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Preventing pluvial flooding and water shortages by integrating local aquifer storage and recovery in urban areas

Koen Zuurbier[1,2*], Bert de Doelder[3], Wilrik Kok[4] and Boris van Breukelen[5]

[1] KWR Watercycle Research Institute ; koen.zuurbier@kwrwater.nl
[2] Allied Waters; koen.zuurbier@alliedwaters.com
[3] Municipality of Rotterdam; br.dedoelder@rotterdam.nl
[4] Field Factors; wk@fieldfactors.com
[5] TU Delft; b.m.vanBreukelen@tudelft.nl
* Correspondence: koen.zuurbier@kwrwater.nl; Tel.: +31 30 60 69 666

Abstract: Water management in urban areas forms an increasing challenge due to intense rainfall events and the increasing water demand for non-potable use. Rainwater harvesting and use can be successful in providing a high-quality additional water source. Due to its limited spatial footprint, large capacity, and potential disinfection, aquifer storage and recovery (ASR) can be an interesting MAR-technique in urban areas. The Urban Waterbuffer concept was developed and tested in the city of Rotterdam (The Netherlands). It aims to locally collect and retain rainwater from 4.5 hectares of different urban areas and pre-treat it with green infrastructure such that it can be used for infiltration by an ASR. It was found that a retention basin was needed to compensate for the low infiltrate rate of the ASR well. The biofilter was camouflaged in the urban space and provided sufficient treatment to meet legal water quality limits. DOC, suspended solids, and Fe concentrations were still higher than operationally desired, and can result in well clogging. A reduction in infiltration capacity at the ASR well was already observed during moments of high Fe concentrations in the infiltration water. A closer microbial risk assessment is required to ensure safe use of the recovered water, but could not be executed with the data collected so-far. The main disinfection is of the rainwater is expected in the aquifer, based on the operation and location of the biofilter and the first plate count results.

Keywords: aquifer storage and recovery; urban; water management; irrigation; water quality; groundwater

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1. Introduction

Water management in urban areas is becoming an increasing challenge. Extreme rainfall events require rapid discharge and retention. Prolonged droughts require external freshwater supply from the sometimes water-stressed surroundings [1]. Groundwater overdraft results in sinking cities like Mexico and Jakarta [2] and saltwater intrusion [3]. At the same time, the number of people living in cities in increasing rapidly [4], while climate change is increasing the need for dedicated water management [5].

Managed aquifer recharge (MAR) may provide an important water management technique for urban areas, for instance for water recycling [6]. This is because aquifers can retain vast volumes with limited spatial footprints aboveground and provide natural treatment, (filtration, sorption, and degradation). For those reasons, MAR can be a very strong combination with rainwater harvesting in urban areas. It can result in retention and discharge of rainwater, a source of high-quality of freshwater, and mitigation of groundwater overdraft and the resulting subsidence and saltwater intrusion. To date, MAR is however primarily used to discharge stormwater [e.g. 7] and in some good Australian examples to where also storage and recovery is involved to store and recovery large volumes of stormwater in a sandy carbonate aquifer [e.g. 8, 9, 10], generally upon treatment in a wetland.

For cities coastal and delta areas like The Netherlands, a specific aquifer storage and recovery (ASR) concept has been developed to cope with local urban water surpluses and non-potable water demand. It is constructed to elegantly fit even in very dense urban areas, without compromising on the required pre-treatment. By exploiting the multiple partially penetrating wells [11], the recovery efficiency in brackish aquifers and the removal of pathogens is to be enhanced, such that the water can be better used upon recovery. A first pilot is realized in the Spangen neighborhood of Rotterdam (The Netherlands). The aim of this paper is to discuss the concept and results of the injection and recovery cycle.

2. Materials and Methods

2.1. Field site

The site is located in the Spangen neighborhood in the city of Rotterdam (The Netherlands). This neighborhood (9500 inhabitants) was built in the early twentieth century for the workers in the rapidly growing harbor. It is situated in the polders close to the river "Nieuwe Maas" (1,500 m to the south) and has a surface level of 1.3 m below sea level (mBSL). The distance from the coastline (tot the northwest) is 22 km. The estimated area connected to the Urban Waterbuffer field pilot is around 46,000 m^2 and consists of squares, parking lots, parks, roofs, and a football stadium. In 1998, a rainwater collection system discharging the local rainwater to the surface water system was constructed in order to relieve the sewage system. After realization of the Urban Waterbuffer, it was found that the drainage of the park east of the area was also connected to the rainwater system.

