Land subsidence by peat oxidation leads to enhanced salinization through boils in Dutch polders

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ABSTRACT

Peat oxidation in deep Dutch polders leads – in addition to subsidence - to the development of new saline boils, enhancing the salinization of these polders. This on-going process is studied in detail in the Middelburg-Tempelpolder. The objective of the study was to get more in-depth knowledge about this process and to assess it for the present situation and for future landscapes (after 10, 50, 100 and 500 years).

INTRODUCTION

Salinization of deep polders of the Netherlands (reclaimed lakes) happens mainly through boils, contributing more than 50% to the total salt load (De Louw, 2013). Boils occur as conduits in the upper aquitard, connecting the underlying aquifer to the surface and allowing groundwater to discharge at high velocities (Figure 1). Concentrated types of groundwater discharge at higher rates like boils, discharge groundwater from deeper strata with more salty groundwater than diffuse types of seepage at low rates. Due to this natural saltwater upconing process (De Louw et al., 2013) the salinity of groundwater discharged by boils is much higher than diffuse types. The saline groundwater in the aquifers originates from marine transgressions during the Holocene.

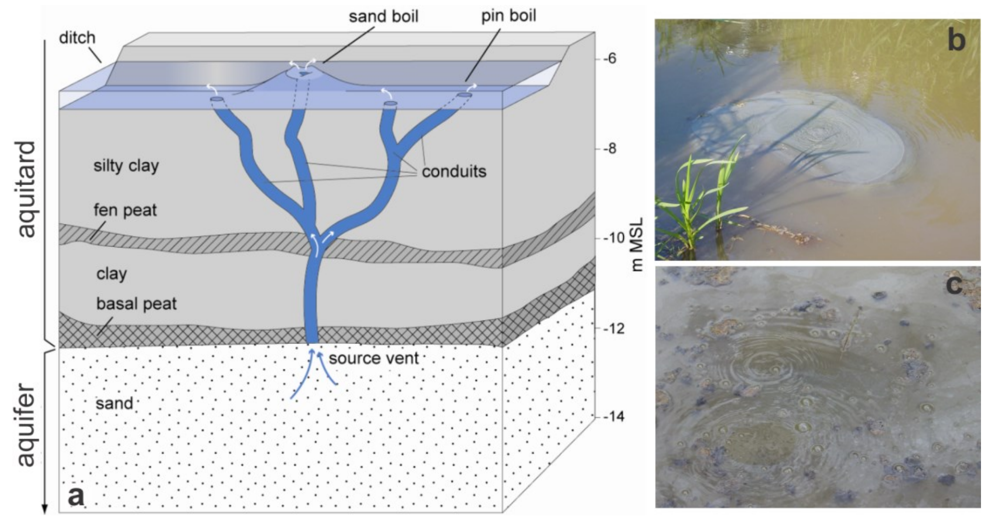

Figure 1. Boils in deep polders: (a) diagram of boils with several conduits in aquitard, (b) sand boil transporting sand from the aquifer (c) a boil emitting water and methane (adapted from De Louw et al., 2013).

Boils develop when the pressure of water in the aquifer is greater than the pressure exerted by the weight of the overlying stratum. Due to the higher water pressure, heaving and cracking of the soil occur, creating flow pathways that lead to the development of boils. This is the reason why boils mainly occur in deep polders where large hydraulic gradients exist and where hydraulic heads of the upper aquifer exceed ground levels (see Figure 2).

