Managed Aquifer Recharge – A Potential Water Treatment Method in New Zealand?

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ABSTRACT

Principle ways of applying Managed Aquifer Recharge (MAR) for water management is presented. Furthermore, the potential pathogen (bacteria/virus) removal capacity of the method is demonstrated by presenting three studies performed in Sweden. The first study was an investigation of a MAR plant for water treatment, utilising basin infiltration of river water. Indicator organisms (bacteria) were measured in the raw water from the river and in the abstracted water from the wells in the plant. Even though the study revealed a MAR plant's typical good performance regarding bacterial removal, the initial concentrations of indicator organisms in the raw water were relatively low and the viruses/protozoa removal was not measured, therefore it was not possible to draw conclusions on the maximum achievable pathogen removal of the method. A column experiment was performed that displayed a 3-log reduction of virus and a 2.4-log reduction of bacteria. To understand the removal from other sites and with under conditions, a literature survey was performed and results were collected from international studies on pathogen removal (bacteria/virus) that showed that a distance of 40-80 m between the infiltration and the abstraction well should provide a removal of 4-6 $\log_{10}$ removal of viruses, equal to the WHO performance target for a raw water concentration of 1-100 viruses (pfu) per litre.

KEYWORDS

MAR, basin infiltration, pathogens, virus, bacteria, reduction

1 INTRODUCTION

Managed aquifer recharge (MAR) is used for treating water for potable use and storing water for future needs by recharging the natural groundwater source. There are several methods of recharging the groundwater; basins, wells, trenches, induction, etc, the main principle being that surface water from a lake or a river is by artificial means made to percolate or flow through porous material such as e.g. sand to recharge the groundwater. The method is not common in New Zealand, but given the large proportion of our agricultural land being situated on alluvial type deposits that are ideally suited to MAR (e.g. Canterbury, Southland, Mackenzie Basin, Otago, Hawkes Bay, Wairarapa, Manuwatu, Waikato) and the large population base located near major rivers or significant aquifers, MAR technology has significant potential in New Zealand. In comparison with other treatment solutions MAR can be a cost effective and environmentally sustainable option. The first of two objectives of this paper is to give an overview of methods applied for MAR.

The World Health Organisation (WHO) has proclaimed pathogens to be the most dangerous waterborne risk to human health. The developing world is exposed to frequent pathogenic outbreaks due to contaminated water and deficient treatment, and despite highly developed water treatment the developed world is still suffering from occasional outbreaks. Parasites, like Giardia and

Cryptosporidium, and pathogenic viruses provide a challenge to the water industry, as they have been found to partly resist disinfection. Thus understanding the reduction of pathogens is an ongoing issue. The second objective of this paper is to provide a general understanding of the potential pathogen (bacteria/virus) removal capacity of the method presenting results from three studies performed in Sweden.

One way of MAR is to infiltrate water in a geological gravel/sand formation. The City of Gothenburg in Sweden has investigated ways of securing its water supply. One alternative of safeguarding the water supply is to utilise a second water resource and for that purpose the Council's Water Management Department is interested in Lake Mjörn, located approximately 30 kilometres from the city. A geological deposit from the ice age is located close by and studies have shown that it is suitable for basin infiltration for potable water production (Figure 1). Three studies were performed to learn about the pathogen removal efficiency, for a potential MAR plant on the site.

Figure 1 A photo visualisation of the planned MAR plant at Lake Mjörn in Sweden.

The first study was an investigation of the Dösebacka plant utilizing basin infiltration for water treatment, utilising basin infiltration of river water from the adjacent river Göta Älv. The objective was to understand the performance of the plant in regard to pathogen removal. Indicator organisms (bacteria) were studied in the raw water from the river and in the abstracted water from the wells in the plant. Even though the study revealed a MAR plant's typical good performance regarding bacterial removal, the initial concentrations of indicator organisms in the raw water were relatively low and the viruses/protozoa removal was not measured, therefore it was not possible to draw conclusions on the maximum achievable pathogen removal of the method.

Thus a second study was performed in an experiment investigating the reduction of viruses and bacteria in large sand columns. The raw water supplied to the columns was spiked with selected organisms that simulated pathogens. E.coli, Coliforms, Enterococci, Cl.perfringens, Bacterophages MS-2 and ΦX174, were measured before and after percolation through the sand columns.

