Sustainable drinking water quality improvement by managed aquifer recharge in Tuusula region, Finland

Unto Tanttu [1*] and Petri Jokela [2]

[1] Tuusula Region Water Utility, Kirkkotie 49, FIN-04310 Tuusula, Finland

[2] Tavase Ltd., Hatanpään valtatie 26, FIN-33100 Tampere, Finland

[*]Correspondence: unto.tanttu@outlook.com; Tel.: +358 400 461526

Tanttu U, Jokela P (2018) Sustainable drinking water quality improvement by managed aquifer recharge in Tuusula region, Finland. Sustain Water Resour Manag. (2018) 4:225–235. https://doi.org/10.1007/s40899-017-0198-0 This is the final accepted manuscript of this journal paper in author-provided format and is freely available at IAH-MAR web site https://recharge.iah.org with permission of Springer.

Abstract: Managed aquifer recharge (MAR) is used for drinking water quality improvement in Finland. Finnish lakes are typically humic containing natural organic matter (NOM). 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. The infiltrated water should have a residence time of at least around one month before withdrawal to provide time for processes needed to break down or remove natural organic matter (NOM). Since 1979 Tuusula Region Water Utility (TRWU) has produced drinking water from lake water using managed aquifer recharge. TRWU operates two MAR plants which do not use precipitation and disinfection chemicals. Raw water is infiltrated without any pretreatment. TRWU has experience from basin, sprinkling and well infiltration. NOM is reduced from 7.7 mgTOC/l to 2.1 -2.6 mgTOC/l before abstraction of the water from wells. Abstracted water is post-treated by limestone filtration and disinfected by ultra-violet radiation before pumping for distribution. A specific feature of the MAR process is the delayed influence of the raw water temperature on the abstracted water temperature. Design and operational experiences of the MAR plants are presented and discussed. Special emphasis is given for NOM reduction, temperature effects, comparison of infiltration techniques and costs.

Keywords: drinking water, ground water, managed aquifer recharge, total organic carbon, water treatment

INTRODUCTION

Groundwater has generally been preferred as drinking water in Finland. Advantages of groundwater include, e.g., low natural organic matter (NOM) content and stable quality compared to surface waters from lakes and rivers. However, the Finnish aquifers are small, typically with an area of only a few square kilometers. 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 NOM derived from the decay of vegetation in the forests and peatlands of the catchment areas (Rantakari 2010). 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 waters is in dissolved form (Mattsson 2010). 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 (Jokela et al. 2007).

As an alternative for chemical water treatment, managed aquifer recharge (MAR) can be used for drinking water production. There are currently 26 MAR plants in Finland (Jokela and Kallio 2015) and the share of MAR treated water of the total drinking water production at waterworks was 17 % in 2015 (compiled from Zacheus (2011, 2016)). 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 (Jensen 2001). MAR can be one of the solutions for sustainable groundwater management globally (Dillon et al. 2012). In drinking water production, during a MAR process NOM is removed by physical, chemical and microbial processes (Kortelainen and Karhu 2006; Kolehmainen et al. 2007, Kolehmainen 2008). In addition, possible cyanobacteria and microcystins, are effectively removed in MAR (Lahti et al. 2001). 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 (Kolehmainen et al. 2009).

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. The infiltrated water should have a residence time of at least around one month before withdrawal to provide time for processes needed to break down or remove NOM. Basin infiltration, i.e., infiltration of surface water through the bottom of an excavated basin, is used most often. Sprinkling infiltration was initiated in the mid 1990's. Sprinkling infiltration comprises 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.

Finland is one of the Nordic countries, located in North Europe. There are four seasons and temperatures fluctuate significantly to the rhythm of the seasons. Regional differences between southern and northern parts of the country are also considerable. Mean monthly temperature in the south may range from +22 ^{0}C in July to -17 ^{0}C in January, whereas in the north, the range is from +17 ^{0}C in summer to as low as -21 ^{0}C in winter. However, the temperature of natural groundwater remains quite constant at roughly +6 ^{0}C. Surface waters are usually covered by ice in the winter, the temperature of the water below dropping to +4 ^{0}C…+2 ^{0}C. In the summertime, surface water temperature may rise over +20 ^{0}C. The effect of temperature needs to be taken into an account when water treatment is considered.

