

Article

Raw Water Quality and Pretreatment in Managed Aquifer Recharge for Drinking Water Production in Finland [†]

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Abstract: The main objective of managed aquifer recharge (MAR) in Finland is the removal of natural organic matter (NOM) from surface waters. A typical MAR procedure consists of the infiltration of surface water into a Quaternary glaciofluvial esker with subsequent withdrawal of the MAR treated water from wells a few hundred meters downstream. The infiltrated water should have a residence time of at least approximately one month before withdrawal to provide sufficient time for the subsurface processes needed to break down or remove humic substances. Most of the Finnish MAR plants do not have pretreatment and raw water is infiltrated directly into the soil. The objectives of this paper are to present MAR experiences and to discuss the need for and choice of pretreatment. Data from basin, sprinkling, and well infiltration processes are presented. Total organic carbon (TOC) concentrations of the raw waters presented here varied from 6.5 to 11 mg/L and after MAR the TOC concentrations of the abstracted waters were approximately 2 mg/L. The overall reduction of organic matter in the treatment (with or without pretreatment) was 70%–85%. Mechanical pretreatment can be used for clogging prevention. Turbidity of the Finnish lakes used as raw water does not necessitate pretreatment in basin and sprinkling infiltration, however, pretreatment in well infiltration needs to be judged separately. River waters may have high turbidity requiring pretreatment. Biodegradation of NOM in the saturated groundwater zone consumes dissolved oxygen. Thus, a high NOM concentration may create conditions for dissolution of iron and manganese from the soil. These conditions may be avoided by the addition of chemical pretreatment. Raw waters with TOC content up to at least approximately 8 mg/L were infiltrated without any considerations of chemical pretreatment, which should be evaluated based on local conditions.

Keywords: drinking water; Finland; managed aquifer recharge; pretreatment; water quality

1. Introduction

The climate in Finland is humid. Water resources are abundant in terms of surface area; the inland waters cover around 10% of the total area of the country and there are about 56,000 lakes in Finland. In addition, a volume of 5.8 million m³/day could theoretically be abstracted from the Finnish

groundwater [1]. Generally, groundwater has been preferred as drinking water. However, the Finnish aquifers are small, typically with an area of only a few km². Small aquifers cannot satisfy the potable water demand in larger cities and, therefore, surface water from lakes and rivers is also used for drinking water production. Finnish lakes are typically humic, containing natural organic matter (NOM) derived from the decay of vegetation in the forests and peatlands of the catchment areas [2]. NOM can be detrimental in drinking water as it is a possible source for bacterial growth. The removal of NOM is one of the main tasks in producing drinking water from surface waters in Finland. Most of the organic matter in surface water is in a dissolved form [3]. Dissolved organic matter can be precipitated by the addition of chemicals during water treatment, after which it is removed as sludge using solids separation methods such as dissolved air flotation [4]. As an alternative for chemical water treatment, managed aquifer recharge (MAR) can be used for drinking water production.

MAR comprises the augmentation of groundwater resources by infiltration of surface water into the ground. MAR can be used in several applications, such as the storing of water for later use, the adjustment of groundwater levels, prevention of salt water intrusion into an aquifer, and the treatment of secondary wastewaters and storm waters, in addition to drinking water production [5]. MAR can be one of the solutions for sustainable groundwater management globally [6]. MAR systems planning is based on hydrogeology and engineering [7]. In drinking water production during a MAR process, NOM is removed by physical, chemical, and microbial processes [8–10]. In addition, possible cyanobacteria, including microcystins, are effectively removed in MAR [11]. Most of the NOM removal takes place in the saturated groundwater zone. When fully saturated, sand column tests were conducted, 76%–81% reduction of total organic carbon (TOC) was achieved. It was also reported that biodegradation accounted for 32%–52% of the dissolved organic carbon removal, with a conclusion that biodegradation has a key role in NOM removal in MAR [12].

A typical MAR plant includes infiltration of lake or river water into an unconfined esker aquifer and withdrawal of water from wells a few hundred meters downstream (Figure 1). The infiltrated water should have a residence time of at least approximately one month before withdrawal to provide time for processes needed to break down or remove NOM. There are currently 26 MAR plants in Finland [13]. Basin infiltration is used most often, sprinkling infiltration was initiated in the mid 1990's. Sprinkling infiltration includes an aboveground pipe network through which water is distributed on top of natural forest soil. Well infiltration or well injection is applied only in a couple of MAR plants in Finland. However, new infiltration wells are being planned and tested.

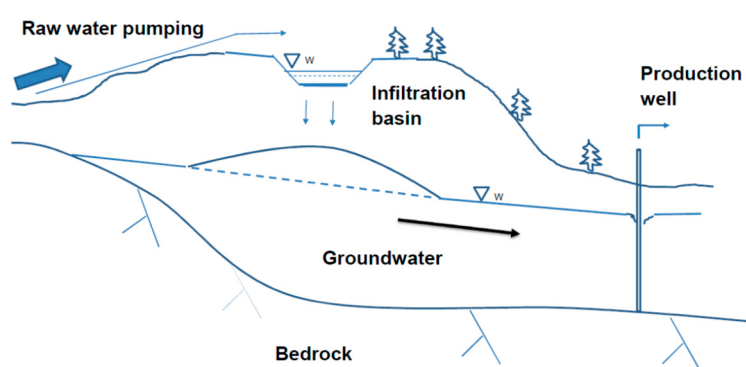


Figure 1. A schematic of a managed aquifer recharge (MAR) process in drinking water production.