The first and second investigations were limited to one specific site and sand material, thus a third study was performed, a literature survey that collected results from international studies on pathogen removal (bacteria/viruses), enabling a comparison with results from investigations performed under different conditions.

2 MICROBIOLOGICAL BARRIER EFFICIENCY

A microbiological barrier is a step in the treatment process that prevents pathogens from reaching the consumer. In Sweden, there is no specific regulation on how efficient a microbiological barrier should be. The guidance, however, recommends the treatment operator to achieve turbidity less than 0.1 FNU and a 99 % (2 $\log_{10}$ when applying disinfection with chlorine) reduction of bacteria, which is regarded as minimum efficiency for a barrier (Livsmedelsverket 2004).

In an investigation (Persson *et al.*, 2005) of chemical precipitation and rapid sand filtration, the reduction of virus and faecal indicator bacteria was between 3 and 4 $\log_{10}$ and 1 to 2 $\log_{10}$ for natural particles with a size of bacteria and protozoa (>1 µm). Ultra filtration with a membrane pore size of 100 nm generated a reduction of 98-99.9 % of natural particles with a size of bacteria, and a reduction of 4.7 to 5.5 $\log_{10}$ of amended bacteriophages (Persson *et al.*, 2005). Slow sand filtration gives a reduction of 1 to 4 $\log_{10}$ of protozoa, and often higher reductions of virus (Logsdan *et al.,* 2002).

The microbiological barrier efficiency depends on two major reduction principles: physical/chemical removal and inactivation or die-off. When water is filtered through sand material the major part of the reduction takes place in the first 2 meters of the material and in MAR there is commonly an early reduction of micro organisms (Huisman, 1983). However, due to e.g. protozoa's high resistance, there might be a risk for possible breakthrough (Schijven, 2001). Micro organisms have been observed to travel tens to thousands of meters (Pang *et al.*, 2005). However, a major part is reduced within 40 meters from the infiltration basin (Engblom and Lundh, 2006). The low infection-dose of parasites and viruses combined with the fact that both have a high resistance to disinfectants and high survival in subsoil environments, makes them important factors in all water treatment applications.

Jörgensen *et al.* (2001) found that after 10 days of transport in the subsurface the reduction of bacteriophages was 6 $\log_{10}$ and after 25 days 8 $\log_{10}$. Schijven (2001) measured an 8 $\log_{10}$ reduction of MS-2 bacteriophages after a transport time of 38 days in saturated soil. Studies in unsaturated zone show a higher efficiency in the reduction of virus (e.g. Jin *et al.*, 2000; Schijven 2001). A hypothesis is that the interface between the gases and liquid plays an important role (Jin *et al.*, 2000). A Swedish study (Blomberg /ed/, 1999) measured an 80 % reduction of bacteriophages in 4 meter of unsaturated soil, which implies a great variance in efficiency.

3 MANAGED AQUIFER RECHARGE

The method of Managed Aquifer Recharge (MAR) is based on the principle of recharging water into the aquifer thus increasing the capacity of the groundwater abstraction by technological means. The method can be used for several purposes, such as:

- Water treatment
- Reuse of wastewater
- Water storage

- Storm water management
- Environmental protection and improvement
- Flood and overflow management
- Improving Urban Environmental Values
- Improving coastal water quality by reducing urban discharge of stormwater
- Salinity remedy and protection of aquifers

Using MAR for water treatment is a common application in Europe. In regions in Sweden gravel aquifers are rare as bedrock is predominant in the surface of the ground. Thus the storage is limited and as there is often a high occurrence of surface water the formations are used for treatment. When it is possible the aquifers are used both for treatment and storage but in general the aquifers are limited in extension and the main purpose is the provide treatment. However, the water needs to have a quite high quality and surface water with lower quality in most cases require some sort of pre treatment; settling ponds, rapid sand filtration and even chemical additions for coagulation could be necessary. Some different ways of applying MAR is illustrated in Figure 2.

