurface are oxidation of peat, as well as shrinkage and compression of Holocene peat and clay. These processes are human-induced.

They result from artificially low phreatic groundwater levels and from overburden pressure generated by man-made overburdens of sand, put in place to ensure that planned buildings or infrastructure will have long-term stability. The low groundwater levels results in aeration of the peat, which facilitates oxidation of organic matter, leading to emission of CO₂. In the past, subsidence was locally exacerbated by peat mining for fuel. Altogether, approximately half of the coastal plain has subsided to below mean-sea level.

Subsidence studies

GeoTOP is the standard tool in land-subsidence studies at TNO-GDN. It covers most of the subsiding coastal plain, has sufficient vertical resolution, and schematizes the distribution of

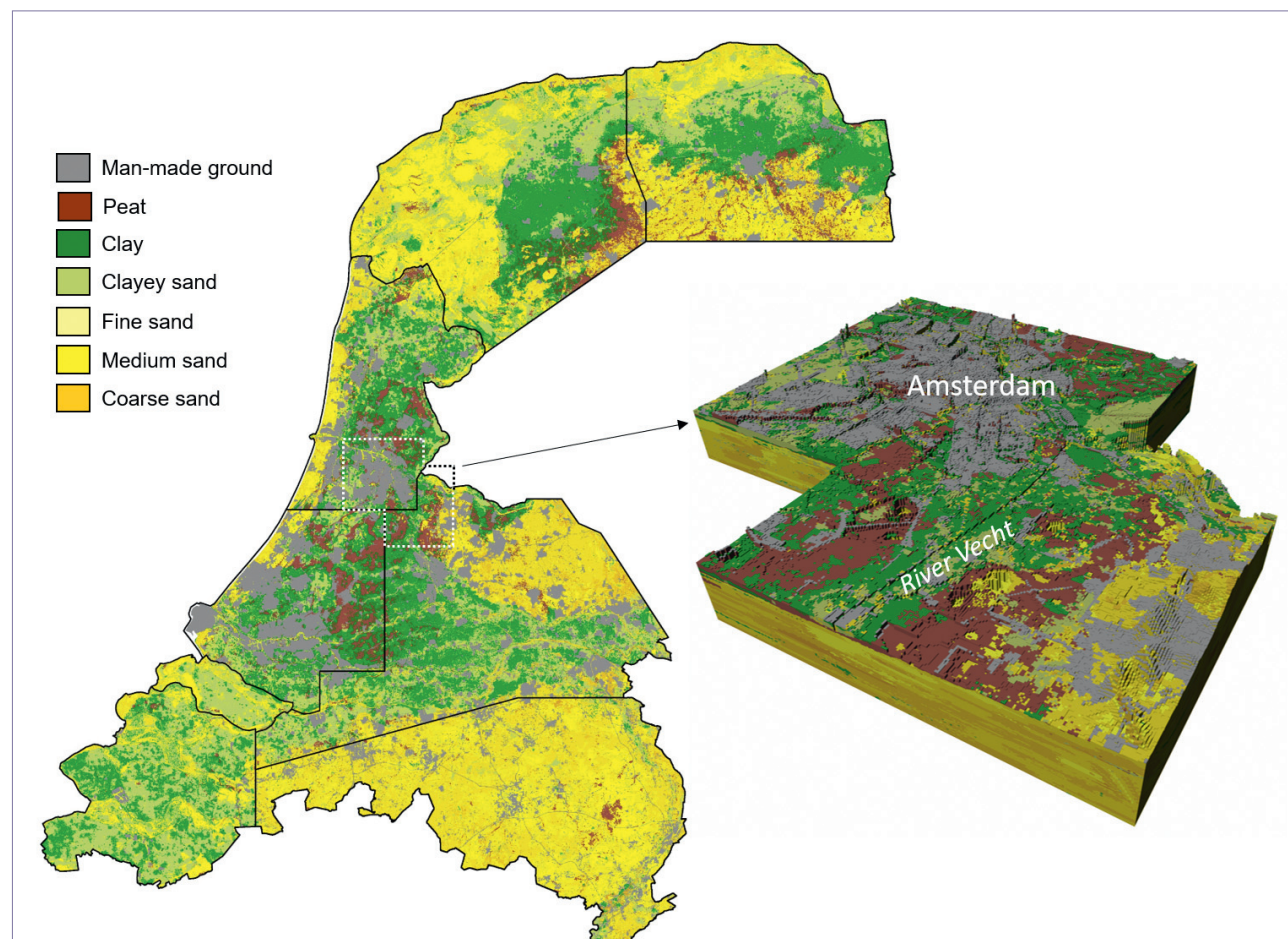


Figure 1 – The eight model areas of GeoTOP, and zoomed-in view of the peat-rich area of Amsterdam. The voxels are attributed with the most likely lithology.