Eskers in Finland are Quaternary glaciofluvial formations which were most commonly deposited by streams that flowed in tunnels beneath the ice during the final deglaciation of the Scandinavian ice sheet. Typically, an esker consists of 20 to 50 m of gravel and sand that is covered by a thin humic soil layer (<10 cm). Eskers, which cover only 2.2% of the total area of Finland [1], are preferred areas for potable water MAR treatment. However, there are also other interests or activities connected with eskers: they can be centers of population, they are considered recreational areas or nature conservation

sites, or they can be sources for extraction of gravel. When MAR plants are being planned, these interests may be contradictory. Public participation is an important feature of MAR planning in Finland [14,15]. Sprinkling infiltration and well infiltration can be attractive for areas not suitable for the construction of basins, e.g., eskers with slopes, and forest areas having recreational values with restrictions of tree cutting. When sprinkling infiltration or well infiltration is used, there is no need to dig and construct basins and the direct physical effects on the landscape are reduced. Recreational values, including minimizing the effects on landscape, are often emphasized in public participation.

Finnish MAR plants were designed and constructed over a span of about 40 years. Raw water quality, local conditions, process design, and operational procedures vary between the MAR plants. Decisions on possible pretreatment may be based on considerations regarding infiltration methods or subsurface processes. Most of the plants have no pretreatment prior to infiltration, whereas some plants have sophisticated pretreatment processes. However, all MAR plants produce good quality drinking water. The aim of this paper is to present experiences of MAR in drinking water production with a special emphasis on raw water quality and pretreatment. Conclusions are drawn on the need for and choice of pretreatment.

2. Description of the MAR Plants

2.1. Locations and Key Figures of the MAR Plants

The studied MAR plants are located in Southern and Central Finland (Figure 2). The oldest plant was opened in 1976 and the newest in 2011, one of the plants is still in the planning stage (Table 1). Capacity of the MAR plants varies between 10,000 and 105,000 m³/day. Three of the plants have no pretreatment, two have chemical pretreatment, and in one plant mechanical pretreatment (i.e., treatment of mechanical or physical nature, such as sieving and sedimentation) is regarded as an option in connection with well infiltration. Basin, sprinkling and well infiltration methods are used. One plant (Virttaankangas) uses river water for infiltration, the others use lake water. The residence time of the infiltrated water in the soil varies between 0.5 and 3 months. Organic matter content of the raw waters varies between 6.5 and 11 mg TOC/L, whereas the organic matter content of the abstracted waters is approximately 2 mg TOC/L at each MAR plant. Before distribution to the trunk mains, water is disinfected by ultraviolet (UV) radiation, chlorination, or both, and, when necessary, the alkalinity and hardness are adjusted.



Figure 2. Names and locations of the studied MAR plants.

Table 1. Key figures of the studied MAR plants.

MAR Plant	Start-Up (Year)	Average Production (m ³ /Day)	Production Capacity (m ³ /Day)	Pre-Treatment	Infiltration Method	Residence Time (Months)	TOC	
							Raw Water (mg/L)	Abstracted Water (mg/L)
Ahvenisto	1976	7800	-	no	basin, sprinkle	3	11	1–2
Vuontee	2000	10,000–15,000	22,000	no	sprinkle	1.5–2	7.2	1.8
Kuivala	1992	22,000	34,000	chem	basin	0.5–3	11 *	1.7 *
Vehoniemi	planned	-	70,000	no/mech	well, sprinkle, basin	1–2	6.5	2 ^
Rusutjärvi	1997	7000	10,000	no	well	1–2	7.7	2.5
Virttaankangas	2011	63,000	105,000	chem	basin	3	9	1.9

Notes: * approximate values, based on KMnO₄ oxidation; ^ estimate; mech = mechanical; chem = chemical; sprinkle = sprinkling; TOC = total organic carbon.

2.2. Ahvenisto MAR Plant

Hämeenlinna Region Water and Sewerage Ltd. (Hämeenlinna, Finland) is responsible for water supply and sanitation in the Hämeenlinna Region and it operates the Ahvenisto MAR plant. Raw water is pumped from Lake Alajärvi, the NOM content of which is high with an average color value of 60 mg Pt/L. Raw water is infiltrated in the Ahvenisto esker, located 3.5 km from the lake with a net elevation of 32 m. There is no pretreatment prior to infiltration. Both basin infiltration (since 1976) (60%) and sprinkling infiltration (since 1996) (40%) are used. There are plans to increase the capacity of the plant by construction of a new raw water pipe line. The plans also include construction of an infiltration well.

There are three infiltration basins. Sprinkling infiltration (Figure 3a) comprises eight areas, which are used periodically. At the moment, four areas are in use and the other four are resting. Sprinkling infiltration areas need periodic rests to prevent excessive vegetation which hinders infiltration. TOC content of the water abstracted from the production wells is 1–2 mg/L, depending on the dilution with natural groundwater which varies well by well from 25% to 50%.