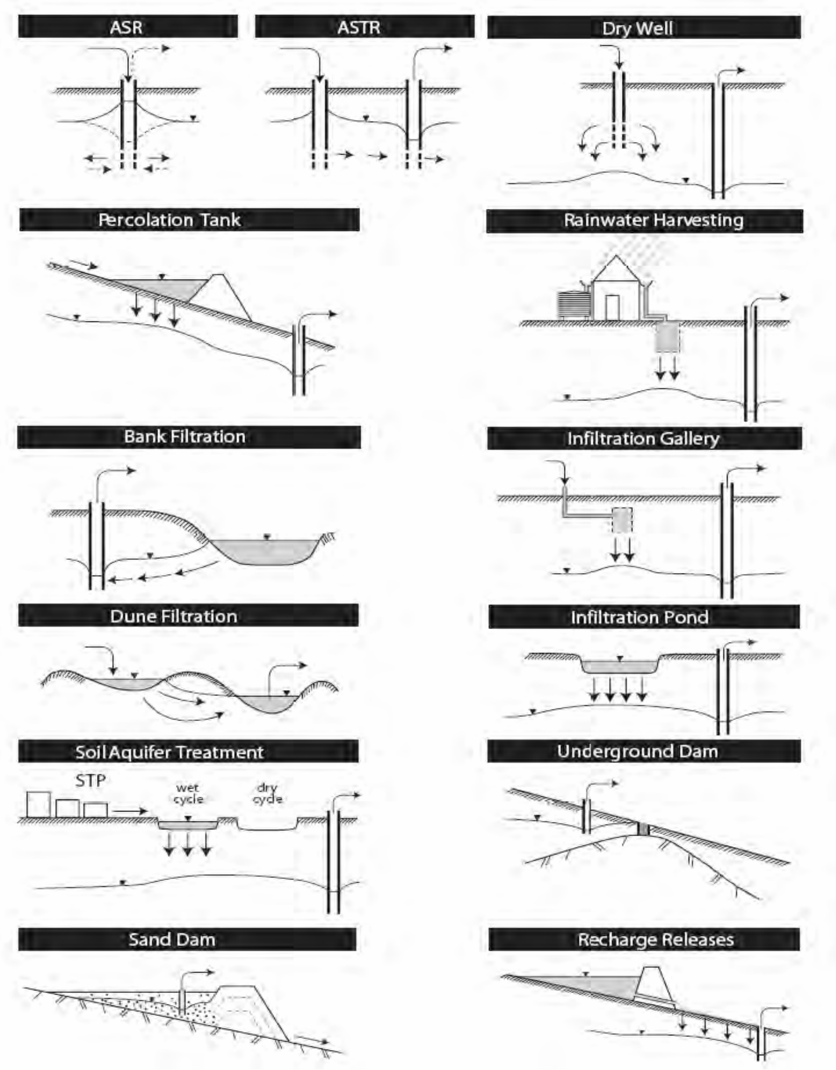


Figure 2 Applications of MAR (In proceedings from ISMAR6 2007)

Irrigation is another method that is not shown in the figure.

4 STUDY 1 – MICROBIOLOGICAL REMOVAL PERFORMANCE OF THE DÖSEBACKA INFILTRATION PLANT

4.1 INTRODUCTION

The objective of this study was to identify the microbiological barrier efficiency at the Dösebacka Artificial Groundwater Recharge Plant. The Dösebacka Artificial Recharge plant is located in south-west of Sweden, close to Gothenburg. The plant is the water supply for 25,000 people in the community of Kungälv and produce approximately 6,000 m^3/d. The layout consists of 9 infiltration ponds ranging from 560 to 2,400 m^2 in size and 15 abstraction wells ranging in pumping from 1 to 18 l/s. The water is pre-treated with sedimentation and the treated water is pH-adjusted with NaOH for corrosion prevention in the distribution net. Two wells that abstract water with a higher turbidity and organic content are post treated with chemical precipitation using aluminium sulphate. There is disinfection equipment available for the drinking water in case of an emergency with microbiological contamination but it is rarely used due to the high quality of the water.