2.2. Set-up of the Urban Waterbuffer Spangen

The Urban Waterbuffer concept was added to the existing rainwater collection system. A threshold was created at the discharge point towards the surface water to create an overflow. A 1400 m^3 large retention basin ('buffer') was constructed using the Rigofill system (Fraenkische, Germany) wrapped in EPDM foil to create a closed basin, without interaction with the local groundwater. The function of this basin was to retain the rainwater (30 mm maximum) during rainfall events, in order to distribute it to the target aquifer for ASR with a lower rate than the rainfall intensity. This retention is crucial as infiltration rates via ASR are generally too low to rapidly discharge intense rainfall. The first treatment step is removal of coarse material and light non-aqueous phases with a Sedipoint system (Fraenkische, Germany) in the pipeline leaving the retention basin. From there, the water is pumped towards a so-called *Bluebloqs* biofiltration system (Field Factors, The Netherlands). The system is based on a combination of slow sand filtration and vertical reedbed filters and is constructed to spatially fit in public space. The surface area of the filter is 90 m^2 and the maximum discharge on the filter is 30 m^3/h, resulting in a designed maximum velocity of 0.3 m/h through this 1 m thick filter with a top layer of sieved 0.4 - 0.8 mm of fluvial sand. Reeds and sedges were planted in the top layer, which was then covered with woodchips. Upon filtration, the water is transported to a standpipe (Ø = 400 mm), 3.0 m high above surface level. From this standpipe, the water flows to the ASR well. The ASR well consist of two partially wells in a single borehole (Ø = 500 mm). The well screening in target fluvial sand aquifer (16.75 to 26.5 m below surface level) is 17-19 m below surface level (W1) and 20 – 26.5 m below surface level (W2). W2 is used for infiltration, W1 is used for recovery. This way, more water is to be recovered with a low salinity [11] and a higher rate of disinfection via aquifer passage may be achieved [12]. Upon aquifer storage, the water is supplied to the nearby football stadium, back to the biofiltration system (as irrigation for the plants), and a water feature. Both infiltration wells perform back-flushes every upon a defined volume of infiltration.

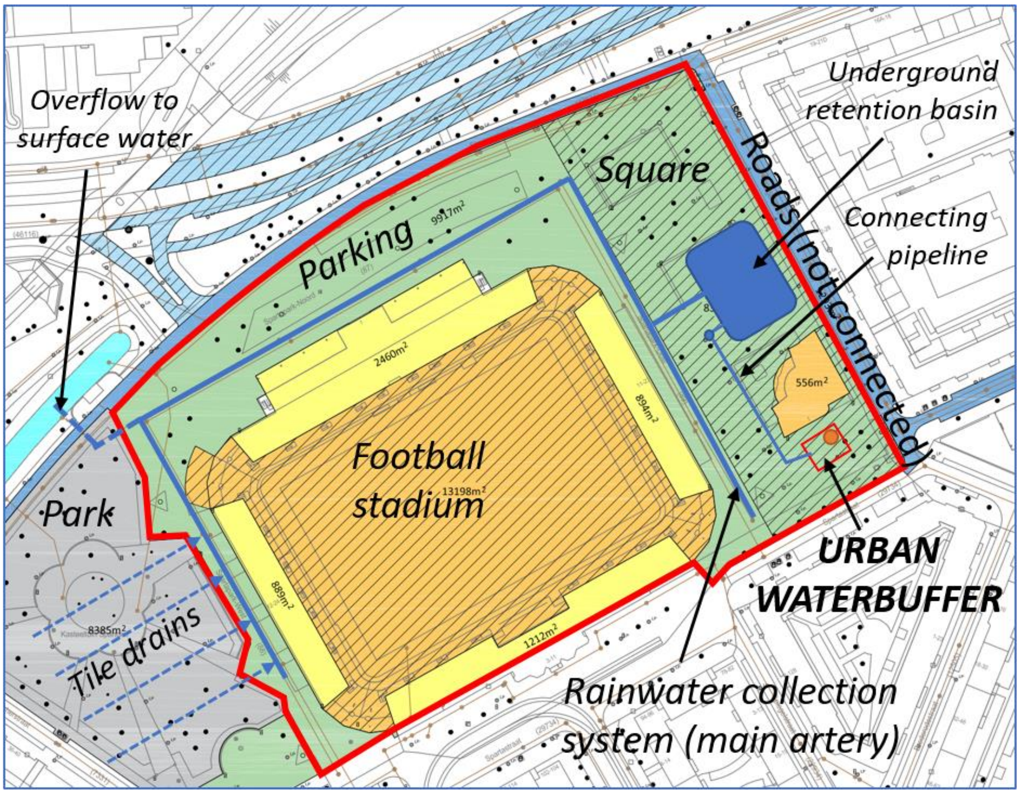

Figure 1. Top view of the Urban Waterbuffer field site in Spangen, Rotterdam. The rainwater collection system collects the water within the red line.