The municipality of Tuusula is located in the Southern Finland, 30 km North of the capital city of Helsinki. Tuusula Region Water Utility (TRWU) is a wholesale water company that provides drinking water for approximately 130 000 inhabitants in Tuusula Region. Since 1979, TRWU has produced drinking water using managed aquifer recharge. The raw water used is high-quality lake water carried by the 120-kilometer tunnel (Päijänne tunnel) quarried in the 1970's. The decision to participate in the tunnel project was made after the natural groundwater resources in Tuusula region were found insufficient. Although the groundwater resources are insufficient, there are unconfined esker aquifers suitable for the production of MAR. 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 meters of gravel and sand that is covered by a thin humic soil layer (< 10 cm).

TRWU has experience from three different infiltration methods and since 2007 it has operated the first MAR plant in Finland using infiltration wells with louver type screens. The objective of the paper is to show that drinking water quality improvement can be accomplished cost-efficiently through MAR and without precipitation chemicals producing high-quality drinking water.

MATERIALS AND METHODS

Key figures of the MAR plants

TRWU operates two MAR plants with almost identical treatment processes. Jäniksenlinna MAR plant has been in service since 1979, while the one in Rusutjärvi started operating in 1997. Raw water is pumped to infiltration without any pretreatment. After abstraction of the recharged groundwater from wells it is treated (post-treatment) with limestone filtration (gravity filtration through a bed of crushed calcium carbonate) to increase the alkalinity and disinfected using ultra-violet (UV) radiation prior to being pumped to the clean water tank and further to the distribution network. (Figure 1, operating details are given in Table 1).

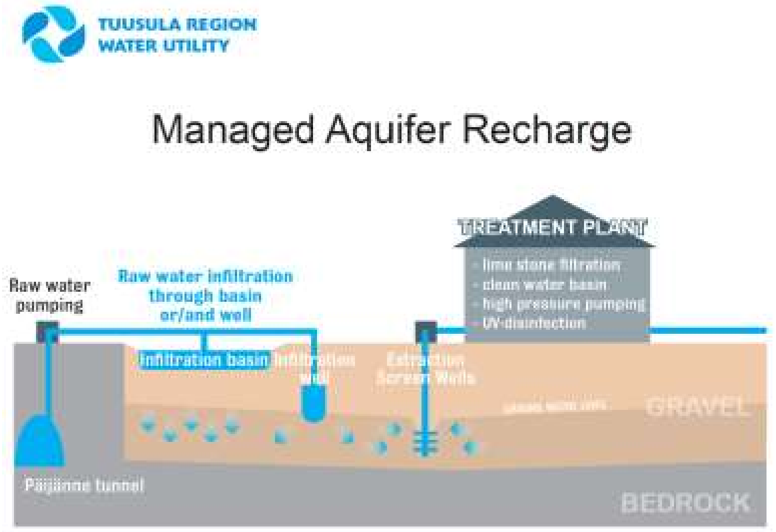

Figure 1. Process chart of TRWU MAR plants (Jäniksenlinna MAR plant comprises both basin and well infiltration, Rusutjärvi MAR plant comprises only well infiltration).

Table 1 Key figures of the managed aquifer recharge plants in Jäniksenlinna and Rusutjärvi.

	Jäniksenlinna plant	Rusutjärvi plant
Daily capacity, max m^3/d	13,200	10,000
Infiltration method	basin (82 %) + well (18 %)	well
Number of recharge wells	3	2
Number of extraction wells	10	6
Screen depth, extraction wells (from surface), m	5-20	5-20
Distance from infiltration to extraction wells, m	400-650	300-700
Unsaturated zone, m	17	12
Detention time in the ground, d	30-60	30–60
Detention time in limestone filtration, minimum h	0.5	0.5
Clean water tank volume, m^3	3,200	1,000

Raw water quality

The raw water used in the plants is lake water carried from Central Finland along a 120-kilometer rock tunnel. The intake is in Lake Päijänne, at a depth of approximately 30 m. The water is high-quality (moderately low TOC, low turbidity) lake water with the parameters presented in Table 2. The samples have been analyzed according to standard methods (Standard Methods 1998).

Table 2 Lake Päijänne water quality parameters in 2014–2015. Average values, except for temperature where extreme values are given. TOC = total organic carbon.

Parameter	Unit	Value
TOC	mgTOC/l	7.7
Temperature	^{0}C	2.4–10.8
Oxygen	mgO_2/l	11.0
Carbon dioxide	mgCO_2/l	1.9
Turbidity	FNU	0.61
pH		7.2
Alkalinity	mmol/l	0.27
Iron	µgFe/l	49
Manganese	µgMn/l	3

The quality of the water remains constant throughout the year with the exception of temperature which varies according to Finland's seasonal temperature fluctuations (gas solubility and hence, e.g., oxygen concentration varies with temperature). In the summertime the water in the tunnel remains relatively cool due to the intake depth and the fact that the tunnel runs through bedrock.