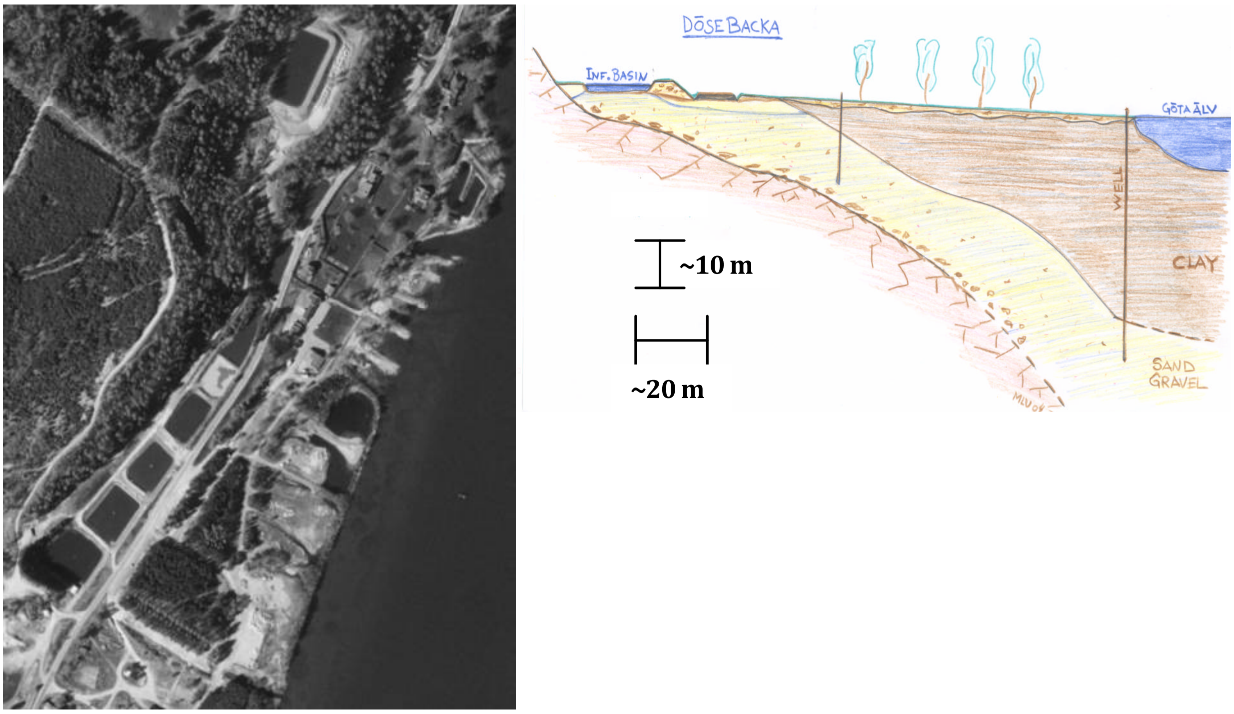


Figure 3 Right/ A flight photo of the Dösebacka Infiltration Plant. Left/ A cross section perpendicular to the river showing the general geological structure under the Dösebacka plant

A suggested model of the Dösebacka aquifer is a 10-15 m single aquifer of sand and gravel, which is sloping from 3-15 m below surface, under the infiltration ponds, to 50-60 m below the surface at the river. The aquifer is partly confined with a layer of clay; thin near the ponds and increasing to 20 to 40 m close to the river. In the north the clay is absent. Below the aquifer lies bedrock, probably heavily fractured (Figure 3).

The hydrology of the aquifer is governed by the gradient from the elevated infiltration ponds down to the river, a groundwater divide, and the induced infiltration in the north. The hydrochemistry reveal two different water types. One with the dominance of infiltrated river water and another that reflects prevalence of local groundwater and influence of saline formation water from the subsurface, which is the case for some wells close to the river. An explanation could be that the infiltrated water does not reach these wells.

4.2 GROUNDWATER FLOW AND RESIDENCE TIME

A computer simulation with MIKE SHE (Figure 4) displays flow paths from the infiltration ponds to the Göta Älv River. Both hydraulic data and seismic investigations suggest a divide in the southerly part of the site, directing the flow into one southeast respectively one northeast path towards the river. This divide is likely made of bedrock or perhaps till. Figure 4 also reveals a gradient from the river suggesting some induced infiltration from the river along the shore. In the north, the absence of a confining layer allows induced infiltration from the river. The thickness of the unsaturated zone varies between 0 to 8 m.