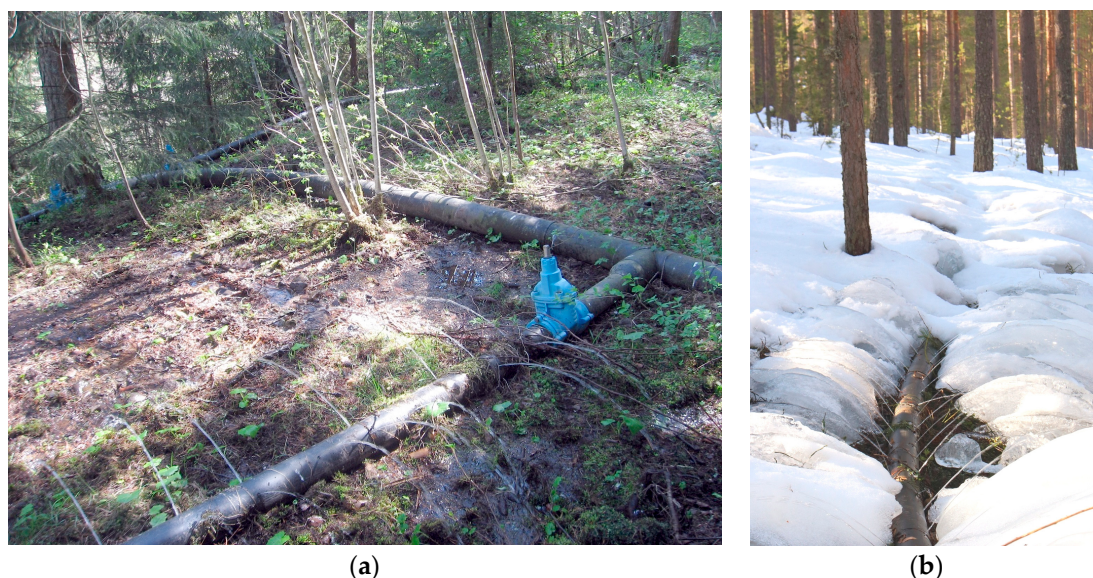


Figure 3. Sprinkling infiltration at (a) Ahvenisto MAR plant in May (Photographer, M. Mäkinen) and (b) Vuontee MAR plant in March (Photographer, J. Tyrväinen).

2.3. Vuontee MAR Plant

Jyväskylä Energy Ltd. (Jyväskylä, Finland) is fully owned by the city of Jyväskylä. Jyväskylä Energy's Water business area is responsible for the water supply in Jyväskylä. The main source for drinking water is the Vuontee MAR plant. The Vuontee MAR plant is the first MAR plant in Finland that utilizes only sprinkling infiltration. Raw water is taken from Lake Kuusvesi from a depth of 12 m. Raw water is infiltrated without any pretreatment in the Vuonteenharju esker located 7 km from the lake with a net elevation of 45 m. There are four infiltration areas, each of which comprises numerous infiltration sites (Figure 3b). Altogether, 20 infiltration sites are in use at the same time. A site is used for a year and then it is left for rest for at least a year during May–June, i.e., at the beginning of a growing season. Water is abstracted from the production wells approximately 500 m downstream of the infiltration sites.

2.4. Kuivala MAR Plant

Kymenlaakso Water Ltd. (Kotka, Finland) is a wholesale company that is owned by three municipalities. It operates Kuivala MAR plant and sells potable water to the waterworks of its owners. Raw water

is pumped from Lake Haukkajärvi to the esker located 1 km from the lake with a net elevation of 40 m. The average chemical oxygen demand of Lake Haukkajärvi water is 11 mg COD_{Mn}/L. (COD_{Mn} (mgO₂/L) of natural lake water corresponds roughly to TOC (mg/L)).

Water is infiltrated in five infiltration areas within 17 infiltration basins (Figure 4a). Approximately 40% of the raw water is infiltrated without any pretreatment. The remaining 60% of the raw water goes through thorough pretreatment, which began in 2006: ferric sulphate (110 mg/L, iron content 13%) is added for coagulation of organic matter, which is removed by dissolved air flotation. Flotation is followed by rapid sand filtration (four lines) for the removal of the remaining solids. The sand filtered water is then led to infiltration. Removed solids (sludge) from flotation and sand filtration are treated by polymer addition and lamella sedimentation, from which the clarified effluent is led to infiltration. After 15–90 days' residence time (which depends on the distance between an infiltration basin and a production well) in the soil, water is abstracted using 14 production wells. The overall reduction of the organic matter content is 85%, measured as the reduction of COD_{Mn}.



Figure 4. (a) Basin infiltration at Kuivala MAR plant in November; (b) Basin infiltration trials at Virttaankangas MAR plant in October 2009 (Photographer, P. Jokela).

A specific feature of the Kuivala MAR plant is the reverse osmosis (RO) unit for fluoride removal. The fluoride content of the raw water is 0.8 mg/L, but due to the high content of fluoride in the soil, the fluoride content of the water abstracted from the production wells increases to slightly over 1.5 mg/L, which is the regulatory limit. Therefore, approximately 30% of the abstracted water is led through RO. These two streams are then mixed and the fluoride content is maintained below 1.5 mg/L. The RO unit was first used in 2003 and it consists of eight lines. No membrane renewal was done before 2008.

