History of managed aquifer recharge in the Netherlands

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General overview

In the Netherlands, unmanaged aquifer recharge started in the early 1900s with the centralized disposal of sewage water in large cesspools, the disposal of groundwater from deep construction pits, and the irrigation of some polder areas where watertables declined due to e.g. groundwater abstraction for drinking water supply.

Currently, there are -- for drinking water supply -- 13 'intentional' basin artificial recharge (BAR), 2 aquifer transfer recovery (ATR), 1 ASR and 23 River Bank Filtration (RBF) systems. They contribute about 17, 1, 0.1 and 6% to a total annual production of 1,100 Mm^3 of drinking water in the Netherlands, respectively.

In addition, there is a rapidly growing number of small-scale ASR systems for agricultural water supply, which store rainwater from the roof of greenhouses or fresh surface water. Urban runoff is increasingly being decoupled from sewage systems and introduced directly into local infiltration ponds or subsurface systems.

Artificial recharge through basins (BAR)

BAR started on a large scale in the coastal dune area, with later expansions inland (Fig.1, Table 1). The reasons to recharge the dune area were to: (i) reverse the severe salinization due to groundwater mining for drinking water supply of cities such as Amsterdam and The Hague; (ii) continue with producing drinking water from the dunes, benefitting from the existing infrastructure; and (iii) reverse the severe decline of groundwater tables in the dunes, which are considered a major nature reserve where wet dune valleys are essential to maintain biodiversity.

The dune infiltration involves a pretreatment near the intake, transport to the dunes, recharge and recovery in the dunes, and a post-treatment. In the period 1965-1975 , public opposition against BAR in the dunes was roused by ecologists who discovered serious eutrophication phenomena in plant communities in and around infiltration ponds. This led to gradual optimizations of the BAR systems through the NESTOR (NEw STyle Of Recharge) approach, which aims at reducing the adverse effects of dune infiltration on nature (Peters et al. 1998).

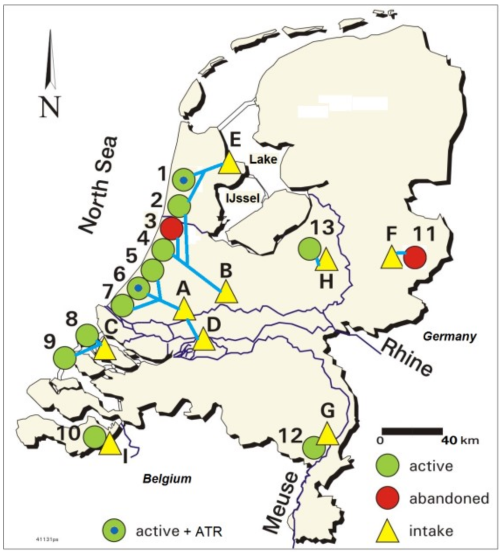

FIG. 1. Location of 11 operational and 2 abandoned BAR production sites in the Netherlands, together with their surface water intake points. On sites 1 and 6 also ATR is applied. Further information in Table 1.

Table 1. Some details on the 13 BAR production sites of which 2 were abandoned, with their surface water intake points.

Site in Fig.1			Start		Intake	Recharge		Pretreatment	System $
No.	Near city	Name	grwater	BAR	Fig.1	Source	Mm3/a	#	Inf / Recovery
1	Castricum		1924	1957	E + (B)	Lake IJssel	25	B+R+C	C/W
2	Wijk aan Zee	Kieftenvlak	1885	1975			17		C/W
3	Overveen	Groot Olmen	1898	1975-1999 †	B	Rhine R.	1	R	B/W
4	Zandvoort	Leiduin	1853	1957			52		C/C+D
5	Katwijk	Berkheide	1878	1940	D or A	Meuse or Rhine R.	25	B+R	B/C+D+Q+W
6	Scheveningen	Meijendel	1874	1955			47		B/D+W
7	Monster	Solleveld	1887	1970			7		B+C/W
8	Ouddorp	Oostduinen	1934	1955	C	Rhine/Meuse estuary	3.5	R	C/D+W
9	Haamstede		1930	1978			3.7		P/W
10	St. Jansteen		1936	1944-1998 ‡	i	Brook	2		C/W
11	Enschede	Weerseloseweg	1892	1952-2004 †	F	Canal	5.5	B+R+pH	B+C/W+Q
12	Heel	Lange Vlieter	-	2002	G	Meuse R.	15	S	P/W
13	Epe		1954	1999	H	Brook	1-2	S	B/W