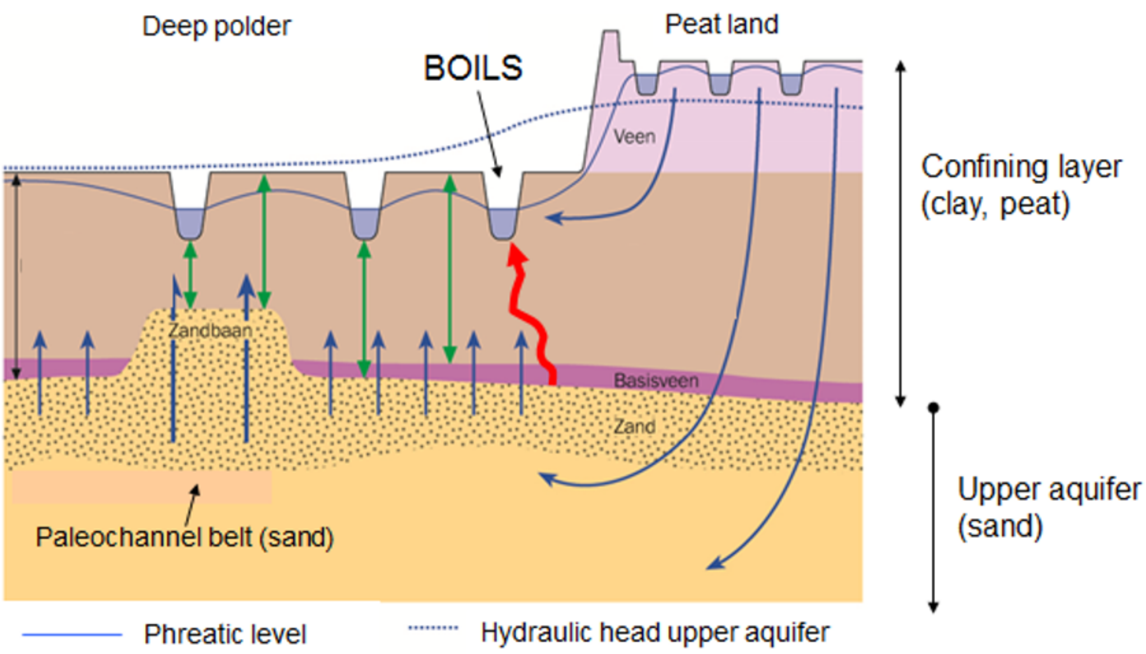

Figure 2. Hydrogeological cross section through a typical deep polder and adjacent elevated peatland. Heaving and cracking of the soil occurs when the water pressure (hydraulic head) in the upper aquifer (blue arrows) exceeds the weight of the overlying confining layer (green arrows).

The topsoil of most Dutch deep polders consists of clay, as most peat has been mined or degraded over the last centuries. However, some polders still have shallow peat remaining. Peat oxidizes when it comes in contact with air (oxygen), resulting in a reduction of peat volume,(oxidation) and consequently land subsidence. The average land subsidence in the Netherlands is about 0,8 mm per year (Van den Born et al., 2015). In oxidation prone areas, typically water levels are maintained by the Water Boards as high as possible to slow down subsidence. This means an average surface water level of about 20 to 60 cm below ground level, which is just deep enough to facilitate dairy farming. To sustain the aforementioned drainage depths under conditions of progressive subsidence, surface water levels must be periodically lowered, evoking new subsidence. This forms a self-perpetuating circle, which lead to meters of subsidence in the Dutch peatlands over the last 10 centuries (Erkens et al., 2016). With ongoing subsidence and decreasing confining layer weights, the risk of new boils development increases and consequently also the salinization of the polder will increase.

The process of land subsidence, the development of boils and related salinization is studied in detail for a deep polder called Middelburg-Tempelpolder (MT-polder). The objective of the study was to get more in-depth knowledge about this process and to assess it for the present situation and for future landscapes (after 10, 50, 100 and 500 years).

METHODS

We have combined modeling with an extensive field survey to collect detailed information about geology, hydraulic heads, land subsidence, heaving and cracking, occurrence and development of boils and the history of boil development.

The field survey contained the following elements:

- Interview of farmers: to collect data about (1) agricultural activities in subsiding areas with boils, (2) location of boils and history of boil development, (3) their view regarding future developments and solutions.
- Detailed geological borehole descriptions (in total 31 geological drillings until 5 to 11 meter depth).
- Weighting of wet bulk density samples of different lithology.
- Installation of 15 piezometers in the aquifer to measure the hydraulic head in the upper aquifer as well as the salinity of the groundwater. At most locations also phreatic piezometers were installed.
- EC (salinity) and temperature routing to map boils and quantify the salinization of the polder.

