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Characterizing preferential groundwater discharge through boils using temperature

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SUMMARY

In The Netherlands, preferential groundwater discharge trough boils is a key process in the salinization of deep polders. Previous work showed that boils also influence the temperature in the subsurface and of surface water. This paper elaborates on this process combining field observations with numerical modeling. As is the case for salinity, a distinct anomaly in the subsurface and surface water temperature can be attributed to boils. Lines of equal temperature are distorted towards the boil, which can be considered as an upconing of the temperature profile by analogy of the upconing of a fresh–saltwater interface. The zone of this distortion is limited to the immediate vicinity of the boil, being about 5 m in the aquitard which holds the boil's conduit, or maximum a few dozens of meters in the underlying aquifer. In the aquitard, heat transport is conduction dominated whereas this is convection dominated in the aquifer. The temperature anomaly differs from the salinity anomaly by the smaller radius of influence and faster time to reach a new steady-state of the former. Boils discharge water with a temperature equal to the mean groundwater temperature. This influences the yearly and diurnal variation of ditch water temperature in the immediate vicinity of the boil importantly but also the temperature in the downstream direction. Temporary nature of the boil (e.g. stability of the conduit, discharge rate), uncertainty on the 3D construction of the conduit and heterogeneity of the subsoil make it unlikely that temperature measurements can be interpreted further than a qualitative level.

1. Introduction

In many low-lying coastal areas, groundwater is saline because of seawater intrusion or because saltwater is not flushed completely by fresh water after the Holocene marine transgression (Custodio and Bruggeman, 1987; Stuyfzand and Stuurman, 2008). In such areas, upward seepage of saline and nutrient-rich groundwater results in the salinization and eutrophication of surface waters. With one-quarter of its surface lying below mean sea level, The Netherlands forms no exception (van Rees Vellinga et al., 1981; van Puijenbroek et al., 2004; van der Eertwegh et al., 2006; de Louw et al., 2011). Because of land subsidence, sea-level rise and climate change, it is expected that this will be enhanced in the near future (Oude Essink et al., 2010).

Seepage is especially important in deep polders. These are artificially drained low-lying areas, in most cases reclaimed lakes, in which the surface water level is regulated by pumping. De Louw et al. (2010) recognized three types of seepage in deep polders: (i) diffuse seepage through the top aquitard, (ii) preferential seepage through permeable paleochannels insisted in the top aquitard and, (iii) preferential seepage through boils. Especially boils received less attention in the literature until recently (de Louw et al., 2010, 2011, 2013), although many studies show that groundwater seepage could occur through preferential pathways (e.g. Becker et al., 2004; Conant, 2004; Kalbus et al., 2009; Kishel and Gerla, 2002; La Sage et al., 2008) and that this may have important implications for the chemical loading to surface waters (Keery et al., 2007; Tesoriero et al., 2009). In general, boils are small vents which connect the underlying aquifer with the surface water or ground level through the top aquitard (Fig. 1a). The large head change over the top aquitard (up to 2.5 m) results in a flow of water through the boil's conduit. Boils occur dominantly in ditches and may be clustered with many conduits or exist as a single boil with one conduit. Fluxes through individual conduits range from 0.5 to 100 m^3/d. Because saline water is found at shallow depth in the aquifer, upconing of saline water to boils occurs, forming a source of salinity for surface waters. De Louw et al. (2010) found that this preferential seepage through boils is the dominant salt source in deep polders and quantified a contribution of 66% to the total salt load for the Noordplas Polders (De Louw et al., 2011). By contrast, boils contribute only about 15% of the total

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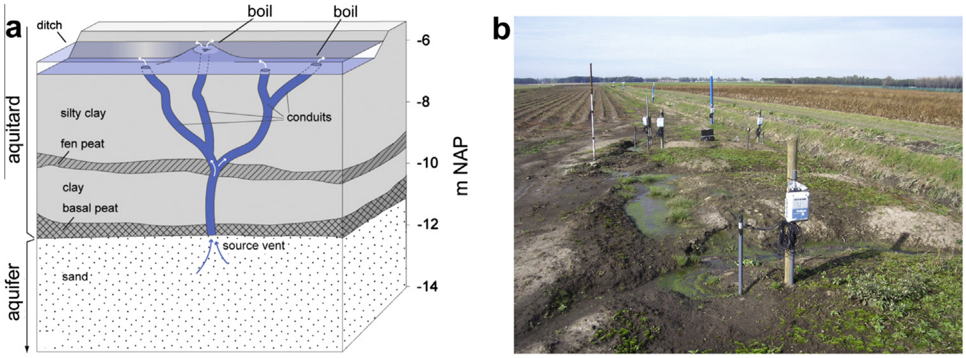

Fig. 1. Schematic diagram of boils with several conduits (a) and an example of monitoring equipment (b) (adapted from de Louw et al., 2013).

water flux into this deep polder. Therefore discharge through boils is a key process in the salinization of Dutch deep polders.