SUMMARY

The Geological Survey of the Netherlands maps the Dutch subsurface systematically in 3D. Here we outline the development of GeoTOP, its recent application in subsidence studies, and its use under a newly implemented key register of the subsurface. Recent studies based on GeoTOP confirm that agricultural areas are more prone to subsidence by peat compression and

oxidation than major urbanized areas. Subsidence is greatest in the central delta, a rural region that emits a lot of oxidation-related CO₂, contributing to the greenhouse effect. Implementation of GeoTOP in the key register enables governmental stakeholders to make the right subsidence-related decisions.

the peat and clay layers prone to subsidence in a consistent and reproducible way (Van der Meulen et al., 2013). Furthermore, its data format and software infrastructure are well suited for easy combination with datasets on other parameters relevant for subsidence studies, such as density of organic matter, phreatic groundwater level, and CO₂ emission.

A recently conducted subsidence study addressed forward modelling of peat oxidation and compression under scenarios of progressively lowered groundwater levels in the coastal plain (Koster et al., 2018a). It revealed that urbanized areas are expected to experience less subsidence in the next 15 to 30 years (< 0.4 m) than surrounding

agricultural areas (0.3 to 0.8 m) (Figure 2). This difference is explained by the presence of man-made overburden in urbanized areas, commonly many meters thick, which has pushed the underlying peat into a position well below the water table and has reduced its void ratio. Here, a lowered phreatic groundwater level will not expose the peat to the atmosphere, preventing it from being oxidized. Furthermore, the low void ratio reduces further compressibility of the peat in response to changing hydrostatic pressure. The predicted difference in subsidence behavior does not apply to areas where groundwater is extracted from deep aquifers. In many coastal plains worldwide, cities are subsiding faster than agricultural land.

We designed a workflow to attribute GeoTOP voxels that classify as Holocene peat with values of organic matter density and carbon content (Koster et al., 2018b; Koster et al., 2020). For this purpose, we created a training dataset of hundreds of measurements on the amount of organic matter, sediment, and void ratio of peat layers sampled in different areas of the coastal plain at different depths. Thus, we were able to identify areas most prone to peat oxidation and associated CO₂ emission in response to predicted lowering of the phreatic groundwater table. The modeling results show that approximately 10% of about 15 km³ peat situated in the subsurface of the entire coastal plain is organic matter, which would yield some 2 billion tons of CO₂ when oxidized. For reference, the current annual CO₂ emission in the Netherlands is slightly less, at 1.9 billion tons (CBS, 2019). Clearly, the remaining peat is a major potential source of CO₂, easily released when unwise land-management decisions are taken. Most of this vulnerable organic matter is found in the central delta (Figure 3). Other hotspots are major cities in the western coastal plain, including Rotterdam and Amsterdam, where peat is heavily compressed and preserved below man-made overburdens of sand.

Following up on deploying GeoTOP for peat compression and oxidation studies, we now aim at parameterizing GeoTOP voxels for predicting clay compaction and shrinkage. In support, we combine GeoTOP with a forward-model workflow that simulates scenarios and stems from compaction studies of deep gas reservoirs (Candela et al., 2020). We also deploy a database containing several thousands of geotechnical measurements collected by TNO-GDN during a nation-wide mapping campaign. Subsidence observations from land levelling, GPS, and satellites (InSAR) are indispen-