Table 1. Type of urban area discharging towards the Urban Waterbuffer Spangen

Type	Area (m²)	Remark
Roof	6,000	Bitumen, Zinc
Paved	18,300	Bricks
Pitch + surrounding	13,200	Artifical gras and pavement
Park	8,400	Green, pavement
Total	**45,900**	**Mixed**

2.3 Monitoring of the Urban Waterbuffer

In order to understand the functioning of the Urban Waterbuffer, a broad monitoring program was set up. The monitoring consists of:

- Electronic water meters (type: Woltman; recorded every 30 minutes):
  - Water pumped to the biofiltration system
  - Water pumped to the standpipe
  - Water infiltrated in W1 and W2 (separately)

- ○ Water recovered from W1 and W2 (separately)
- • Water levels using pressure, EC, and temperature sensors:
- ○ Retention basin (pressure, every 30 minutes)
- ○ Biofiltration system (pressure, every 30 minutes)
- ○ Standpipe (pressure, every 30 minutes)
- ○ Water from retention basin (EC, every 30 minutes)
- ○ Water from W1 and W2 (EC, every 30 minutes)
- ○ Monitoring well (MW) 1: conductivity, pressure, and temperature via CTD Divers (Van Essen, The Netherlands), every 15 minutes
- • Water sampling and analysis (see Table 2) on the following parameters:
- ○ Macrochemistry: EC, pH, Temp, Dissolved Oxygen, Turbidity, Na, Cl, Ca, K, Mg, Fe, Mn, HCO_3, NH_4, NO_3, PO_4, SO_4, trace elements
- ○ Full scan: Macrochemistry, DOC, suspended solids, heavy metals, oil, BTEXN, PAH (EPA), glyphosate and AMPA, E.Coli, Enterococci, plate count (37 °C).