2.5. Vehoniemi MAR Plant

Tavase Ltd. (Tampere, Finland) is a wholesale company owned by six municipalities and it plans to construct and operate a drinking water MAR plant in the Vehoniemi-Isokangas esker in the southern part of Finland. The MAR plant will consist of three MAR sites in separate aquifers with a total capacity of 70,000 m³/day. Tavase Ltd. has conducted extensive research at the planned sites and has submitted a permit application to the authorities for the MAR plant. Raw water will be taken from Lake Roine and pumped to infiltration areas located 1–7 km from the lake with a net elevation of 20–70 m. Three infiltration methods will be used: basin infiltration will be applied for approximately one third of the total capacity, whereas parallel well infiltration and sprinkling infiltration systems will be constructed for infiltration of the rest. Well infiltration (Figure 5a) will be the primary infiltration method, but sprinkling infiltration can be used when necessary. No pretreatment will be needed for basin and sprinkling infiltration. However, an optional drum sieving was designed for well infiltration.

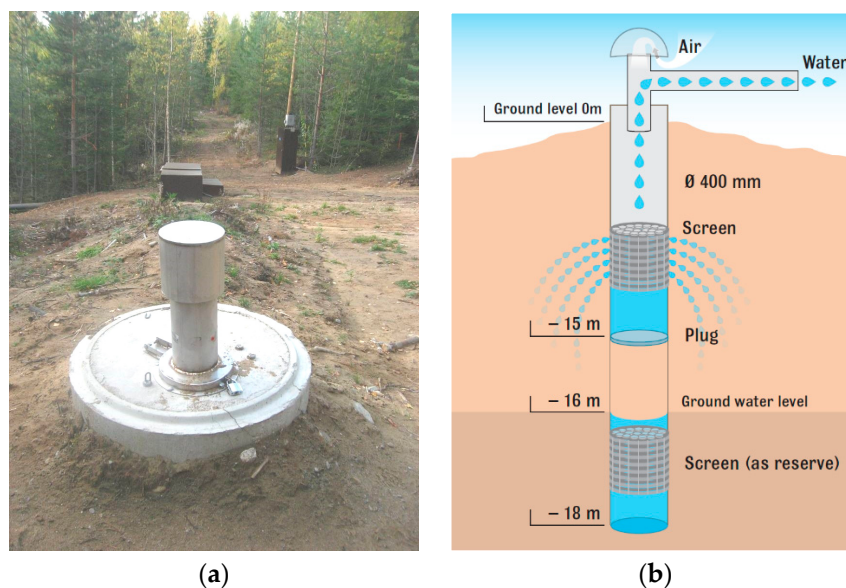


Figure 5. (a) An Infiltration well at Vehoniemi MAR site, with the wellhead in the forefront and influent flow metering box in the background (Photographer, M. Mäkinen); (b) The principle of well infiltration at Rusutjärvi MAR plant: infiltrated water is led to the unsaturated zone with an option to lead it directly to the saturated zone.

2.6. Rusutjärvi MAR Plant

Tuusula Region Water Utility is a wholesale company owned by four municipalities. It operates two MAR plants with a total capacity of 23,000 m³/day and sells drinking water to the waterworks of its owners. Rusutjärvi MAR plant was opened in 1997, first utilizing sprinkling infiltration. Sprinkling infiltration was replaced by well infiltration in 2007, and it was the first MAR plant to use infiltration wells with louver type screens in Finland. The raw water is taken from Lake Päijänne then transported from Central Finland by a 120 km long tunnel leading to the capital area of Helsinki. There is no pretreatment prior to infiltration. The principle of well infiltration at Rusutjärvi is shown in Figure 5b.

2.7. Virttaankangas MAR Plant

Turku Region Water Ltd. (Turku, Finland) is a wholesale company owned by nine municipalities. It operates the largest MAR plant in Finland and sells drinking water to its owners. Raw water, taken from River Kokemäenjoki, is pretreated near the water intake and then pumped 30 km with a net elevation of 70 m to the Virttaankangas esker for infiltration in 19 infiltration basins (Figure 4b). Water is abstracted from 13 production wells and led by gravity a distance of 60 km to the users in the Turku Region.

The pretreatment process consists of mechanical solids removal by drum sieving followed by chemical treatment. Natural organic matter is precipitated by the addition of polyaluminum chloride. The precipitated solids are removed by dissolved air flotation and finally by rapid dual media filtration.

3. Comparison of the Raw Water Sources and MAR Processes

Good quality raw water sources are important for drinking water production. The impact of municipal or industrial wastewater discharges into the lakes described here is at a minimum. The River Kokemäenjoki watershed used to be a recipient of discharge from the forest industry, but after the closing of two pulp mills during the 1980s, the water quality of the river started to improve rapidly. Currently, a major impact on the water quality is the diffuse pollution from agriculture.