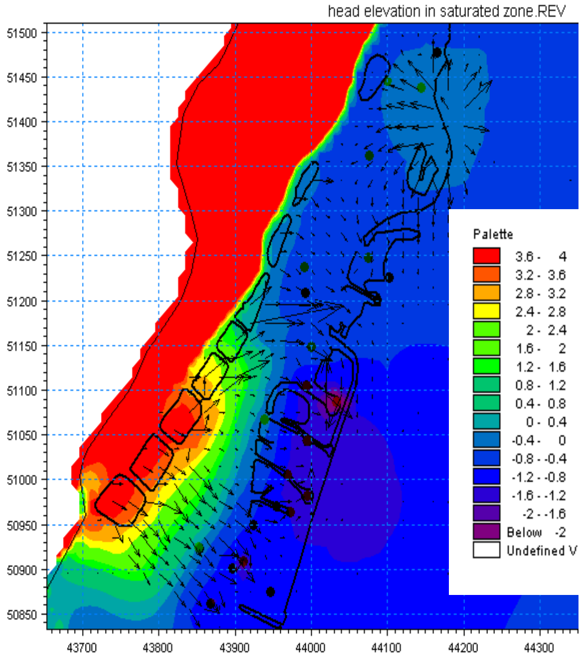


Figure 4 The flow paths at the Dösebacka AR plant generated with numerical calculation in MIKE SHE (with kind permission of DHI, Sweden).

4.3 WATER QUALITY

Turbidity and salinity are the two main water-quality issues at the Dösebacka site. Turbidity is probably related to fines that follow the abstracted water in wells with a short subsoil transport time. The salinity is believed to do with captured relict water from the period after the deglaciation when the area was inundated by the sea prior to and during the land rise. Wells with chloride also show concentrations of manganese and occasionally nitrite, probably connected to low oxygen concentrations in the relict water. There is a potential risk of microbiological breakthrough due to the shorter subsoil transport time experienced in some wells, and coliforms have been detected at times, but the chemical precipitation constitutes a barrier for that reason.

*Table 1 Average Water Quality for some parameters (from 4-9 samples over the period) in Dösebacka May 2003-May 2004 * detection level <2 cfu/100 ml*

PARAMETER	Unit	Göta Älv	Pond	Well GRP 1	Well GRP 3	Well GRP 7	Well GRP 9	Drink W.
Slowly growing bacteria	cfu/ml	3100	>3100	93 - 100	0 - 10.0	48 - 50	5.0 - 13	33 - 38
Microorganisms, 22°C 3d	cfu/ml	1400	>2400	95 - 100	0 - 10.0	0 - 10.0	2.5 - 10.0	5.5 - 5.8
Coliform bacteria 35°	cfu/100ml	>340	>350	0 - 1.0	0.22 - 1.0	0 - 1.0	0 - 1.1*	0 - 1.0
E.coli	cfu/100ml	>46	>38	0 - 1.0	0 - 1.0	0 - 1.0	0 - 1.1*	0 - 1.0
Hardness	°dH	1.5	1.4	1.5	1.5	7.7	1.7	3.3
Fe (++)	mg/l	0.12 - 0.13	0.12 - 0.13	0.014 - 0.053	0.0067 - 0.051	0.086	0.046 - 0.071	0 - 0.050
Cl (-)	mg/l	8.3	8	7.7	8.3	180	9.5	56
EC	mS/m	10	9.9	9.9	11	82	11	33
Mn (++)	mg/l	0.0083 - 0.025	0.0029 - 0.020	0 - 0.020	0 - 0.020	0.23	0 - 0.020	0.034
Nitrite nitrogen	mg/l	0.0028	0.003	0.00078 - 0.0014	0.00044 - 0.0012	0.0076	0.00020 - 0.0011	0.011
Ammonium nitrogen	mg/l	0.025	0.029	0 - 0.0078	0 - 0.0078	0.62	0.0010 - 0.0080	0.07
pH		7.2	7.2	6.9	7.1	7.8	6.9	8.1
Turbidity	FNU	5.2	4.9	0.85	0.72	1.1	1.6	0.54
Alkalinity	mg/l	20	20	21	27	120	22	61
COD-Mn	mg/l	3.7	3.7 - 3.9	0.56 - 1.0	0 - 1.0	0.22 - 1.0	0.70 - 1.1	0.20 - 1.0
Colour		22	22	5.0 - 5.6	5.0 - 8.3	5	9	2.0 - 5.0

4.4 METHOD

The pathogens (infectious microorganisms) were simulated with traditional indicator bacteria of faecal contamination known to occur in the river; total Coliforms, E.coli, Enterococci and Clostridium perfringens. The methods for the different analyses are listed in

Table 2.