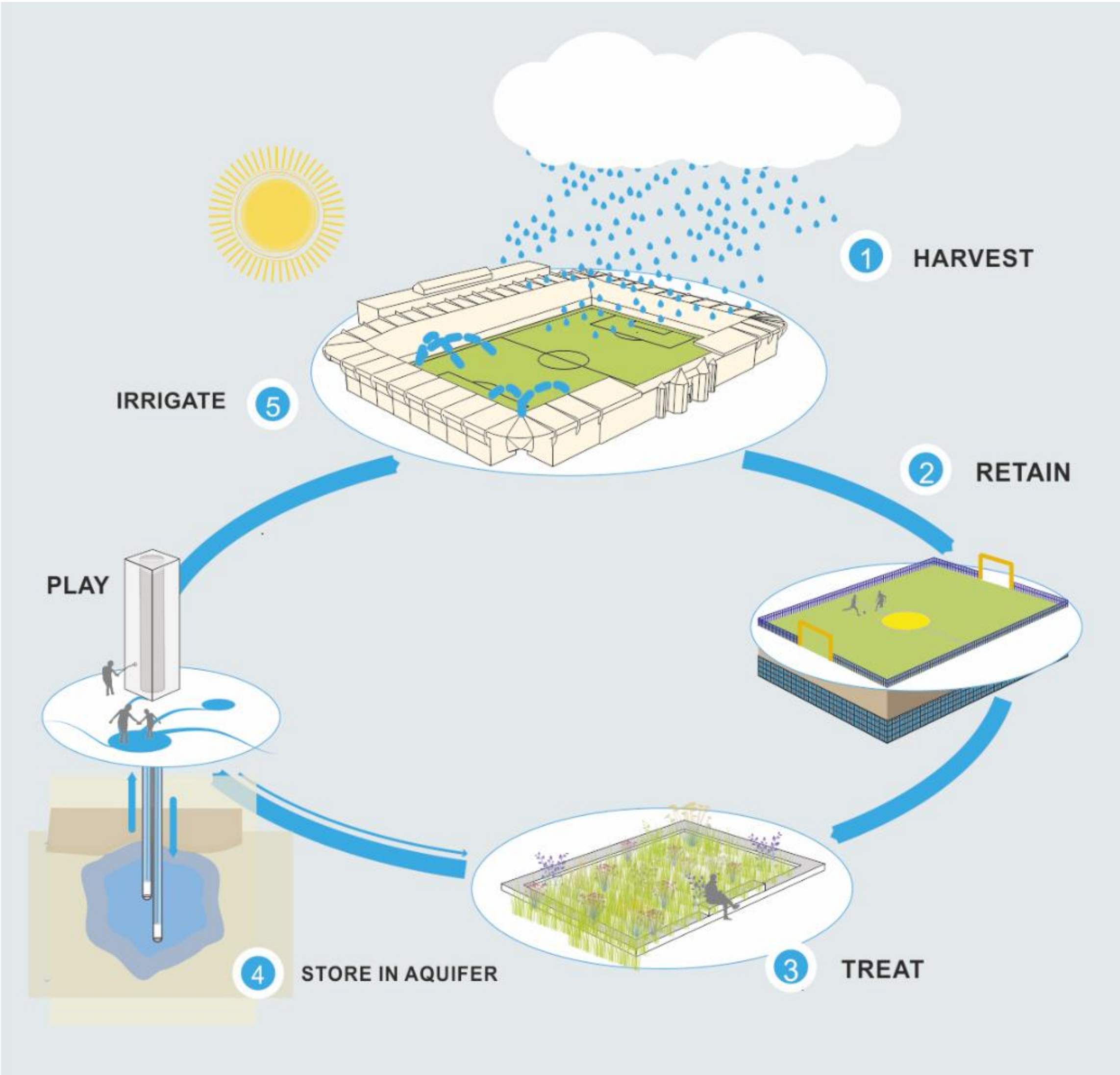

Figure 2. Outline of the Urban Waterbuffer in Spangen, Rotterdam.

Table 2. Water sampling at the Urban Waterbuffer Spangen.

Date: (dd-mm-yyyy)	15-5-2018	10-9-2018	24-9-2018	22-10-2018	12-11-2018	18-12-2018	14-1-2019	28-1-2019	26-2-2019	29-3-2019	22-4-2019	20-5-2019	
week #:	*37*	*38*	*40*	*44*	*47*	*51*	*2*	*4*	*8*	*9*	*16*	*20*	
Location													*Analyses:*
Groundwater at MW1	■				■		■	■	■				Macrochemistry
Rainwater		■	■	■	■	■		■	■	Pro	jec	ted	Full scan
Infiltration water		■	■	■	■	■		■	■				Full scan
Recovered water								■	■				Full scan