#: B = detention in basin or abandoned meander loop; C = Activated carbon filtration + O3 + UV
R = sedimentation or microfiltration + coagulation + RSF; S = sedimentation

$: B = Basin; C = Canal; D = Drain; P = Pit; Q = horizontal well; W = vertical well. ‡ : since 1998 for industry

ATR and ASR

In the Netherlands, Aquifer Transfer Recovery (ATR) utilizes separate wells for infiltration and recovery at 100-200 m distance, mainly for continuous production of drinking water, but also to store some volume. In 1990 after many trials since the 1930s, 2 systems were put in operation (Fig.1), where ~4 Mm^3 of highly pretreated surface water is annually feeding about 20 recharge wells on each location.

Aquifer Storage Recovery (ASR) is being applied for drinking water supply only on a very small scale. ASR is, however, rapidly expanding in the supply of (i) rainwater from roofs for crop irrigation in greenhouses, and (ii) freshwater for irrigation of orchards (Zuurbier 2016).

River Bank Filtration (RBF)

The first river bank filtrate was pumped for public drinking water supply in the Netherlands, probably in 1879 along the Rhine River at pumping station Nijmegen (Site 42 in Fig.2). In 1950 15 well fields pumped 11 Mm^3 and in 2014 23 pumping stations produced 59 Mm^3 of Rhine bank filtrate. In 1998 the first Meuse bank filtrate was pumped near Roosteren (site 80 in Fig.2).

The quality deterioration of the Rhine River, especially in the period 1920-1975, had at least 3 impacts on the preparation of drinking water from Rhine River water: (a) a switch in the period 1928-1962 from the direct intake and treatment of river water, to the pumping of Rhine bank filtrate on 10 stations; (b) the closure of 17 well fields pumping Rhine bank filtrate in the period 1944-2000; and (c) extension of the classical treatment (aiming at removal of iron, manganese, ammonia and methane), with processes removing organic contaminants.

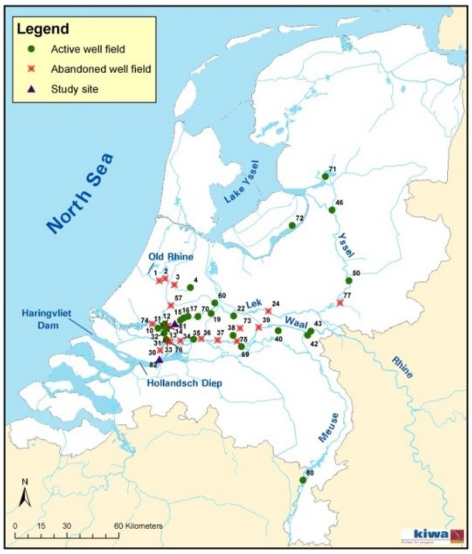

FIG. 2. Location of all public supply well fields pumping >10% river bank filtrate in the Netherlands, with distinction between active and abandoned sites.

Research

The introduction of MAR systems in the mid 1900s raised and continues to nurture many technical and scientific questions. In the period 1940-1975, research mainly focused on the engineering aspects of MAR systems, regarding the minimum travel time needed to remove pathogens, the attenuation of salinity and temperature fluctuations in the infiltration waters, the clogging of basins and wells, and the effects of aquifer passage on main constituents. This knowledge fueled the bulk of the handbook on artificial recharge by Huisman & Olsthoorn (1983).