Water quality of the water bodies used as raw water sources for the MAR plants is shown in Table 2. Water quality in Lake Alajärvi shows a clear influence of humic substances, which incorporate

elevated concentrations of iron and nitrogen compared to that of the less humic lakes. The color value and TOC concentration are the highest of the studied lakes as well. However, there has been no need for pretreatment at Ahvenisto MAR plant which utilizes both basin and sprinkling infiltration. The organic matter contents in Lake Kuusvesi and Lake Päijänne are clearly lower compared to that of Lake Alajärvi and there are no elevated concentrations of iron. The nitrogen concentration is higher in Lake Päijänne than in Lake Kuusvesi, showing an impact of the catchment area. The major difference between these lakes is in the turbidity, which is clearly lower in Lake Päijänne. Vuontee MAR plant utilizes sprinkling infiltration without any pretreatment of Lake Kuusvesi water. Low turbidity (low suspended solids concentration) of Lake Päijänne water is beneficial for the well infiltration process of the Rusutjärvi MAR plant, which has no pretreatment. There have not been any clogging problems at the Rusutjärvi MAR plant.

The organic matter content (TOC, COD_{Mn}) is the lowest in Lake Roine. Turbidity is higher compared to Lake Päijänne due to higher biomass concentrations of algae. Also, the phosphorus concentration is slightly higher. The turbidity increase in Lake Roine takes place typically during natural turnovers, i.e., during short periods in spring and autumn when the stratification in the lake breaks down rapidly. When the lake freezes after the turnover in the autumn, diatoms sink to the bottom of the lake and start to decompose consuming oxygen and releasing iron and manganese from the bottom sediments. During that period, water intake near the bottom should be avoided. For Vehoniemi MAR plant, two water intake pipes have been designed. Most of the time, water will be taken from a depth of 16 m with stable quality and cool temperature, but during turnovers, water can be taken from near the lake surface to avoid diatoms. Both basin, sprinkling, and well infiltration will be used at the Vehoniemi MAR plant. Based on the experience of the other MAR plants, no pretreatment has been designed for basin and sprinkling infiltration. However, because there is a sporadic occurrence of diatoms in the raw water, an option for drum sieving was designed prior to well infiltration.

The water quality of River Kokemäenjoki differs from the lakes, especially because of high fluctuation caused by seasonal variations. Turbidity can be an order of magnitude higher compared to the turbidity in lakes. The effect of diffuse loading due to run-offs is seen in high maximum concentrations of nitrogen and phosphorus. Virttaankangas MAR plant uses efficient pretreatment to equalize the raw water quality prior to infiltration by basin infiltration.

A clear trend has been observed in the quality changes of the raw waters. Generally, pollution load to the water bodies has decreased in Finland, but, maybe as a consequence of the climate change, organic matter content of the waters has increased. Organic carbon concentrations of Lake Päijänne, Lake Kuusvesi, and River Kokemäenjoki at the water intakes were, on average, 7.7, 7.2 and 9.1 mg/L, respectively, in 2015. Compared to the average values in Table 1, the concentrations have increased by 7%–15%. This is in agreement with a recent study covering the same geographical area, where a trend of 1%–2% annual increase for organic carbon concentrations during a time period of 1990–2013 was calculated and partially attributed to an increase of annual rainfall [16]. However, the MAR processes have not been changed even though the quality of the raw water has changed.

Table 2. Water quality (mean, minimum, and maximum) of the water bodies used as raw water sources of selected MAR plants from 2000 to 2010. Data collected from official monitoring records, except where indicated.

Parameter	Unit	Ahvenisto MAR Lake Alajärvi		Vuontee MAR Lake Kuusvesi		Vehoniemi MAR Lake Roine Surface ¹		Vehoniemi MAR Lake Roine Depth 16 m ¹		Rusutjärvi MAR Lake Päijänne		Virttaankangas MAR River Kokemäenjoki	
		2000–2010 (n = 23)		2001–2009 (n = 13–127)		2003–2010 (n = 12)		2003–2010 (n = 12)		2000–2010 (n = 22)		2000–2010 (n = 120)	
Turbidity	FNU	1.5	(0.3–5.6)	1.2	(0.4–2.4)	2.1	(0.54–3.4)	2.5	(1.0–6.1)	0.5	(<0.3–0.7)	6.6	(0.9–17)
Suspended Solids	mg/L					2.0	(<1–4.4)	2.2	(0.8–4.3)	<2.0		5.1	(0.5–13)
pH		7.1	(6.7–7.7)	6.8	(6.0–8.4)	7.2	(6.9–7.5)	5.9	(5.7–6.1)	7.2	(6.8–7.7)	7.1	(6.8–7.5)
Color	mg Pt/L	60	(35–100)	16	(0–25)	20				24	(15–40)	50	(25–100)
Electric conductivity	mS/m	8.5	(7.8–9.5)	4.4	(3.0–7.9)	6.6	(6.3–6.8)	6.7	(6.4–7.3)	6.8	(6.7–7.1)	9.5	(7.8–13.2)
Iron	µg/L	380	(76–660)	83	(1–470)	80	(23–140)	95	(39–150)	46	(25–79)	380	(120–990)
Manganese	µg/L	29.0	(5–54)	53	(2–490)	25	(6–54)	75	(19–330)	11	(<10–18)		
Nitrogen	µg/L	590	(390–930)	380	(300–490)	360	(290–450)	380	(280–490)	500	(390–590)	910	(450–2300)
Phosphorus	µg/L	11	(6–22)			12	(8–15)	12	(9–17)	7.7	(5–11)	25	(14–50)
COD _{Mn}	mg O ₂ /L	12	(8.2–18)	5.6 ²		4.5	(3.6–5.6)	4.3	(3.7–5.0)	6.4	(5.4–8.4)	9.1	(7.2–15)
TOC	mg/L	10.3		6.7		6.5 ³	(6.0–7.6)	6.0	(5.7–6.1)	6.7 ⁴	(6.2–7.0)	7.9 ⁵	(6.8–9.0)

Notes: COD_{Mn} = Chemical oxygen demand, determined by KMnO₄ oxidation; TOC = total organic carbon. ¹ At point of the planned water intake (Tavase Ltd.); ² 2011 (n = 1, Jyväskylän Energia Ltd.); ³ Lake Roine 2009 (n = 58, Tampere Water); ⁴ Päijänne Tunnel 2010–2011 (n = 4, Tuusula Region Water); ⁵ 2010 October (Turku Region Water Ltd.).