Infiltration techniques

Basin infiltration

The oldest and most traditional recharge technique still in use is basin infiltration. At the Jäniksenlinna plant, this technique has been used since 1979. There are three infiltration basins. Raw water is introduced to the basins with cascade aeration (Figure 2). The top layer of the infiltration basins is screened, even-grained 0.8 – 1.2 mm fine gravel. The gravel layer is between 30 and 80 cm thick. The three basins have a total area of 4,500 m^2, and the largest achieved infiltration water volume so far is 13,000 m^3/day, equal to a surface load of 0.12 m/h.

In summer there is algae growth on the top of the gravel layer that is usually removed, partially manually, once a year. The basin is emptied and the gravel surface left to dry so that it is then easy to peel the algae off the gravel. A minor amount of gravel is however removed in the process which means that the gravel layer gets gradually thinner and more gravel must be added. In the past 35 years, gravel has been added twice, alongside with a more thorough cleaning of the basin. During winter ice cover is formed on the basin surface, but this does not prevent infiltration (Figure 3).

Figure 2. Basin infiltration in summer. On the right: inlet with cascade aeration.

Figure 3. Basin infiltration in winter.

Sprinkling infiltration

At the Rusutjärvi plant, a new technique, sprinkling infiltration, was tried out for ten years between 1997 and 2007 (Figure 4). Originally sprinkling infiltration was chosen because the esker ridge is a protected nature conservation area and there was no possibility to cut trees and excavate infiltration basins in the esker. Sprinkling infiltration system could be installed without tree cutting and excavation.

The problem with the sprinkling infiltration technique lay in the channeling and the surface run-off of the recharge water, as these factors led to a failure to infiltrate water where intended. In addition, changing vegetation necessitated continuous changes in the infiltration areas. For these reasons, sprinkling infiltration was discontinued at the Rusutjärvi MAR plant in 2007 and replaced by well infiltration.

Figure 4. Sprinkling infiltration technique used at the Rusutjärvi plant in 1997 – 2007.

Well infiltration

Due to the problems faced with sprinkling infiltration, the decision was made in 2006 to start an experiment to infiltrate raw water directly to the ground via an infiltration well. The first infiltration well with a louver type screen started operating in January 2007. The louver type screen comprises a series of narrow openings framed at their longer edges with horizontal slats. This method of infiltration had not been used in Finland before, and the system was therefore built as an experiment project, so that returning to sprinkling would be possible if that became necessary. The system has run without problems since the start-up.

Figure 5 presents the principle of well infiltration. Raw water is led into the 400 mm diameter well by gravity through the well head casing. Also air is sucked into the well through a ventilation pipe. The well was fitted with a plug on top of the ground water level so that the infiltrating water will exit the well through a screen to the unsaturated zone. This was done in order to prepare for the possible need to increase the infiltration capacity by removing the plug and to let the water leave the well through the screen in the lowest part of the well. There has however not been any reason to do so.

During the year 2015, an average of 2,400 m^3/d of water was infiltrated, with the single largest daily amount being 3,800 m^3 (44 L/s). There have not been any problems of clogging or with the quality of water.

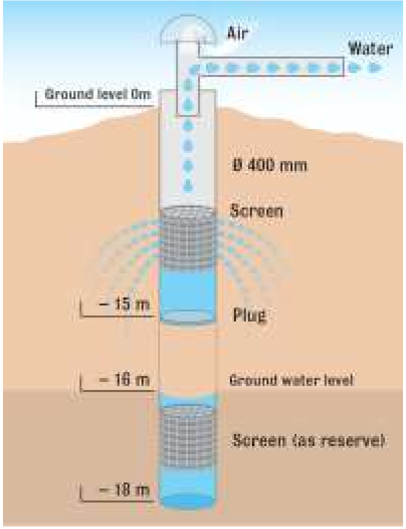

Figure 5. The principle of well infiltration in an unconfined esker aquifer at the Rusutjärvi MAR plant. Raw water is led into the well by gravity.