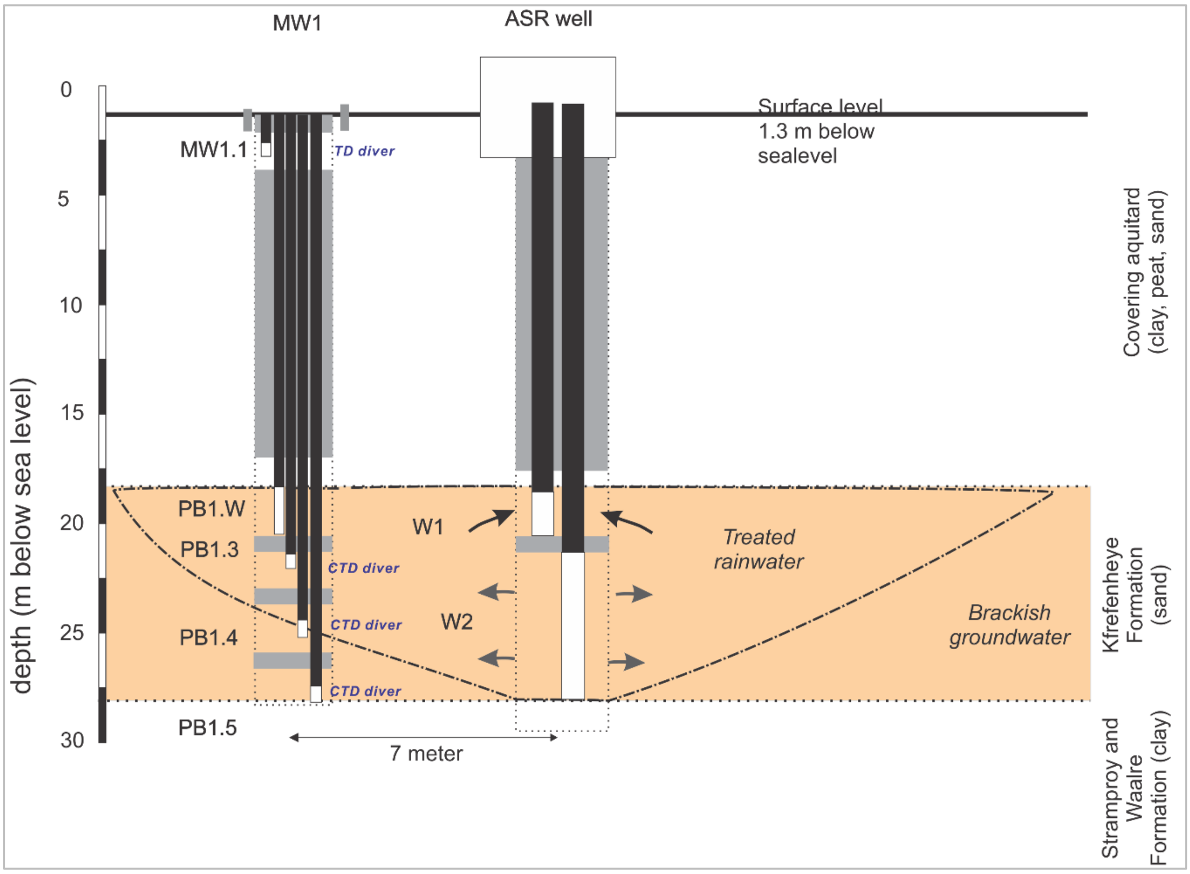

Figure 3. Cross-section of the ASR well and the monitoring well at the Urban Waterbuffer Spangen (Rotterdam).

3. Results

3.1. First operation of the Urban Waterbuffer Spangen

The operation of the Urban Waterbuffer started with a test phase of the biofilter. In this phase, the treated water (2390 m^3) was disposed of on the Rotterdam sewerage system. Four grab samples were taken to assess its quality, before starting the infiltration. The water quality analysis results showed no concentrations above background levels (measured in May, 2018) or were below target concentration, leaving no objections to infiltrate the water. This infiltration started early November (Figure 3b), using W1 only. After a stable infiltration rate in November, followed a decrease in December. In January, both W1 and W2 were used, while from February onward, only W2 was used for infiltration, as planned. In these periods, the infiltration rate remained relatively stable. During the first 4 months of operation, almost 4000 m³ of rainwater was infiltrated and around 500 m³ was recovered during back-flushes and irrigation of the football pitch. The Urban Waterbuffer was able to lower the basin level rapidly upon rainfall events (Figure 4a). The EC of the infiltration water was found to be remarkably high for rainwater, especially in periods with a low level in the retention basin. During moment with significant rainfall (like December 2018), a clear dilution was observed.