4. Aspects on Chemical Pretreatment

4.1. Coping with Raw Water Quality Fluctuations at Virttaankangas MAR Plant

River Kokemäenjoki water is screened at the water intake using two parallel bar screens (spacing between the bars 5 mm) to remove coarse solids. Screened raw water is then pumped to the pretreatment building where it is led through rotary drum filters (four parallel lines, filter opening size 300 µm, design flow $4 \times 1100 \text{ m}^3/\text{h}$). Drum filtered raw water is coagulated at pH 6.5 by the addition of 24 mg/L of polyaluminum chloride (commercial liquid PACl, aluminum content 9%). After coagulation and flocculation, solids are removed in clarification by dissolved air flotation (eight lines, hydraulic surface loading $5 \text{ m}^3/(\text{m}^2 \cdot \text{h})$) followed by rapid dual media (sand/anthracite) filtration in the same basins. Filtered water is pumped to infiltration. Backwash water from filtrations is led to lamella sedimentation. Clarified effluent from the lamella sedimentation is released back to the river (limit for maximum suspended solids concentration is 70 mg/L), and the sludge is pumped to sludge treatment. Turbidity and suspended solids are efficiently (>94%) reduced during the pretreatment. In addition, the TOC concentration is halved (Table 3).

Table 3. Raw water quality (River Kokemäenjoki) and pretreatment results at the Virttaankangas MAR plant in 2015. Definition: TOC = total organic carbon.

Parameter	n	Unit	Raw Water Quality (before Pretreatment)				After Pretreatment				Average
			Min.	Max.	Median	Mean	Min.	Max.	Median	Mean	Reduction
Turbidity reduction	50	FNU %	2.6	21	6.6	6.9	<0.2	1.3	0.23		97
Suspended Solids reduction	43	mg/L %	2.2	19	7.1	8.0		<0.5			>94
TOC reduction	48	mg/L %	9.2	12		9.1	3.8	5.3	4.1	4.2	54

The original purpose of the pretreatment design was to ensure stable water quality for infiltration by the elimination of turbidity and suspended solids, accomplished by mechanical pretreatment only. As a result of the permit process, and considering the historical industrial pollution load to the river, the authorities also required chemical pretreatment with a statement that “the pretreated water may contain only dissolved compounds”. The original chemical treatment, designed after the permit process, consisted of contact filtration in which the precipitated organic matter and solids were removed in rapid dual media filtration without preceding clarification. However, it was noted that the operation of the eight filtration lines was difficult regarding the backwashing cycles and chemical precipitation. A part of the aluminum chemicals escaped the filtration process and aluminum hydroxide precipitation continued during infiltration in the infiltration basins. The precipitation reduced the infiltration capacity of the basins because of the formation of film-like layers at the bottom of the infiltration basins. All this increased the need to scrape the basins. When the pretreatment process was upgraded with the addition of clarification by dissolved air flotation, the role of the dual media filters became more like a polishing stage and there is no longer a need for extra scraping of the infiltration basins. Further, as a result of several years of successful operation of the MAR plant, and based on the monitoring data, the authorities removed the condition in 2015 that the pretreated water could contain only dissolved compounds.

After the subsurface processes, the abstracted water contains 8–11 mgO₂/L and less than 6 µgFe/L, while the TOC concentration is 1.9 mg/L. The share of natural groundwater is 15%. The results show that at the Virttaankangas MAR process, the oxygen consumption due to biological degradation of TOC does not promote iron leaching from the soil. On the other hand, it has been discussed that it might be beneficial to the TOC biodegradation if the infiltrated water also contained some of those

large molecular fractions of organic matter which are mainly removed in the pretreatment. The largest fractions may be liable to be adsorbed in the aquifer. Adsorption can enhance biodegradation by retaining organic matter in the aquifer and, thereby, increases its bioavailability [17].

4.2. Maintaining Dissolved Oxygen Levels at Kuivala MAR Plant

Extensive research for the Kuivala MAR plant was started in the early 1980s. The MAR plant was granted a permit by the authorities in 1987. There were no requirements for pretreatment. After the start-up of the MAR plant, both basin infiltration and sprinkling infiltration were used without any pretreatment. Sprinkling infiltration areas were converted to infiltration basins in 2001, after which sprinkling infiltration was used for testing purposes on a new site until it was completely discontinued in 2007. When compared to basin infiltration (hydraulic surface loading $0.5\text{--}1.5\text{ m}^3/(\text{m}^2\cdot\text{h})$) it was noted that sprinkling infiltration needed a larger footprint area. In addition, the sprinkling infiltration sites needed to be changed frequently to ensure adequate recovery time for the forest soil after infiltration.