Combined well & basin infiltration

In the Jäniksenlinna MAR plant infiltration field, there are now three wells with an infiltration capacity below expectation. Low capacity is attributed to the soil properties (low hydraulic conductivity) in the well vicinity. For this reason these wells were fitted with an overflow to allow water to infiltrate to basin infiltration (Figure 6). The resulting infiltration capacity of this combined well and basin infiltration has however remained somewhat low at approximately 1,300 m^3/d. In order to reach the goal of 4,000 m^3/d, another infiltration area with basin infiltration has been built.

Figure 6. Combined basin & well infiltration at the Jäniksenlinna plant: an infiltration well on the right with an overflow connection to the infiltration basin.

RESULTS AND DISCUSSION

Water quality after the MAR process (abstracted water)

Water is pumped from pipe screen wells in the ground. At the Jäniksenlinna MAR plant, the abstracted water quality varies greatly from well to well. There are considerable quality variations even between water from wells in the same well field, especially regarding iron and manganese. At the Rusutjärvi MAR plant, there is no such variation, and iron and manganese contents are both low being clearly less than the national guideline maximum concentrations (Fe < 200 µg/l, Mn < 50 µg/l).

Table 3 presents well-specific quality as mean values and extremes from 2014 – 2015. The Jäniksenlinna MAR plant is represented by wells 8 and 6. Well 8 is located close to the infiltration area, where the share of natural groundwater is smaller and hence the impact of the infiltrated water larger. Well 6 is located at the far end of the well field, where the share of natural groundwater is highest. The differences of the well locations can be detected from the water quality data: the dissolved oxygen concentration is higher (due to the high oxygen concentration of the infiltration water) and consequently iron and manganese concentrations are lower in well 8. At the Rusutjärvi MAR plant the differences between wells are small and well 8 represents average well water quality of the well field.

Table 3 Abstracted water quality in two Jäniksenlinna MAR plant wells and one Rusutjärvi MAR plant well in 2014 – 2015. * = results below detection limit, mean cannot be calculated, § Kortelainen and Karhu (2001, 2006).

Parameter	**Unit**	**Jäniksenlinna**				**Rusutjärvi**	
		well 6		well 8		well 8	
		mean	fluctuation	mean	fluctuation	mean	fluctuation
TOC	mg TOC/l	2.1	1.6–4.0	2.6	2.4–2.9	2.5	2.1–2.7
Temperature	^{0}C	6.2	6.0–7.0	6.4	4.5–7.6	6.1	5.6–7.0
Oxygen	mgO_2/l	< 0.2	< 0.2–1.7	3.2	1.5–4.8	6.7	5.2-9.4
Carbon dioxide	mgCO_2/l	16.9	15.0–23.0	8.9	5.8–11.0	7.2	6.4–8.1
Turbidity	FNU	9.6	3.0-31	0.4	0.3–0.6	0.3	0.1–0.7
pH		6.7	6.5–6.9	6.9	6.8–7.0	7.0	6.8–7.1
Alkalinity	mmol/l	0.49	0.46–0.52	0.38	0.35–0.42	0.41	0.39–0.44
Iron	µgFe/l	1,800	1,200–4,000	*	< 15–27	*	< 15
Manganese	µgMn/l	210	150-250	*	< 3	*	< 3
Share of infiltrated water§	%	< 70		90		80	

The most important treatment result is the reduction of NOM measured as total organic carbon (TOC). Abstracted water average TOC concentration is 2.1 mgTOC/l and 2.6 mgTOC/l and average TOC reduction is 73 % and 66 % for the Jäniksenlinna MAR plant and the Rusutjärvi MAR plant, respectively. These values are in accordance with results from other Finnish MAR plants with the general finding that TOC concentrations of MAR treated surface water are close to 2 mgTOC/l (Jokela et al. 2017). In Finland, natural groundwater TOC content is typically below 2 mgTOC/l.

Infiltrated water mixes with natural groundwater in the saturated zone and the degree of admixture may explain differences in water quality between separate abstraction wells. The proportion of surface water to natural groundwater in a water sample can be detected using isotopic methods. Natural oxygen and hydrogen isotope ratios are different in surface water and groundwater due to larger evaporation from surface waters compared to groundwaters.

Isotope studies were conducted both at the Jäniksenlinna MAR plant (Kortelainen and Karhu 2006) and the Rusutjärvi MAR plant (Kortelainen and Karhu 2001). At Jäniksenlinna MAR plant 90 % of water in well 8 was originally infiltrated surface water. Well 6 water was not analyzed, but the overall MAR plant final water consisted of 70 % of infiltrated water and 30 % of natural groundwater. Well 6 is located at the far end of the well field, where the share of natural groundwater is highest and thus the share of infiltrated water must be less than in the overall MAR plant final water, i.e. less than 70 %. The Rusutjärvi MAR plant final water consisted of 80 % of infiltrated surface water and 20 % of natural groundwater. Well 8 water was not analyzed, but at the Rusutjärvi MAR plant the differences between wells are small and well 8 represents average well water quality of the well field. The small differences were also supported by the isotope proportion results from six analyzed wells.