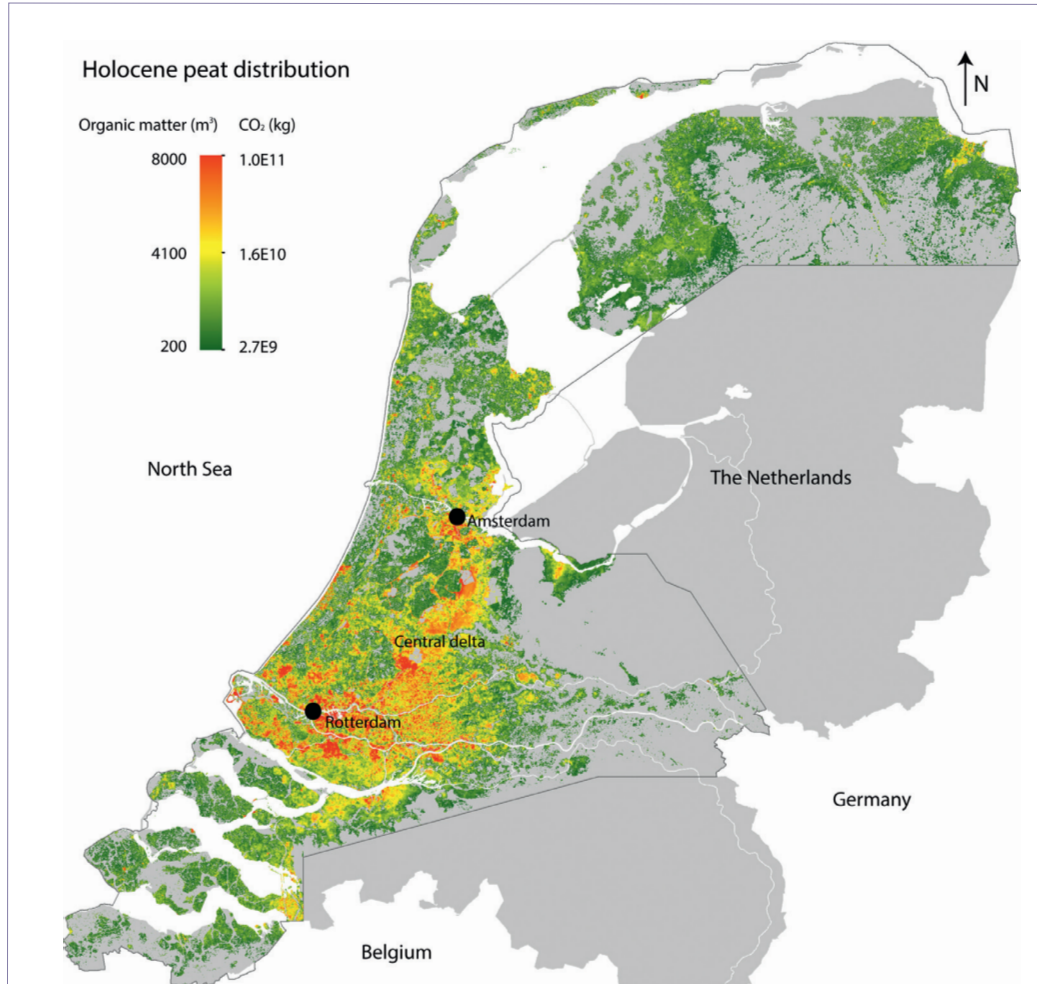


Figure 2 – Peat thickness, subsurface lithology, and subsidence through compression and oxidation of peat in the Rotterdam area, for a 0.5 m lowering of the phreatic groundwater level during 30 years (Koster et al., 2018a). For the legend of the subsurface lithology, see figure 1, and for location of the Rotterdam area see figure 3. The hatched areas in the maps denote urbanized zones.

sable in cross-checking the forward model during data assimilation. Combining GeoTOP and this forward-model workflow is a critical step forward in identifying and quantifying the contribution of each of the processes causing subsidence, and eventually in supporting informed decision making on groundwater management. Knowledge-based decisions balancing conflicting interests of stakeholders, minimizing and mitigating subsidence and associated CO₂ emissions, are a key component of sustainable governance.

Key Register of the Subsurface

As of 1 January 2020, GeoTOP is part of the Key Register of the Subsurface, and therefore embedded in law. The aim of the key register is to improve the accessibility of subsurface information for a broad spectrum of applications, including spatial planning, construction, and assessment of risks such as land subsidence. Under Dutch law, projects or studies paid for by governments at all levels are required to consult existing and contribute newly collected data and data products to the key register. Now that it is mandatory to consult GeoTOP, its use will intensify and feedback of its accuracy and functionality is expected to increase substantially.