The organic matter content of the raw water source, Lake Haukkajärvi, has increased continuously as can be seen from the long-time monitoring data (Figure 6). High humic substance content is also represented by a high color value of 60 mg Pt/L. During the subsurface processes, humic substances biodegrade, consuming oxygen dissolved in water. At the Kuivala MAR plant, the share of natural groundwater in the aquifer is approximately 10%, thus, the dilution factor is small. Before the implementation of the pretreatment process, during 1992–2005, dissolved oxygen concentrations in the abstracted water decreased gradually from the level of 10–12 mg/L to the level of 5–8 mg/L. If dissolved oxygen concentrations decrease too much, the possibility of iron and manganese dissolution from the soil to the water increases. As it was foreseen that the organic matter content of the raw water would continue to increase, it was decided to construct a pretreatment plant for the reduction of the organic matter in the raw water. According to the research conducted, there were also indications that high organic matter concentrations and decreased dissolved oxygen levels might increase fluoride dissolution from the soil.

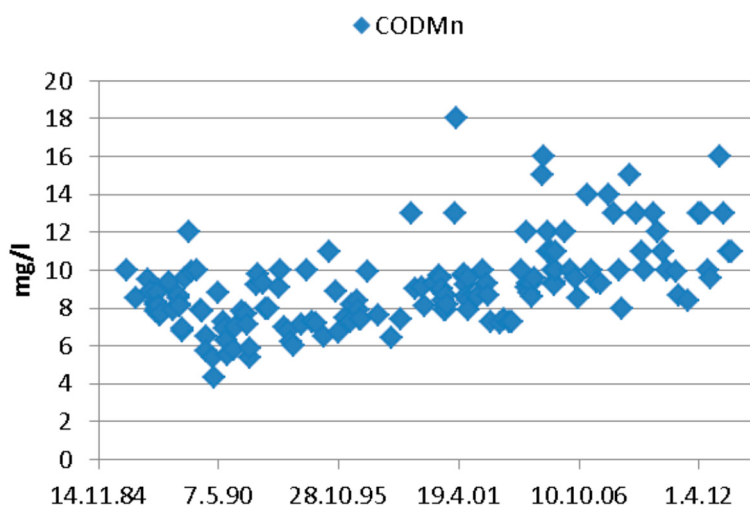


Figure 6. The development of organic matter content of Lake Haukkajärvi measured as COD_{Mn} (monitoring data from the database of the Finnish Environmental Institute) [18].

Ferric coagulation followed by dissolved air flotation and sand filtration removes organic matter and reduces the turbidity from 1.15 formazin nephelometric units (FNU) of the raw water to 0.5 FNU. The pretreated water (60%) is mixed with the raw water (40%) before infiltration. The partial pretreatment keeps dissolved oxygen levels high enough to prevent dissolution of iron and manganese: concentrations in the abstracted water are less than 30 and 20 µg/L, respectively.

5. Discussion

Finnish humic lake and river waters are generally well suited for MAR in drinking water production. TOC concentrations of the raw waters presented here vary from 6.5 to 11 mg/L and after MAR the TOC concentrations of the abstracted waters are approximately 2 mg/L which comply with recommendations in Finland. Thus, the overall reduction of organic matter in the treatment (with or without pretreatment) is 70%–85%. Similar colored waters are also found in Sweden [19] and other countries with a boreal climate [20]. MAR has a long history in Sweden with more than 30 MAR plants and reductions of organic matter corresponding to those of the Finnish MAR plants [21]. Most of the MAR plants in Finland do not have any pretreatment, but raw water is infiltrated directly using basin, sprinkling, or well infiltration. Basic considerations regarding the need and choice of pretreatment stem from the quality of the raw waters, infiltration methods, and local conditions, all of which may interact with the decision making.

High and rapid variations in the raw water quality may initiate the need for pretreatment to stabilize the operational conditions of the MAR. Changes are typical for river waters, as in the case with the Virttaankangas MAR plant, where the average raw water turbidity is 6.9 FNU with peak values up to 21 FNU. After the pretreatment, the average turbidity is reduced to 0.23 FNU with maximum turbidity of 1.3 FNU, which represents good quality Finnish lake water turbidities. Pretreatment can also be used for the removal of specific substances or compounds which are regarded as harmful. During the permit processes for the Virttaankangas MAR plant, demands were raised for the removal of industry-originated mercury that was supposed to get released from the bottom sediments of the river. However, according to the monitoring conducted by Turku Region Water Ltd., the mercury concentrations of the pretreated water have always been below the detection limit of 0.005 µg/L and specific requirements for the concentration of mercury were not set.