The higher share of natural groundwater (containing less NOM) in well 6 may be the reason for lower TOC concentration compared to the other two wells as shown in Table 3. Thus the higher share of natural groundwater may help to produce MAR treated water with low TOC concentration. On the other hand, the oxygen concentration of natural groundwater may be low, which can lead to elevated concentrations of iron and manganese. The oxygen concentration of infiltration water is high. It can be close to saturation concentration, because of aeration by, e.g., using cascade inlet to infiltration basin, air suction in well infiltration or sprinkling in sprinkling infiltration. The oxygen concentrations in well 8 at the Jäniksenlinna MAR plant and well 8 at the Rusutjärvi MAR plant are high enough to maintain very low iron and manganese concentrations.

Water quality after post-treatment

Based on samples taken monthly at the plants, the post-treated water quality is presented in Table 4. The quality of the water pumped from the MAR plants to the network meets the European Union requirements and recommendations for drinking water quality in all aspects.

Table 4 Water quality after post-treatment (treatment plant outlet) at the Jäniksenlinna and Rusutjärvi MAR plants in 2014 – 2015. (* = mean cannot be calculated, results below detection limit).

Parameter	Unit	Jäniksenlinna		Rusutjärvi	
		mean	fluctuation	mean	fluctuation
Temperature	^{0} C	6.6	5.9–7.6	6.7	6.2–7.2
Oxygen	mgO_2/l	6.6	5.2–7.0	8.5	7.0–9.8
Carbon dioxide	mgCO_2/l	4.1	3.9–5.4	2.7	2.0–3.4
Turbidity	FNU	0.4	5.4–3.0	0.5	0.2–0.8
pH		7.6	7.4–7.8	7.7	7.4–7.8
Alkalinity	mmol/l	1.1	1.1–1.3	1.0	0.9–1.2
Iron	µgFe/l	15	< 15-16	*	< 15-32
Manganese	µgMn/l	6.9	5.0–12.0	*	< 3-6

Quality changes at each stage of the water production process

Iron and manganese

Iron and manganese contents pose a problem common to Finnish groundwaters. In surface waters the contents are low, and this applies to the recharge water at the Jäniksenlinna and Rusutjärvi MAR plants, too. At the Rusutjärvi MAR plant there are practically no iron and manganese content changes in the ground (cf. Tables 2 and 3), and therefore iron removal has not been necessary. However, this is not the case at the Jäniksenlinna MAR plant, as was presented in Table 3. At the Jäniksenlinna plant, iron removal was in the past conducted using slow sand filtration, which took place outside in the open space. This was discontinued in 2012 because an open space treatment as the final treatment step before the pumping for distribution was considered a water quality risk. At the moment, there is no separate technique used specifically for iron and manganese removal. Most of the iron and manganese in the abstracted water are removed during post-treatment by limestone filtration. Limestone filtration is backwashed four times a year and the spent backwash water is infiltrated back to the soil. Abstracted water with high iron and manganese contents is not let into the post-treatment process at all. For future needs, construction of a process based on two-phase rapid sand filtration is under way.

The changes of iron and manganese contents at the Jäniksenlinna MAR plant at various phases of the process are presented in Figure 7. Well water contents are mean contents of water from all the wells, weighted on the estimated volume of water pumped from each well. Comparison of well water concentrations in Figure 7 with iron and manganese concentrations of well 6 in Table 3 emphasizes the differences of water quality between the wells in the same aquifer. Average iron and manganese concentrations are 1800 µg/l and 210 µg/l in well 6, respectively, whereas the corresponding concentrations for the whole MAR plant (10 wells) are 130 µg/l and 46 µg/l, respectively. In practice, abstraction needs to be targeted more to those wells with higher oxygen concentrations and hence lower iron and manganese concentrations. According to the isotope tests the infiltrated water is not distributed equally to all the wells, and at a distance of 700 m from the infiltration ponds, the proportion of natural groundwater increased to 52 -57 % in one well (Kortelainen and Karhu 2006). While there may be a risk of elevated iron and manganese concentrations in some wells, it needs to be stressed that the main purpose of the MAR treatment of humic surface water is NOM removal and this must be accomplished by the design of the plant (e.g., a long enough residence time in the soil). However, it seems clear, comparing the Jäniksenlinna MAR plant and the Rusutjärvi MAR plant (Figure 7, Table 3), that a higher share of infiltrated water distributed evenly in the well field produces more stable quality abstracted water.