The modeling exercises involved:

- Groundwater modeling of hydraulic head in upper aquifer using Seawat (present situation)
- Construction of 3D-geological model (present situation)
- Producing maps of the risk index (for heaving/cracking and, hence development of saline boils) (present situation), the index being the ratio of overburden weight and hydraulic head at the base of the confining layer.
- Modeling land subsidence using land subsidence model Phoenix (Geisler, 2015) due to peat oxidation and resulting landscapes after 10, 50, 100 and 500 years.
- Modeling hydraulic heads for future landscapes resulting from land subsidence after 10, 50, 100 and 500 years.
- Calculating the risk index of the development of saline boils for the future landscapes 10, 50, 100 and 500 years after present.
- Quantifying the salinization of the polder through boils for the different future landscapes.

Finally, potential policy actions for the Water Boards concerning water management of the polder and for the farmers will be formulated based on this combined field and modeling study. The results of this regional study will be extrapolated to all other deep polders with shallow peat occurrence, which are undergoing significant land subsidence by peat oxidation.

RESULTS

This study started in October 2017 and will finish in May 2018 and the most significant results will be presented at the SWIM. In this extended abstract, merely some highlights of the results will be presented since both the field survey and modeling exercises are halfway.

The modeled hydraulic head exceeds ground level for about 50% of the MT-polder with the largest hydraulic heads up to 0.75 cm above ground level at the edges of the polder (Figure 3). The confining layer is 3 to 6 m thick, consists of peat and clay, and serves as an aquitard on top of the upper aquifer. Saturated peat has a much lower weight than clay, 0.9-1.1 g cm^{-3} and 1.3-1.6 g cm^{-3} respectively. The combination of large hydraulic heads and the subsoil consisting largely of peat, results in high risks for saline boil developments (Figure 3). These preliminary calculations are based on regional and national scale data.

The collected data of lithological composition of the confining layer and hydraulic heads during the field surveys will be used to improve the reliability of the model calculations. With the improved models, the different hydraulic heads and risk for saline boils developments due to land subsidence will be calculated for the future landscapes (10, 50, 100 and 500 years). Two water management scenarios will be assessed: (1) surface water levels follow the land subsidence to maintain favorable conditions for agriculture, (2) surface water levels will be fixed to slow down land subsidence. For the first water management scenario, areas with peat at the surface will subside with a rate of approximately 5 mm/year leading to ~0.25 meter of land subsidence in 50 years. Land subsidence will continue until all peat has been oxidized. With the fixed level scenario soil subsidence will slow down due to increasingly wet conditions (less oxygen intrusion). The subsidence will eventually stop when the land surface subsides to the fixed water levels causing anoxic conditions preventing the oxidizing of peat. However, this will lead to the disappearance of traditional dairy farming agriculture due to wet conditions.