Analysis	**Detection level**	**Method**
Coliforms 35ºC MPN	<1 No/100 ml	Colilert18 (Manufacturer: IDEXX)
E.coli 35ºC MPN	<1 No/100 ml	Colilert 18 (Manufacturer: IDEXX)
Coliforms 35ºC MF	<1CFU/100 ml	SS 0281672
E.coli 44ºC MF	<1 CFU/100 ml	SS 0281672 mod
Enterococci 35ºC MF	<1 CFU/100 ml	SS EN ISO 78992 utg 1
Cl.perfringens (pres) MF	<1 CFU/100 ml	ISO/CD 64612 021220
(MF=Membrane filtration, MPN=Most Probable Number, CFU=colony forming unit, No= Number):		

Table 2 The methods for the different analyses.

Samples were taken twice a week in one of the infiltration ponds and in 4 abstraction wells for four weeks in February 2004. The study was preceded by about 34 days of bad water quality in the river, caused by storm weather. The detention time (travel time) for the subsurface water transport is estimated to vary in Dösebacka between 6 and 75 days in others (Lundh *et al*, 2005). Therefore the period of 60 days from the first of January to last of February 2004 was considered to be long enough to detect a possible breakthrough.

Abstraction wells for the study were chosen to represents different detention time, different areas of the plant, different water characteristics and different locations in relation to the river Göta Älv. The chosen infiltration pond represented all ponds and was located in the middle of the chain of ponds (nine in total).

The log reduction in the aquifer, meaning between basin F and the observed wells, was calculated as (negative sign to make the reduction positive):

$$\log_{10} \text{reduction} = -\text{Log}_{10}(C/C_0) \qquad [-]$$

where C is the measured concentration in a specific well in CFU or No per water volume, C_0 is the initial concentration in pond F in CFU or No per water volume.

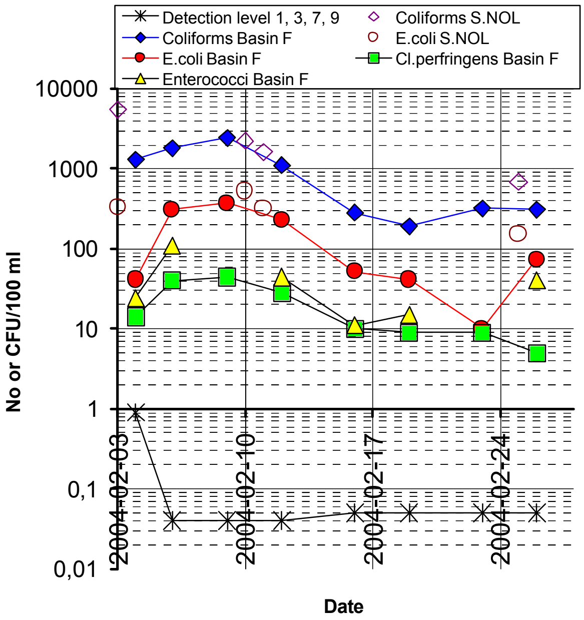


Figure 5 The concentration of the studied bacteria in basin F and the correlation to measurements in the river (S.Nol). Bacteria were not detected in the wells and the detection limits for the analysis of bacteria concentration in the abstraction wells are shown.

4.5 RESULTS AND DISCUSSION

Comparing the concentration of bacteria in basin F and the detection level in Figure 5, generates a $\log_{10}$ reduction between 3.0-4.7 calculated as the difference between the observed maximum in the infiltration pond and the detection limit or the single detections (Table 3). As there were so few detections of bacteria in the wells it has been difficult to quantify the barrier capacity and the experienced values should be considered as minimum values.

Table 3 Observed Log_{10} reduction in the study.

Microorganism	Log_{10} reduction
Coliform bacteria	4.7
E.coli	3.9
Enterococci	3.4
Cl.perfringens	3.0

E.coli is known to die off rather rapidly and coliforms are found and proliferate in the environment (Water Quality and Treatment, p 2.15) and could thus exist naturally in the wells. However, total coliforms is professionally used to assess water treatment efficiency and the fact that coliform bacteria was not detected in the study makes the results more believable – the high concentration of bacteria observed in the beginning of the period of bad quality do not seem to have breached through the aquifer.