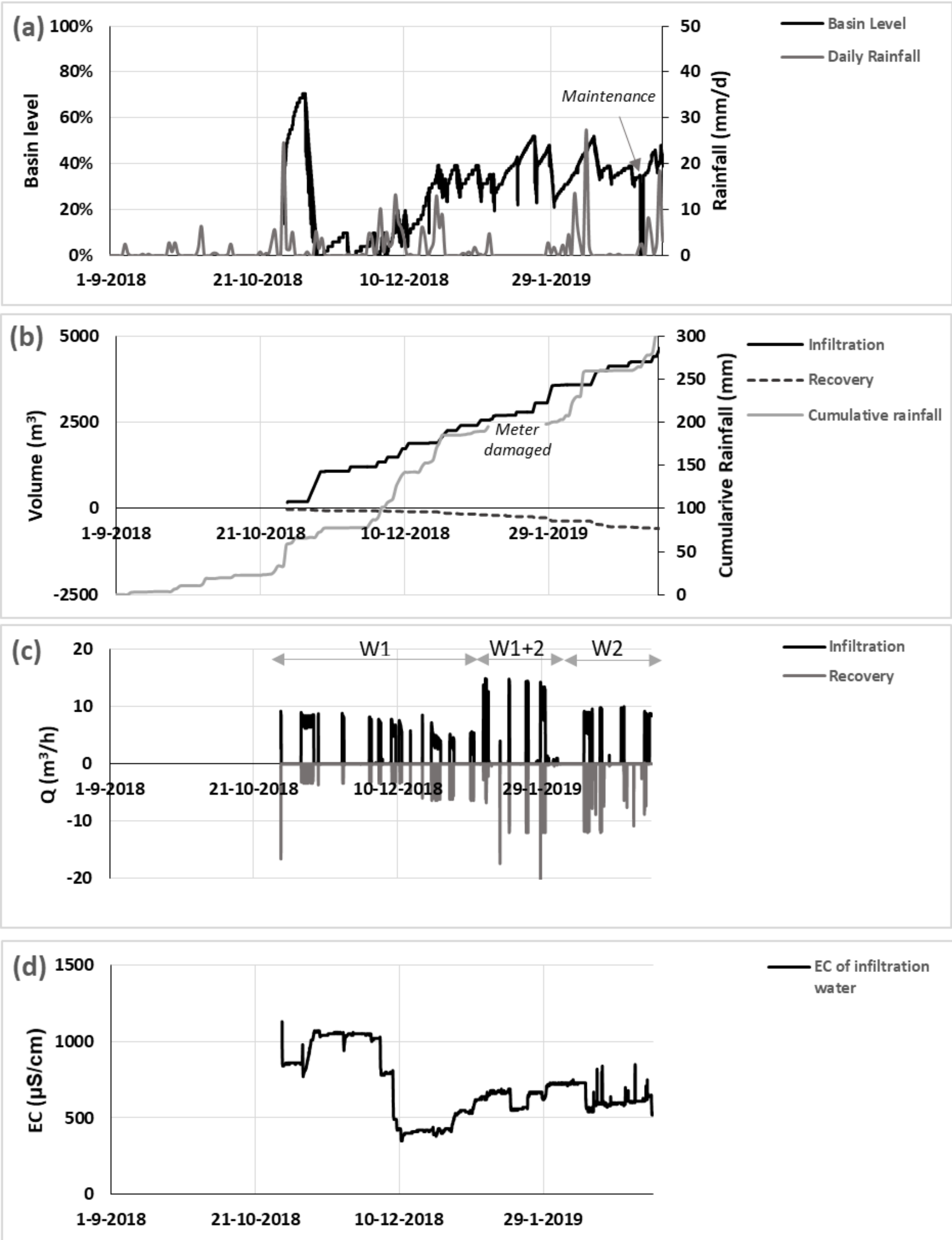

Figure 4. Electronically recorded data of rainfall and basin level (a), pumping (b, c), and EC (d) of the infiltration water.

3.2. Water quality analyses

The first rounds of water quality measurements show that the collected rainwater is already relatively clean, with only turbidity, suspended solids, total-Fe, DOC, and Zn exceeding the targeted concentrations. Thanks to a 73% decrease in Zn concentration, there were no chemical legal exceedances in the infiltration water. The high removal may be explained by the fact that more than half of the Zn in Dutch rainwater is bound to particles [13], which will be largely removed in the biofilter.

The remaining parameters of concern relate to increased risk of physical, chemical, and biological well clogging. Especially the high incoming concentrations of iron (merely dissolved, as shown by additional analysis in October 2018) can have strong negative impact on well clogging, despite a 35% removal by the biofilter. The 40% reduction in infiltration capacity observed at W1 in December 2018 (Figure) coincided with a firm peak in the Fe concentration in the infiltration water (up to 1.8 mg/l). Its source was found to be shallow groundwater intruding the rainwater collection system via tile drains and leakages, as was later found by mapping the Fe concentrations in the rainwater system. This source was confirmed by the composition of the shallow groundwater, which was sampled in a shallow piezometer installed centrally at the square and showed high Cl, Na, NH_4, and Fe concentrations.

Based on the plate count results, the biofilter did not perform any disinfection. On the contrary, there was even a slight increase observed, which might be due to the fact that the biofilter is accessible for public and animals (pets). The results suggest that the main disinfection step is provided by the aquifer only. Analysis on E.Coli and enterococci were unfortunately performed with a too high detection limit. Therefore, they could not provide any useful information.

The water quality arriving at MW1.2 does not show distinct changes with respect to the infiltration water: the observed concentrations are within the ranges observed during infiltration and the lower Na, Cl, and NH_4 concentrations in combination with the higher Fe concentrations suggest that the observed water was infiltrated in December 2018.