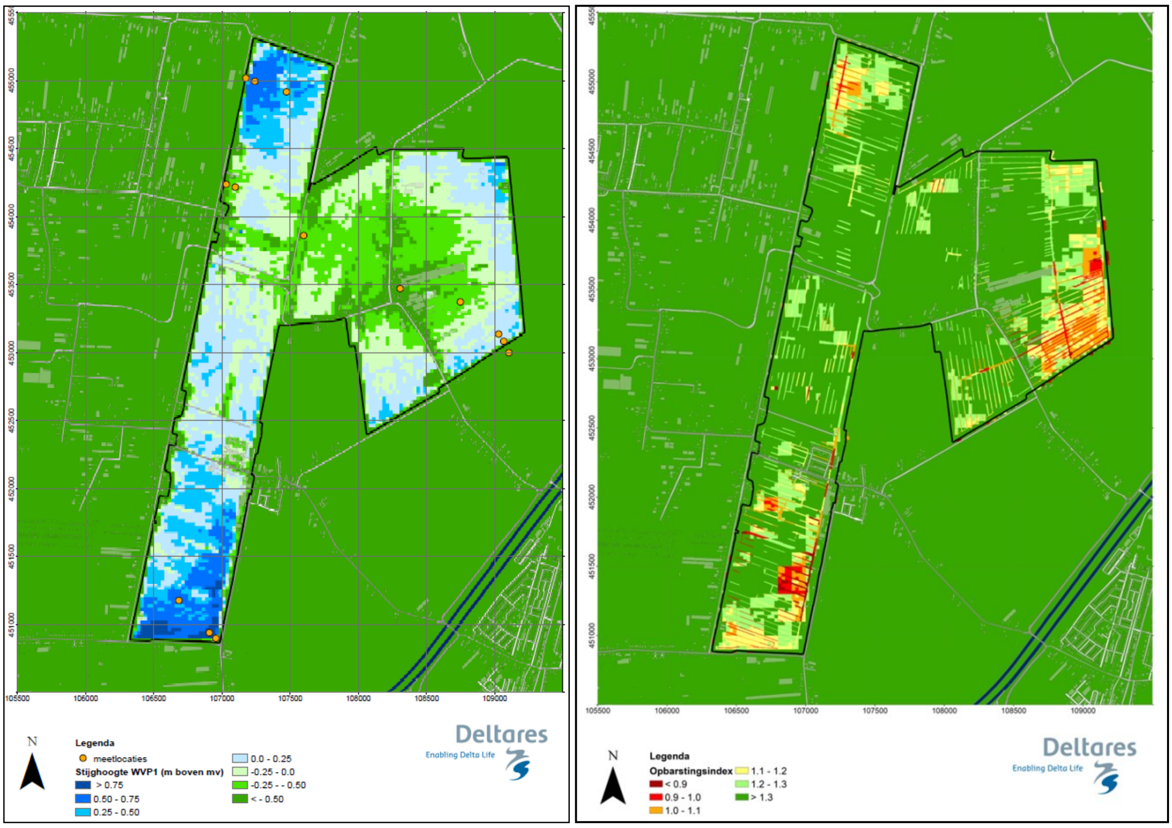

Figure 3. Left: The modeled hydraulic head in the upper aquifer, referenced to ground level. At the edges of the polder, the hydraulic head rises up to 80 cm above ground level causing high risk for boil development. Right: The risk for the development of saline boils for the MT-polder. A value lower than 1.1 indicates a high risk for boil development, a value higher than 1.1 indicates a low risk.

First calculations show that land subsidence will increase the risk for boil development and consequently enhances salinization for most areas. However, for some areas the opposite is true. Due to regional land subsidence, the hydraulic head will be lowered too and when the reduction of the hydraulic head outranges the weight reduction by peat oxidation, the risk of boil development decreases. The development of new boils will therefore be stagnated for these areas when only land subsidence is taken into account. However, all activities that reduce the weight of the confining layer, such as excavations and lowering of surface water levels, may lead to the development of new boils and consequently enhanced salinization. The field surveys result in new insights and confirms existing theory about boil developing and salinization. According to the farmers, most boils are old and only a few have developed recently. However, the old boils still discharge saline groundwater and when they occur on land, the boils limit the agricultural production due to wet and saline conditions and in-accessibility of the land for machines due to the low bearing capacity of the soil. Most boils developed directly after the formation of the polder (reclamation of lake) at the end of the 19th century. But also during periods with increased hydraulic head conditions (e.g. due to reduced groundwater extraction), lowered surface water levels, constructing ditches and canals or other activities when soil is removed, have caused the development of boils. Figure 4 shows pictures of boils in the MT-polder. During a short frost period, the boils in the ditches were clearly visible as holes in the ice (Figure 4c-d), due to the constant temperature of the groundwater of 10.5 ^{o}C being discharged via boils. For two ditches with a total length of 950 m at the north-eastern edge of the MT-polder in total 60 large boils and 66 small boils were visually mapped during the frost period, resulting in a boil density of 1 boil every 7.5 meter. About 75% of the boils found in the field occur in the zones where the calculated risk for boils development is high (Figure 3). With the data locally collected in the field, the risk calculations will be improved significantly.