Turbidity (suspended solids) of the Finnish lakes used as raw water does not necessitate pretreatment in basin and sprinkling infiltration. Accumulated solids at the bottom of an infiltration basin can be scraped off once a year or more rarely. With sprinkling infiltration, it is important to let the infiltration sites rest frequently, e.g., using a site for infiltration for one year followed by one to three years of rest. The experience from the Rusutjärvi MAR plant shows that well infiltration without pretreatment can be used for several years without any signs of clogging. Raw water turbidity of the Rusutjärvi MAR plant is one of the lowest in Finland, on average it is 0.5 FNU. Experience of the use of infiltration wells with raw waters of higher turbidity are limited in Finland, but clogging and clogging management are well reported issues worldwide [22–24]. Well infiltration is planned for the Vehoniemi MAR plant. The average turbidity values and suspended solids concentrations of the raw water are 2.1–2.5 FNU and 2.0–2.2 mg/L, respectively. For most of the year, the values of these water quality parameters are less than the average, which should not induce clogging problems. A drum sieve can be used for pretreatment during sporadic occurrence of diatoms. However, pretreatment may be avoided by the construction of well and sprinkling infiltration systems parallel in the same recharge area. The additional investment costs for a sprinkling pipe network are minor compared to that for well construction. The use of parallel systems gives flexibility in operation, for e.g., during the occurrence of diatoms, sprinkling infiltration can be used instead of wells and there is no need for raw water pretreatment. Conversely, because sprinkling is used only during one part of each year, the impacts of sprinkling on vegetation, and hence the required area for sprinkling, are reduced [13].

During infiltration, the dissolved oxygen concentration of the recharge water increases by aeration and approaches the saturation concentration, which depends on temperature. Natural conditions in esker aquifers are generally aerobic. Biodegradation of NOM in the saturated groundwater zone consumes dissolved oxygen from the recharged water. The higher the NOM content, the higher the dissolved oxygen consumption. If dissolved oxygen concentration in the groundwater zone sinks low enough, conditions for dissolution of iron and manganese from the soil increase. In the case of elevated iron and manganese concentrations in the abstracted water, a new treatment step for

their removal would be needed. Iron and manganese dissolution may be avoided by the addition of chemical pretreatment for the raw water to cut the NOM content.

According to the results from the MAR plants discussed, raw waters with TOC content up to at least approximately 8 mg/L are infiltrated without any considerations of chemical pretreatment. Further, at the Ahvenisto MAR plant, no pretreatment is needed although the TOC content of the raw water exceeds 10 mg/L. On the other hand, the Kuivala MAR plant with corresponding raw water quality utilizes chemical treatment for a part of the raw water. It is noteworthy that the shares of natural groundwater in the abstracted waters are 10% and 25%–50% at Kuivala and Ahvenisto, respectively. A higher share of natural groundwater provides more dissolved oxygen. However, aquifer properties, including the soil composition, vary locally and have influence on the MAR process. At the Virttaankangas MAR plant, an efficient chemical treatment process is used, but it has been discussed that the subsurface processes might be improved with somewhat higher NOM content of the infiltration water.

When chemical treatment is used, it is important that the precipitation process is operated with care. At the Kuivala MAR plant, it was found that it is easier to infiltrate raw water than chemically pretreated water. At the Virttaankangas MAR plant, there were similar experiences before the renovation of the pretreatment process. The actual reasons for the different infiltration properties of the raw water and chemically pretreated water remain unclear in the case of the Kuivala MAR plant, but in the case of the Virttaankangas MAR plant, the decreased infiltration properties were attributed to continuing chemical precipitation in the infiltration basins.

The use of treated municipal wastewater (recycled water or reclaimed water) for MAR is increasing worldwide, and is related to water scarcity. Major concerns about the safety of this exploitation route as an alternative water source are connected to microbial and chemical contaminants occurring in the treated wastewater [25–28]. Recycled water is not used at Finnish MAR plants. The MAR process removes pathogens efficiently, both bacteria and viruses [29–39]. Risks of contamination of the recharge process are reduced by the choice of good quality raw waters and protection of the recharge areas from external, possibly harmful activities (such as gravel extraction or handling of petroleum). The fate of pathogenic microbes and chemical contaminants in the Kokemäenjoki watershed and the subsequent drinking water production process at the Virttaankangas MAR plant were extensively studied in a multidisciplinary research project. There are municipal wastewater treatment plants several kilometers upstream of the raw water intake in the River Kokemäenjoki, and indicator and pathogenic microbes were found in surface water samples. However, the microbes were not found in the abstracted water [37]. It was concluded that even though surface waters contained pathogenic microbes, they could not pass through the MAR process, which was verified both by sampling and analyzing, and modeling [38]. The study included model simulations on chemical transport [39] and economic assessments of risks [40]. The overall conclusion of the microbiological, chemical, and economic risk assessments was that the multistage MAR process maintains both consumers' good health and the stability of the local economy in the current situation [41].

6. Conclusions

MAR in unconfined esker aquifers is used for NOM removal from humic lake and river waters in Finland. NOM is removed or decomposed by natural processes of which biodegradation has a key role. There is no need for pretreatment at most of the MAR plants. The need for pretreatment may arise if the raw water turbidity or NOM content is high or if there are high and rapid fluctuations of the raw water quality. Mechanical pretreatment can be used for clogging prevention. Chemical treatment can be used for lowering the NOM content prior to infiltration to maintain high enough dissolved oxygen concentration in the saturated groundwater zone. However, the decision for the construction of chemical pretreatment should be based on data of local conditions, including aquifer and soil properties.

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Abbreviations

The following abbreviations are used in this manuscript:

COD _{Mn}	Chemical oxygen demand, determined by KMnO ₄ oxidation
FNU	Formazin nephelometric units
MAR	Managed aquifer recharge
NOM	Natural organic matter
RO	Reverse osmosis
TOC	Total organic carbon

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