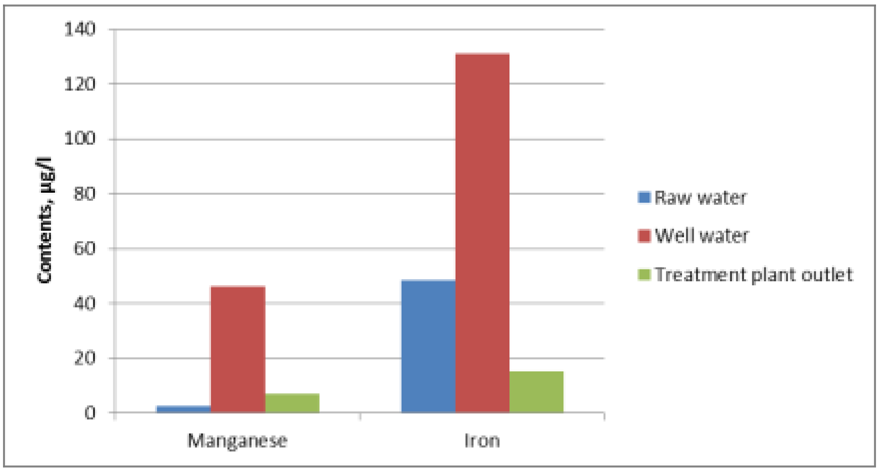

Figure 7. Iron and manganese mean contents at various stages of the process at the Jäniksenlinna MAR plant in 2014–2015. Maximum recommended concentrations given in the Finnish national guidelines for drinking water are 200 µg/l and 50 µg/l for iron and manganese, respectively.

Other quality parameters

Data on turbidity, pH, alkalinity, carbon dioxide, hardness, oxygen, chloride, TOC and temperature at the Jäniksenlinna MAR plant, as mean figures from 2014 - 2015, are shown in Figure 8. Well water quality has been calculated as mean contents of water from all the wells, weighted on the estimated volume of water pumped from each well. Chloride and TOC concentrations have not been measured from water after the post-treatment, as the assumption is that they remain unchanged during the process. Chloride concentration of the abstracted water has always been below 10 mg/l both at the Jäniksenlinna and Rusutjärvi MAR plants (Finnish national guidelines' recommended maximum concentration is 25 mg/l).

The data in Figure 8 show the decrease of TOC and oxygen concentrations during the MAR treatment while simultaneously there is an increase in carbon dioxide concentration. Corresponding findings regarding the relationship of organic matter and oxygen concentrations have been reported also from other Finnish MAR plants (Jokela et al. 2017). The role of aerobic bacteria (consuming dissolved oxygen) in the biodegradation of NOM has been proved by extensive research both in the laboratory and at Finnish MAR plants (Kolehmainen 2008).

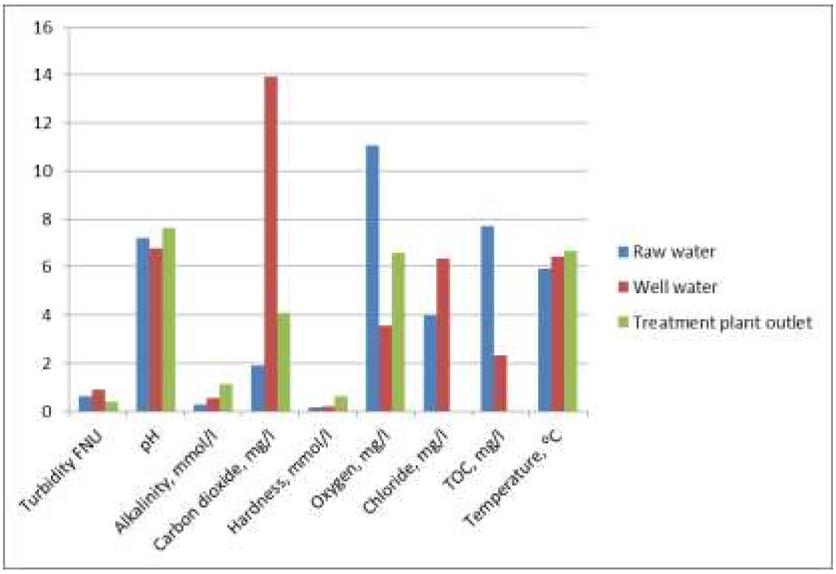

Figure 8. Quality parameters (mean values) from the Jäniksenlinna MAR plant at various stages of the process in 2014 – 2015.