Temperature has been successfully applied as a tracer to determine seepage from groundwater into surface water (Anderson, 2005; Becker et al., 2004; Conant, 2004; Constantz, 1998; Lapham, 1989; Lowry et al., 2007; Niswonger et al., 2005; Silliman et al., 1995; Stallman, 1965; Stonestrom and Constanz, 2003). It is expected that boils also influence groundwater temperature and, in case the discharge is in a ditch, ditch water temperature. Hoes et al. (2009) for instance identified localized seepage in a ditch (some of which were probably boils) using the Distributed Temperature Sensing (DTS) technique whereby a fiber optic cable is used as a sensor. De Louw et al. (2010) showed that boils have an important effect on the temperature distribution in the aquitard. Temperature isolines are clearly influenced by the upconing of water with constant temperature from deeper in the aquifer.

In this paper we elaborate on the effect preferential seepage through boils has on temperature of the surface water and the subsoil. Secondly, heat is used as a tracer to supplement the knowledge of the characteristics and dynamics of boils. Field measurements on groundwater and surface water at three different settings in which boils occur and numerical modeling of heat transport is therefore combined.

2. Material and methods

2.1. Field sites and observations

Preferential seepage through boils was monitored in detail at three sites (Fig. 2), each with a different geological context. Site A is located in the Haarlemmermeer polder and is characterized by a top aquitard of Holocene clay and peat layers with a thickness of 6 m. A number of boils are visible at the surface, at a distance of about 10 m from a ditch. Site B is situated in the Noordplas polder and has a 7 m thick top aquitard. A number of boils are present in the side of a ditch. At the location of the boils, the thickness of the aquitard is reduced to 3 m by the occurrence of a small (width of about 20 m) paleochannel. No aquitard occurs at location C, also located in the Haarlemmermeer polder. The site is an old tidal channel with only localized clay lenses in the aquifer. Because the absence of stiff clay, locations with increased local seepage are distributed in the ditch over a length of about 30–40 m. Presence of conduits occur only temporary. Moreover, the position and activity of the boils at site C change regularly due to varying weather conditions (changes in atmospheric pressure). Boil activity is the highest during periods of low atmospheric pressure. The phenomenon that the discharge of springs and open wells var-

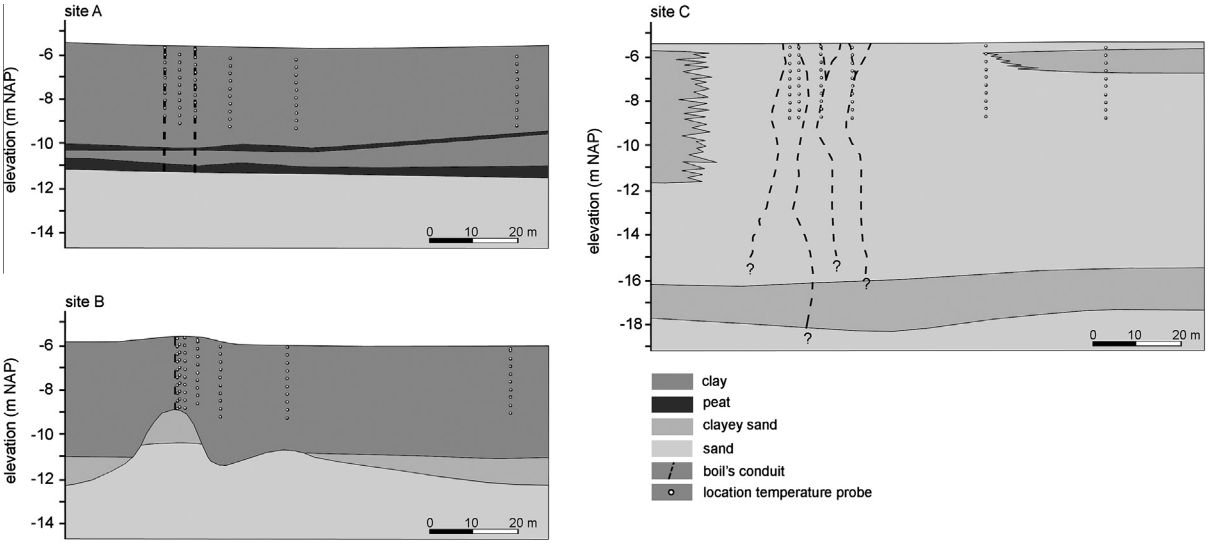

Fig. 2. Geological cross-sections and location of the temperature probes for the three sites.