4. Discussion

In this paper, the concept of the Urban Waterbuffer and the first results during operation are presented. Based on the realization and the first monitoring results, it appears that a viable concept of urban ASR has come available, but also that certain critical issues require further attention.

The main issue relates to the clogging potential created by the infiltration water. High concentrations of Fe were observed in the incoming rainwater and were insufficiently removed by the biofilter. The implication is that stimulated aeration is required before or while the water enters the biofilter to enhance iron precipitation and enable removal by the sand filtration in the biofilter. Also removal of suspended solids and DOC were found to be too low to ensure stable infiltration without clogging. Further research must focus on the performance of the biofilter during prolonged operation with further build-up of a Schutzdecke on top to increase removal of particles [14] and the growth of the vegetation in the next summer season, which may positively impact the DOC removal [15].

Another critical issue is the safe reuse of the stored water upon recovery. In the concept, aquifer passage is essential for disinfection and subsequent safe use of the rainwater, since the biofilter will presumably not perform sufficient disinfection. Although the water is injected deeper in the aquifer with respect to the zones of recovery, short flow paths between W2 and W1 and therefore short residence times may exist when recovery follows quickly after injection, which may result in insufficient removal of bacteria and viruses. This needs careful evaluation via for instance a QMRA [16] and if needed: a modification in the control system to prevent recovery for a certain time after infiltration.

To be demonstrated is the final recovery efficiency of the chosen set-up, with a long well screen for injection in the lower ~2/3 of the aquifer and a very short well screen for recovery at the top, a concept that can significantly enhance freshwater recovery [11]. In that context, the experienced, relatively elevated EC of the stormwater at the UWB in Spangen due to the intrusion of shallow groundwater, Rotterdam can be beneficial by limiting the density difference ratio [17].

5. Conclusions

A local urban ASR set-up using collected rainwater was developed and tested in the city of Rotterdam to prevent pluvial flooding and provide non-potable water. The pre-treatment was based on biofiltration system at street level. It was found technically viable to realize and operate this ASR scheme and supply water with an apparently acceptable quality. The risk of groundwater contamination was found to be limited after the removal of zinc by the biofilter. The main operational risk was found to be the high concentration of Fe passing the biofilter and potentially DOC and suspended solids, which may induce clogging of the ASR well. A clear decrease in infiltration capacity was found to coincide with high concentrations of Fe in the infiltration water, underlining that a higher degree of Fe removal is required. A closer assessment of microbial risks is required, in which the disinfection provided by the target aquifer will be a crucial aspect.

Table 3. Water sampling at the Urban Waterbuffer Spangen

	EC	pH	Turbidity	DO	Susp. solids	Cl	Na	Ca	K	Mg	Fe-tot	Mn-tot	HCO3	NH4	NO3	P-Phosphate	SO4	DOC	As
	mS/m	-	NTU	mg/L	mg/L	mg/l	mg/l	mg/l	mg/l	mg/l	µg/l	µg/l	mg/l	mg/l	mg NO3/l	mg P/l	mg/l	mg C/L	µg/l
Legal limits infiltration					0.5	100	120	-	-	-	-	-	-	3.2	50	6.9			18.7
Operational limits infiltration [18]			1.0		0.2						10							2	
Limits recovery						500	350				500		150						
Native groundwater (4)	4135	6.8				1110	558	180	16	75	11875	1073	738	27.0	0	0.18	0.6		
Rainwater (7)	800	7.5	7.7	3.1	5.6	113	68	60	5.7	14.2	1251	407	189	1.0	0.7	0.06	42	12.0	<4
Infiltration (7)	810	7.5	3.1	2.3	2.1	123	72	60	6.1	13.7	817	254	184	0.7	0.3	0.05	47	6.6	<4
MW1.2 (Feb 26)	639	7.8	2.2	0		70	44	72	5.1	12	1800	210	210	0.55	0.0	0.05	37		
Recovered (2)	673	7.5	3.3	1.4	5.3	59	39	76	4.8	9.7	570	122	235	1.0	0.0	0.12	38	9.8	6.2