The importance of temperature

The temperature of water pumped from the Päijänne-tunnel varies according to seasons, with the exception that in the summertime it remains relatively low. This is due to the depth of the intake, at approximately 30 m, as the lake water is stratified and the water temperature is lower than on the surface level. The tunnel running through the bedrock is another factor in keeping the water temperature low.

Figure 9 presents temperature fluctuation of the raw water and the abstracted water pumped from well 14 at the Jäniksenlinna MAR plant over the course of two years. In raw water, temperature fluctuation between summer and winter is greater than in the abstracted water. In addition, according to the empirical data, raw water temperature change influences the abstracted water temperature only after a time period which is roughly twice the hydraulic retention time in the soil. At the Jäniksenlinna MAR plant this means a few months delay. In Finnish conditions, this is beneficial for water distribution. In summer, low temperature is beneficial in terms of decreased bacterial activity in the network, and it also makes drinking water more enjoyable. In winter, a slightly higher temperature reduces the risk of freezing in the distribution network.

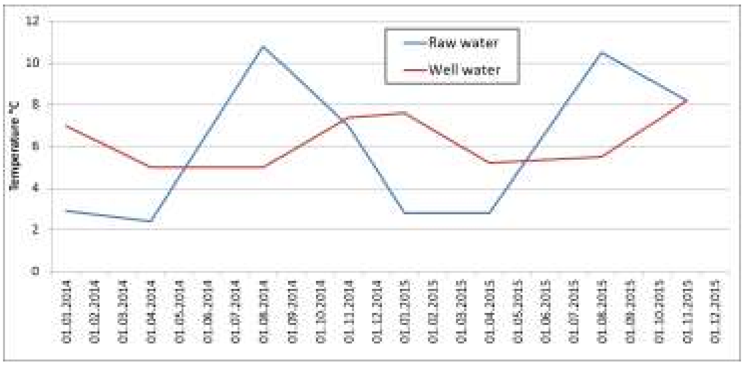

Figure 9. Temperature fluctuations in raw water and in the abstracted water pumped from well 14 at the Jäniksenlinna MAR plant in 2014–2015.

Comparison of basin and well infiltration

Costs

With both basin and well infiltration, the costs are very low. Construction costs for both infiltration methods are similar. There is a slight difference in favor of well infiltration in operational costs, as the basin has to be emptied yearly to partially manually remove the algae. For this reason well infiltration has been seen as more care and maintenance free method, and there has not so far been need to backflush or clean the wells.

Water quality

Between the two infiltration methods, any difference in the quality of water pumped from the wells has not been detected. Studies carried out in 1998-2003 showed that, in basin infiltration, the total organic carbon (TOC) decomposition was practically nonexistent in the unsaturated zone, and the actual change in TOC content did not take place before the saturated zone (Helmisaari et al. 2005). The long detention time (30 - 60 days) enables more efficient biodegradation of TOC in the saturated groundwater zone compared to the detention time of less than one day in the unsaturated zone. It was this fact that encouraged the well infiltration experiment, where the share of the unsaturated zone is minimal.

Algae growth

The algae growth on top of the gravel in basin infiltration increases the hydraulic resistance of water flow through the gravel layer. After the cleaning of the basin, water infiltrates into the ground typically from a very small area. After some time the water layer gets larger and eventually deeper in time. On the other hand, algae growth and its removal have not been considered to play a significant role in removing organic carbon, so well infiltration is clearly the better solution in this sense.

Risk of clogging

A risk associated with well infiltration is clogging. Should there suddenly appear particles causing clogging in raw water, or should the screens lose their penetration abilities due to biological growth, the need to clean the wells would then be apparent. So far, this has not been necessary. Basin infiltration is therefore the more secure solution in this sense.

Environmental values

Infiltration basins invariably require larger areas of land. Eskers are preferred areas for drinking water MAR treatment. However, eskers are often considered recreational areas or nature conservation sites, with restrictions of tree cutting and the building of basin structures may be impossible. Infiltration well, on the other hand, only requires a few square metres of land, although building the required pipe lines to the well may also turn out a challenge. When it comes to environmental values, well infiltration is in any case superior to basin infiltration.

