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Effects of intake interruptions on dune infiltration systems in the Netherlands, their quantification and mitigation

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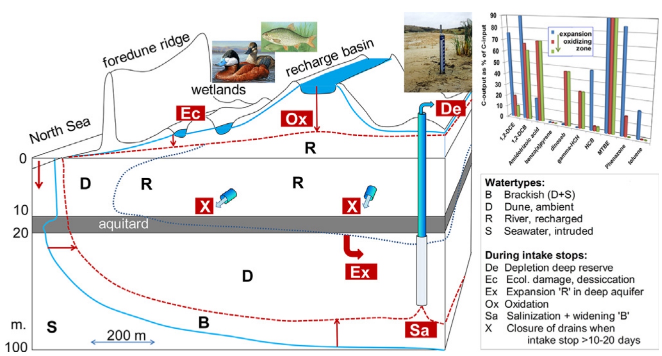
HIGHLIGHTS

- Frequency and duration of intake stops will increase due to climate change.
- Hydrological, hydrochemical and ecological effects are serious but manageable.
- Effects of salt water intrusion and aquifer oxidation can be predicted.
- A magnitude scale for intake stops (MIS) is proposed.
- Presented mitigation strategies help to cope with intake interruptions.

GRAPHICAL ABSTRACT



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ABSTRACT

In the coastal dunes of the Western Netherlands, managed aquifer recharge (MAR) is applied for drinking water supply since 1957. The MAR systems belong to the Aquifer Transfer Recovery (ATR) type, because recharge and recovery are operated without interruption. This makes these systems very vulnerable to intake interruptions, which are expected to increase in frequency and duration due to climate change. Such interruptions are problematic, because: (i) groundwater recovery from dunes needs to continue to supply fresh drinking water to the Western Netherlands; (ii) risks of salt water intrusion are high, and (iii) MAR bordering wet dune slacks with an EU Natura 2000 status cannot survive for long without MAR.

In this paper, effects of intake stops are discussed and quantified. The hydrological effects consist of the decline of water tables, disappearance of flow-through dune lakes, reservoir depletion, salt water intrusion, disruption of rainwater lenses, and entrapped air hampering a rapid refill of the groundwater reservoir. Water quality effects include changes in (i) redox environment of the flushed aquifer, impacting the behavior of nutrients, calcium, sulfate and organic micro-pollutants, and (ii) the mixing ratio of water types. The main ecological impacts comprise the dying of organisms in recharge ponds and dune lakes, and a decline of biodiversity.

Effects of very long intake interruptions (years) are predicted via historical observations during the long overexploitation period (1900–1957) prior to MAR. A closed form analytical solution for safe yield of a semiconfined aquifer is proposed, together with a related upconing risk index. Both also apply to the pumping from any fresh water lens without MAR.

Abbreviations: ASL, above sea level; ASR, aquifer storage recovery; ATR, aquifer transfer recovery; BAR, basin aquifer recharge; BSL, below sea level; DOC, dissolved organic carbon; MAR, managed aquifer recharge; MIS, magnitude of intake stop(s); MSL, mean sea level; MTBE, methyl tertiary butyl ether; OMP, organic micro pollutant; SAT, soil aquifer treatment; SDBI, safe depth to brackish interface.

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Some mitigation strategies are discussed, such as a dual intake, raising the storage capacity, earlier mud removal, and accelerated refilling of the reservoir. A magnitude scale for intake stops (MIS) is proposed.

1. Introduction

Managed aquifer recharge (MAR) is increasingly applied in the world, in various ways, to restore groundwater tables, reverse salt water intrusion, store water for later use, improve the infiltrated surface water quality, or dispose of undesired water (Todd, 1959; Huisman and Olsthoorn, 1983; Asano, 1985; Dillon, 2005; Bouwer et al., 2008). The various MAR systems can be roughly subdivided into 2 systems (Chadha, 2002): direct (e.g. recharge basins and injection wells) and indirect (e.g. river bank filtration and groundwater dams).

Most direct systems are discontinuous, because either (i) the recharge is periodically stopped, due to lack of (good) water to infiltrate, freezing conditions in winter, or the necessity to frequently remove mud from infiltration basins, or (ii) the recovery is periodically stopped because the stored water is not needed. Examples of such systems are Soil Aquifer Treatment (SAT) and Aquifer Storage and Recovery (ASR). SAT systems are applied where sewage effluent or other wastewater is to be reused or polished up by aquifer passage (Fox et al., 2006). ASR systems aim at storing abundant water in the rainy season in an aquifer for later use during droughts (Pyne, 2005; Maliva and Missimer, 2010).

Aquifer Transfer Recovery (ATR) systems belong to the continuous, direct MAR category (Dillon, 2005). They consist of infiltration means (basins or wells), an aquifer to flush and store, and a remote recovery system composed of wells, drains or canals. They normally have a continuous supply of high quality infiltration water, a continuous water demand, and the need to use aquifer passage for water quality improvements.