GeoTOP's spatial resolution renders it useful for neighborhood as well as national levels. The model is expected to become the standard for land-subsidence studies financed with money from municipalities, waterboards, provinces and other governmental entities. These stakeholders and their contractors can now deploy GeoTOP to study the effects of changes in phreatic water levels or land use change. They will be able to assess and compare local to national subsidence-related risks associated with different scenarios of water-table lowering and other lowland-management measures.

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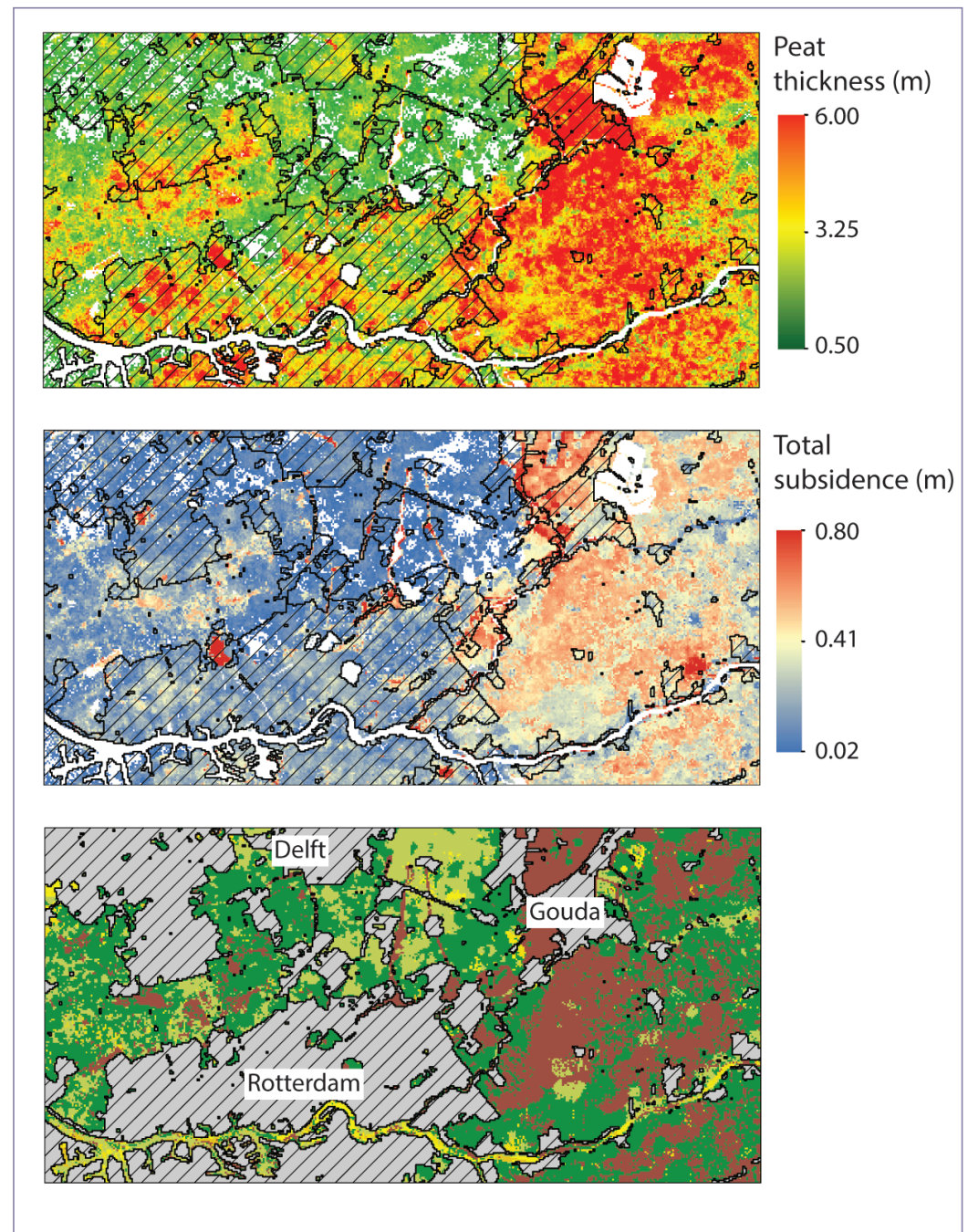


Figure 3 – Spatial distribution of Holocene peat in the area covered by GeoTOP (except for the southernmost GeoTOP area), with associated volumes of organic matter and maximum amounts of CO₂ emitted in case of oxidation (after Koster et al., 2018b).

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