It is not possible to differentiate between die off and sorption as reduction mechanisms. Enterococci or Cl.perfringens, that are more persistent than Coliform and E.coli, were found only at one occasion and in a very low concentration This ought to imply that, regardless of mechanism, a general $\log_{10}$ reduction of about 3 (99.9% reduction) is valid for the Dösebacka plant and might be even higher for certain pathogens, which is indicated by the higher reduction of coliforms. The reduction could also be less for the same reason; the one indication of the persistent organism could imply that pathogens that are more persistent than Cl.perfringens and Enterococci, might be less reduced. However, this requires more specific studies with other tracer organisms.

Even though the period of four weeks of water sampling was considered as a sufficient observation period for the purpose of the study, the detention time in the subsurface has only been verified for one well (well 9) while the others are estimated from temperature variations in the groundwater (Lundh *et al,* 2005). Therefore there might exist longer transport times in the subsurface for the abstracted water in well 1, 3 and 7. The longer the transport in soil, however, the lower the risk of breakthrough is, which makes this aspect less important.

Finally, it should be pointed out that the study has investigated the reduction of indicator organisms for faecal contamination, not any actual pathogen, which means that the reduction is only an indication of the pathogen reduction in Dösebacka, based on the assumption that the indicator organisms studied are behaving similar to the pathogens in die off and sorption.

4.6 CONCLUSIONS

The conclusion is that the microbiological barrier in the Dösebacka aquifer works relatively well with an efficiency of at least 99.9%. (3 $\log_{10}$ reduction). The study suggests that the plant is capable of handling variations in bacteria concentration in Göta Älv during a normal year. That corresponds to a concentration of 999 E.coli per 100 ml in the infiltration pond if the limit for acceptable water quality for drinking water use, <1 CFU per 100 ml, is to be satisfied. However, the reduction is probably higher for those pathogens that resemble the behaviour and die off of coliforms.

5 STUDY 2 - REDUCTION OF PATHOGENIC MICROORGANISMS IN UNSATURATED ZONE – A COLUMN EXPERIMENT

5.1 OBJECTIVES

The main objective of the study was to investigate the microbiological barrier efficiency and the reduction of NOM in the unsaturated zone in artificial recharge of groundwater by pond infiltration by:

- Quantifying the reduction of bacteria and viruses utilizing pulse-response amending with indicator bacteria and bacteriophages as models for viruses,
- Quantifying the reduction of NOM
- Investigating the reduction efficiency of Iron Oxide Coated Olivine sand (IOCO)

5.2 IOCO-SAND

Iron oxide coated olivine (IOCO) sand is a filter material with an improved ability of removing NOM compared to conventional filter sand (Chang *et al*., 1997, McMeen & Benjamin 1997). The material consist of olivine sand [$(Mg, Fe)_2SiO_4$] that is coated with a thin layer of iron oxide. Studies (Jonsson 2003, Berggren *et al.,* 2004) have shown a great potential of removing NOM in the unsaturated zone by adding a 30-cm layer of IOCO-sand on the top of the filter bed. It is also possible to overlay the IOCO-layer with ordinary filter sand as a maintenance layer without the efficiency declining. Hypothetically, there should also be an improved efficiency in reducing pathogens.

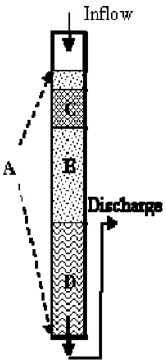
5.3 METHOD

5.3.1 EXPERIMENTAL SETUP

Five 6-m PVC-plastic pipes with a diameter of 0.3 m were raised and filled with 5.4 m of sand from the Gråbo glacial delta formation. Study cases were configured of 1, 2 and 4 m of unsaturated zone overlaying varying depths of saturated zones. (Table 4). Two columns contained 2.5 m of Gråbo sand including 0.3 m layer of IOCO-sand in study cases with 2 m of unsaturated zone. The sand was analysed (Lundh *et al* 2006) and the hydraulic loading was 25 ml/min, which resulted in an infiltration rate of 0.5 m/d. The raw water was taken from the Lakes Delsjöarna in Göteborg, Sweden, and brought to the top of the column in soft transparent PVC-hoses where it was distributed by dripping on the sand infiltration surface.