Intake interruptions (stops) are and have always been a problem for MAR systems. For ATR systems they form a particular problem, because they are supposed to continuously deliver water after aquifer passage. This means that an intake interruption has to be coped with by one or a combination of the following options: (i) continuing the recharge via another intake if available; (ii) drawing water from the stored volume, (iii) drawing water from sources elsewhere, or (iv) reducing the delivery of drinking water.

In this contribution, we focus on dune infiltration systems in the Netherlands, which belong to the very vulnerable ATR type. Vulnerability to intake interruptions is high for 3 reasons. Firstly, the dune systems rely on surface water from the Rhine River or Meuse River, both of which are periodically heavily polluted (Aquapedia, 2014; Vliet and Zwolsman, 2008). Secondly, there is a high risk of intrusion of adjacent North Sea water and upconing of saline groundwater below the fresh groundwater lens, as experienced in the past (Stuyfzand, 1989b, 1993). And thirdly, the dune infiltration systems also support wet dune slacks with an EU Natura 2000 status. They contain protected flora and fauna, which cannot survive for long due to dependence on conditions sustained by MAR.

Climate change is expected to exacerbate the situation by increasing the frequency and duration of droughts and peak flows for both the Rhine River and Meuse River (Zwolsman and Van Bokhoven, 2007; Sjerps et al., 2017). Pollutants with a constant discharge will be less diluted during droughts, whereas water turbidity may become too high during peak flows. In addition, temperatures during summer droughts may become a problem due to a rise of air temperature and more effects of thermal pollution by e.g. nuclear power plants during low flow periods. The current water quality standards for water to infiltrate with the purpose to supply drinking water after recovery, as posed by the Dutch government (IB, 1993; see Table 5 for an incomplete listing), are of course crucial for intake stops.

The increasing risk of longer and more frequent intake interruptions for the Dutch dune infiltration systems triggered the study reported here. We believe that the Dutch situation is not unique in this respect, because all MAR systems either suffer from intake interruptions or thrive on them. The effects discussed or even quantified here, as well as the mitigating measures proposed, are therefore of general interest.

To date the effects of full intake stops have been very limited for all dune infiltration sites thanks to their relatively short duration, and the ability to abstract water from stored water or to continue infiltration with water from another source. Observations on effects are therefore mainly based on small scale infiltration stops (limited to one or a few recharge basins) in connection with mud removal or renovation. Effects of prolonged full intake interruptions without back-up by another source water are predicted by analytical solutions or extrapolation of historical observations during the long period of overexploitation (1900–1957) prior to MAR.

2. Dune infiltration sites

Currently, there are 8 operational dune infiltration systems in the coastal area of the Netherlands at the edge of the Rhine River delta, in the southeastern marginal part of the North Sea basin (Fig. 1 and Table 1). They contribute about 15% to a total annual production of 1100 Mm^3 of drinking water in the Netherlands. The preparation of drinking water from surface water by dune infiltration involves pretreatment near the intake, transport to the dunes (10–60 km), recharge by basins and recovery by wells, drains and canals after on average 70 m aquifer passage in 70 days, and post-treatment (Fig. 2). Growing water demands necessitated a steady increase in recharge and recollection. This was achieved by extension of recharge facilities at the expense of

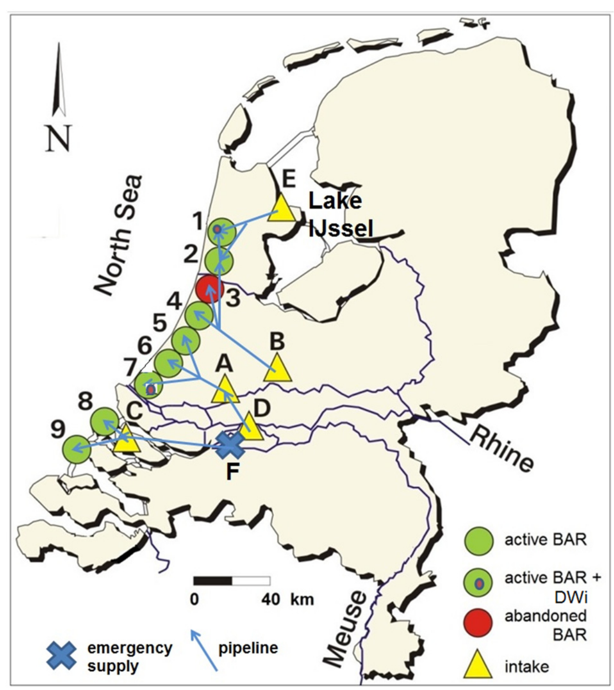

Fig. 1. Location of 8 operational and 1 abandoned basin aquifer recharge (BAR) production sites in the Netherlands, together with their surface water intake points. DWi = deep well injection. Further information in Table 1.