In the period 1965-1985, the worsening quality of the Rhine and Meuse Rivers provoked research into the behavior of macroparameters, nutrients, heavy metals and some classical organic micropollutants during detention in spreading basins and aquifer passage (Piet & Zoeteman 1980; Stuyfzand 1988, 1998a). It also stimulated research into the effects of eutrophication on algae blooms in recharge basins and on oligotrophic phreatophytic plant communities in dune valleys around them (Van Dijk 1984). It was discovered in the 1980s that rainwater lenses can form in between infiltration ponds and remote recovery systems, and that flow-through (seepage) lakes in between can disrupt these lenses and stimulate local eutrophication (Stuyfzand 1993). This research was based on multitracing to discern infiltrated riverwater from autochthonous dune groundwater (locally infiltrated rainwater). Later hydrochemical studies yielded further insight in the performance of various (potential) tracers (Stuyfzand 2010), the behavior of trace elements (Stuyfzand 2015), the behavior of organic micropollutants (Noordsij et al. 1985; Hrubec et al. 1986, 1995; Stuyfzand 1998b; Stuyfzand et al. 2007; Eschauzier et al. 2010) and pathogens (Schijven 2001; Medema & Stuyfzand 2002).

Various modeling approaches were pursued to simulate and predict the behavior of pollutants, radionuclides, bacteria and viruses, and main constituents during detention in recharge basins and during aquifer passage. One of the first models was Easy-Leacher (Stuyfzand 1998c), which is a 2D reactive transport code set in EXCEL spreadsheet, combining chemical reactions (volatilization, filtration, dissolution-precipitation, sorption, (bio)degradation), with empirical rules regarding the reaction sequence. It assumes a constant input quality, flow and clogging layer conditions, but takes account of the leaching of reactive aquifer constituents. More sophisticated models were built using the MODFLOW/MT3DMS and PHREEQ-C based reactive multicomponent transport model PHT3D incl. reaction kinetics (Prommer & Stuyfzand 2005; Wallis et al. 2010; Antoniou 2015). On the other hand, simpler models set in Excel spreadsheet were developed such as Reactions+, a mass balance (inverse) model to identify and quantify the inorganic mass transfer between for instance the infiltrating surface water and a well downgradient (Stuyfzand 2010), and INFOMI, an analytical model to predict the behavior of trace metals and organic micropollutants (Stuyfzand 1998c).

In the period 1973-1982, extensive research on the clogging mechanisms of infiltration wells was carried out by Kiwa (renamed KWR in 2006). This yielded the new clogging potential indicators Membrane Filter Index (MFI; Schippers & Verdouw 1980) and Assimilable Organic Carbon (AOC; Hijnen et al. 1998). Also, the insight was born that a cumbersome clogging can only be prevented by a thorough pretreatment (incl. at least a coagulation step and rapid sand filtration) leading to MFI < 2 and AOC <10 µg C/L, combined with frequent backpumpings of short duration (Olsthoorn 1982; Peters et al. 1989).

The clogging of recovery wells or drains has always been a hot topic in MAR systems, because of their extreme vulnerability. Studies by Van Beek (2010) revealed among others, that BAR and ATR systems are more vulnerable to (bio)chemical clogging by hydrous ferrihydrite, whereas RBF wells in the anoxic fluvial plain are prone to clog by aquifer particles that are retained by the borehole wall if damaged by residual drilling muds.

The current research is mainly on the following key topics:

- Optimizing ASR systems in brackish to saline aquifers (e.g. for agriculture) by reducing bubble drift and bubble buoyancy, and thereby raising the recovery efficiency (Zuurbier 2016),
- Optimizing ASR systems for drinking or rain water storage by reducing water-sediment interaction (Anthoniou 2015),
- Determining the capacity of BAR systems to cope with intake stops, while minimizing the potential damage to wet dune valleys and reducing water quality problems due to e.g. changing redox conditions.
- Determining and predicting the behavior of emerging priority pollutants such as pharmaceuticals, personal care products, new pesticides, nanoparticles etc.
- Identifying weak points in BAR systems where pathogens in the infiltration water or from land bound animals can survive on their way to the recovery system.

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