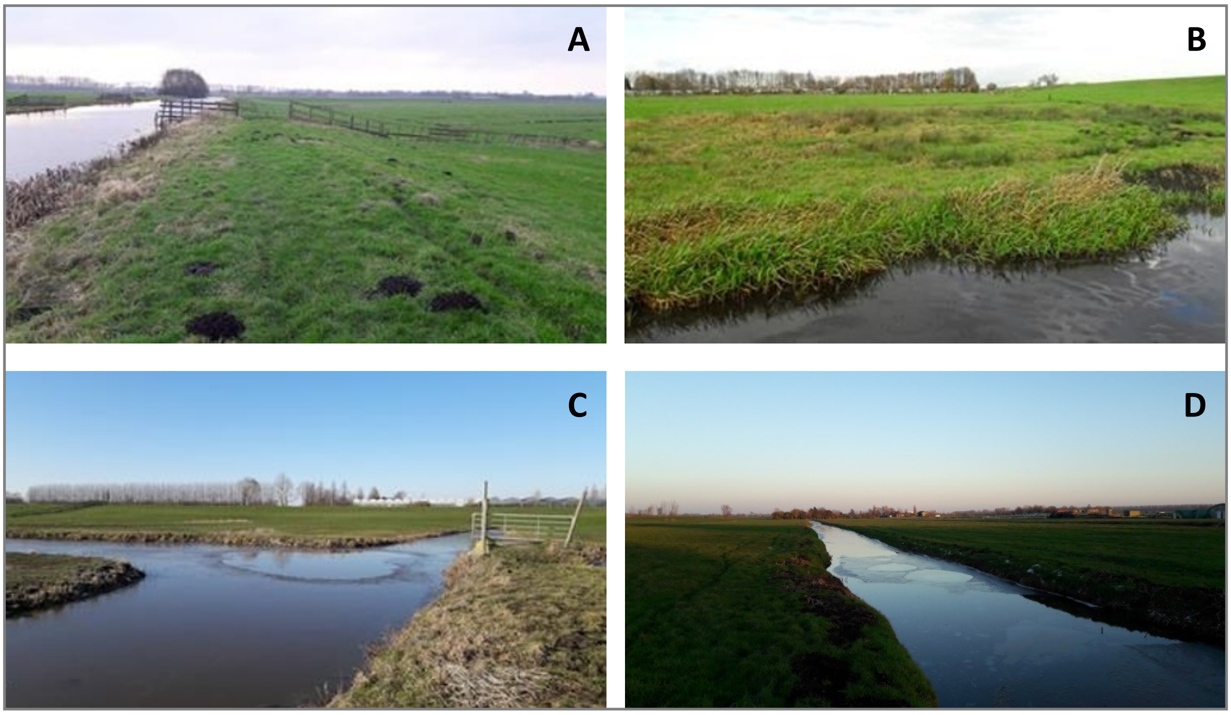

Figure 4. (A) Height difference of 3 meter between peat land (left) and deep polder with shallow peat occurance (right) causing large hydraulic gradients. (B) Boil on land surface causing wet saline conditions and soft soil. (C) and (D) Boils in surface water which don't freeze due to constant temperature of 10.5 ^{o}C of discharging groundwater.

From the 15 installed piezometers, groundwater from the upper aquifer just below the confining layer was sampled, and the salinity was measured. According to earlier findings (De Louw, 2013), almost all groundwater directly below the confining layer was fresh (EC < 1.200 µS/cm) except for three piezometers in the centre of the polder, and most boils were saline (EC 4.000 – 10.000 µS/cm). Boils have a much higher salinity than the diffuse types of groundwater seepage due to saltwater upconing whereas diffuse seepage only discharges groundwater from the top of the aquifer. Hydraulic head measurements in the installed piezometer confirm the modelled larger hydraulic heads at the edge of the polder (0.20-0.6 m above ground level) than in the centre of the polder (just above or below ground level). The measured hydraulic heads in the south-eastern part of the MT-polder are lower than the modelled ones which is probably due to the increased discharge of groundwater as a result of a large number of boils in this part of the polder. These boils were not incorporated in the model and this effect on the hydraulic head was therefore not accounted for.

SUMMARY

From the results so far the following preliminary conclusions can be made:

- Collecting local data increased the knowledge about the boil development process and improved the models (groundwater, geology, land subsidence).
- The combination of large hydraulic heads and shallow peat in the subsurface results in high risks for saline boil development.
- Land subsidence by peat oxidation result in both a reduction of the hydraulic head and weight of the confining layer. The ratio determines whether this would lead to an increase or decrease of the risk of boils development.

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