Post-treatment

The alkalinity of the abstracted water is increased to reduce its corrosive properties using limestone filters. The limestone filter comprises a tank filled with crushed calcium carbonate. The abstracted water is led through the filter tank thus allowing time for the calcium carbonate to react with the water. With limestone filtering, carbon dioxide content decreases while alkalinity and hardness increase. Advantages of limestone filtration include simple and reliable operation with no risk of increasing the pH too much. The process also takes out the remaining iron and manganese. At the Jäniksenlinna MAR plant, there have been problems with these contents, as there is no separate iron removal. This has resulted in a more frequent need to backwash the filters. Currently, a separate treatment system for waters with iron and manganese is under construction, using two-phase rapid sand filtration. Both filtering stages will be preceded by aeration.

Prior to being pumped from the treatment plant the water is disinfected using UV radiation. The traditional, widely used chlorine disinfection has not been seen as necessary, and no microbiological problems have been detected in the distribution network. The MAR process removes efficiently pathogens (Jørgensen et al. 2001; Medema and Stuyfzand 2002). 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). All this has made it possible to provide the clients with chemical-free organic product.

Costs

The production costs of MAR treated water can be divided into capital costs and operating costs (Table 5).

At TRWU the capital costs related to the MAR process include the annual fee for the Päijänne tunnel (including the costs of construction and refurbishment of the tunnel) and the write-offs depreciations for the TRWU's own structures such as pumps, raw water pipes, infiltration wells and basins. These write-offs depreciations present the costs now in quite a favourable way, as such a large part of these structures have already been written off.

With the total volume of 6.45 million m^3 of MAR treated water produced in 2015, the capital costs are approximately 0.028 euro/m^3 and the operating costs are approximately 0.021 euro/m^3.

The total costs in the MAR treated water production are approximately 0.049 euro/m^3. However, this figure does not include labour for which there are no exact statistics. Labour costs can be roughly evaluated at tens of thousands of euros at the highest, so their effect on the total costs is not significant. Also the write-offs for the TRWU's own structures are low, as most structures in use have largely been written off already but are in good operational condition.

In addition to the two MAR plants TRWU operates a number of small groundwater plants (share of the total production is 30 %). The total costs of all water production related costs (including the above mentioned MAR costs) are 0.194 euro/m^3 and the total costs of water distribution (distribution pumping, networks and water tower) are 0.166 euro/m^3. The total costs of TRWU are thus 0.36 euro/m^3. The selling price of water is 0.36 euro/m^3 without the value added tax (which is 24 %).

Table 5 Costs of MAR production at Tuusula Region Water Utility in 2015 (calculated in 2017 currency).

	Euro	Euro	Euro/m^3
Capital costs			
tunnel annual fee	167,000		
write-offs for own structure	11,000		
Total capital costs		178,000	0.028
Operating costs			
fee for the use of the tunnel system	47,000		
energy used in pumping (pumping of recharge water)	79,000		
other costs, including service purchases	11,000		
Total operating costs		137,000	0.021
Total costs		**315,000**	**0.049**

CONCLUSIONS

MAR has been found as a sustainable and cost-effective way for the removal of NOM from surface waters. NOM is decomposed or removed by natural processes of which biodegradation in the saturated groundwater zone has a key role. Large share and even distribution of good quality infiltrated water in the aquifer, compared to natural groundwater, helps to maintain oxic conditions in the vicinity of the abstraction wells and prevent iron and manganese dissolution.

Infiltration wells have environmental advantages over infiltration basins in terrain overlying eskers, and after 10 years of operation have been shown to have slightly lower maintenance requirements and hence less operating costs. While they may potentially be more vulnerable to clogging than basins, this has not been observed in operations so far.

Another major positive feature of the MAR process is the delayed influence of the raw water temperature on the abstracted water temperature. In the summer, the coolness of tap water makes it more enjoyable to drink and also decreases biological growth in the distribution network. In the winter, the water is slightly warmer which reduces the risk of freezing in the distribution network. Further, drinking water treatment by MAR is economically feasible. The combined capital and operating costs of the MAR treated water production can be as low as 0.049 euro/m^3.

TRWU has provided its customers with high-quality MAR treated drinking water since 1979. The use of MAR enables water treatment without precipitation chemicals and disinfection chemicals (chlorine compounds) allowing TRWU to advertise the water as ”organic”.

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