	Ba	Cd	Co	Cu	Hg	Pb	Mo	Ni	Zn	Naftalene	SUM PAH (EPA)	Benzene	Ethylbenzene	Toluene	SUM xylenes	Mineral oil	AMPA	Glyphosate	Plate count
	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	kve/mL
Legal limits infiltration	500	0.35	0.7	1.3	0.01	7.4	3.6	20	65	0.01	-	0,2	4	7	0,2	50	<0.1	<0.1	
Operational limits infiltration [18]																			
Limits recovery																			
Native groundwater (4)																			
Rainwater (7)	42	<4	<2	<5	<0.02	<5	<2	<5	155	<0.05	0.2	<0,2	<0,2	<0,2	0.2	<50	0.03	<0.01	440
Infiltration (7)	36	<4	<2	<5	<0.02	<5	12[a]	11	42	<0.05	0.2	<0,2	<0,2	<0,2	0.2	<50	0.04	<0.01	470
Recovered (2)	37	<4	<2	<5	<0.02	<5	2.2	9.3	37	<0.05	0.2	<0,2	<0,2	<0,2	0.2	<50	0.08	<0.01	65

[a] *Only 1 of 7 samples had a concentration of 63 µg/l, the other 6 were <2 µg/l .*

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. McDonald, R.I., et al., *Water on an urban planet: Urbanization and the reach of urban water infrastructure.* Global Environmental Change, 2014. 27: p. 96-105.
2. Erkens, G., et al., *Sinking coastal cities.* Proc. IAHS, 2015. 372: p. 189-198.
3. Werner, A.D., et al., *Seawater intrusion processes, investigation and management: Recent advances and future challenges.* Advances in Water Resources, 2013. 51(0): p. 3-26.
4. United Nations, *World Urbanization Prospects: The 2018 Revvision*, U.N.E.a.S. Affairs, Editor. 2018. p. 2.
5. Hughes, S., E.K. Chu, and S.G. Mason, *Climate change in cities.* Innovations in Multi-Level Governance. Cham: Springer International Publishing (The Urban Book Series), 2018.
6. Bekele, E., et al., *Water Recycling via Aquifers for Sustainable Urban Water Quality Management: Current Status, Challenges and Opportunities.* Water, 2018. 10(4): p. 457.
7. Dillon, P., *Future management of aquifer recharge.* Hydrogeology Journal, 2005. 13(1): p. 313-316.
8. Vanderzalm, J.L., et al., *A comparison of the geochemical response to different managed aquifer recharge operations for injection of urban stormwater in a carbonate aquifer.* Applied Geochemistry, 2010. 25(9): p. 1350-1360.
9. Hatt, B.E., A. Deletic, and T.D. Fletcher, *Integrated treatment and recycling of stormwater: a review of Australian practice.* Journal of environmental management, 2006. 79(1): p. 102-113.
10. Page, D., et al., *Effect of aquifer storage and recovery (ASR) on recovered stormwater quality variability.* Water research, 2017. 117: p. 1-8.
11. Zuurbier, K.G., W.J. Zaadnoordijk, and P.J. Stuyfzand, *How multiple partially penetrating wells improve the freshwater recovery of coastal aquifer storage and recovery (ASR) systems: A field and modeling study.* Journal of Hydrology, 2014. 509(0): p. 430-441.
12. Smeets, P.W.M.H., G.J. Medema, and J.C. van Dijk, *The Dutch secret: how to provide safe drinking water without chlorine in the Netherlands.* Drink. Water Eng. Sci., 2009. 2(1): p. 1-14.
13. Boogaard, F. and G. Lemmen, *De feiten over de kwaliteit van afstromend regenwater*. 2007. p. 20.
14. McNair, D.R., et al., *Schmutzdecke Characterization of Clinoptilolite-Amended Slow Sand Filtration.* Journal - American Water Works Association, 1987. 79(12): p. 74-81.
15. Stein, O.R. and P.B. Hook, *Temperature, Plants, and Oxygen: How Does Season Affect Constructed Wetland Performance?* Journal of Environmental Science and Health, Part A, 2005. 40(6-7): p. 1331-1342.
16. Smeets, P.W.M.H., et al., *Practical applications of quantitative microbial risk assessment (QMRA) for water safety plans.* Water Science and Technology, 2010. 61(6): p. 1561-1568.
17. Zuurbier, K., et al., *Identification of potential sites for aquifer storage and recovery (ASR) in coastal areas using ASR performance estimation methods.* Hydrogeology Journal, 2013. 21(6): p. 1373-1383.
18. Russel, M., (ed.), *Clogging issues associated with managed aquifer recharge methods*, ed. I.C.o.M.A. Recharge. 2013. 212.