Table 4 Column properties and case studies

Column	Total depth (A)	Unsat. zone[1] (B)	IOCO (C)	Sat.zone (D)
K0	5.4 m	-	-	2 and 4 m [1,2]
K1	5.4 m	4 m	-	1.5 m
K2	5.4 m	2 m	-	3.5 m
K3	5.4 m	2 m	-	3.5 m
K4	5.4 m	1 m	-	4.5 m
K5	2.5 m	2 m	0.3 m	0.5 m
K6	2.5 m	2 m	0.3 m	0.5 m



1) was actually approx.10 cm less but is rounded off for readability reasons.

2) top 2 and 4 m of saturated zone was studied.

5.3.2 REDUCTION OF BACTERIOPHAGES

The reduction of bacteriophages was measured during three pulse response experiments (experiment 1, 2 and 3), using bacteriophages MS-2 (ISO 10705-1, International Organization for Standardization, 2002b) and ΦX174 (ISO 10705-2, International Organization for Standardization, 2002a) as models for viruses. A solution of phages was added to the raw water during a 40-min period in experiments 1 and 2, while in experiment 3 the amending was continuous for 7 days in order to reach a steady state of reduction. The concentration of bacteriophages in the added solution in experiment 3 was only 0.5 % of those in experiments 1 and 2 due to practical experimental reasons.

The calculation of the reduction in the unsaturated zone was based on the measured peak concentration in the response curve for each column during one experiment. All columns received the same pulse concentration of bacteriophages. The $\log_{10}$-reduction = $-\log_{10}(C_{max}/C_0)$ was calculated for each case, where C_{max}=maximum concentration and C_0=initial pulse concentration. As C_0 varied, e.g.

in experiment 3, the C_0 is represented by the peak of the pulse concentration and regarded as the maximum load that the columns experienced. The uncorrected filter factor C_f was calculated from:

$$-\log_{10} (C_{max}/C_0) = C_f \text{ x depth of zone} + \text{Constant.} \qquad \text{[eq.1]}$$

The dispersion in the water, calculated from tracer experiments with NaCl, was handled as a dispersion factor C_d from the relationship:

Analysis	**Detection level**	**Method**
Coliforms 35ºC MPN	<1 No/100 ml	Colilert18 (Manufacturer: IDEXX)
E.coli 35ºC MPN	<1 No/100 ml	Colilert 18 (Manufacturer: IDEXX)
Coliforms 35ºC MF	<1CFU/100 ml	SS 0281672
E.coli 44ºC MF	<1 CFU/100 ml	SS 0281672 mod
Enterococci 35ºC MF	<1 CFU/100 ml	SS EN ISO 78992 utg 1
Cl.perfringens (pres) MF	<1 CFU/100 ml	ISO/CD 64612 021220

(MF=Membrane filtration, MPN=Most Probable Number, CFU=colony forming unit, No= Number):

$$-\log_{10}(C_{max}/C_0) = C_d \text{ x depth of zone} + \text{Constant,} \qquad \text{[eq.2]}$$

Finally, the accurate filter factor F was gained through the correction formula:

$$F=C_f - C_d. \qquad \text{[eq.3]}$$

5.3.3 REDUCTION OF BACTERIA

Experiment 4 was performed as a pulse response experiment with duration of 12 days to reach steady state in reduction. The pulse suspension consisted of pre-treated wastewater from Ryaverket in Göteborg, in which the analyzed (

Table 2) microorganisms exist in high numbers. In order to keep a relatively steady concentration in the pulse solution, a new batch was prepared every day during the experiment. Pre-treated wastewater was added to the raw water to reach a 2% wastewater contamination, which is a higher concentration than commonly encountered in the raw water from the Göta Älv River; the raw water supply for Göteborg Water. Furthermore, the concentration of wastewater was kept low to prevent high concentrations of suspended solids that could clog the infiltration surface of the column.

Coliforms, *E.coli*, enterococci and *Clostridium perfringens* were chosen as model organisms in this study. *Cl. perfringens* is especially interesting due to its spore forming ability. Spores show a resistance comparable to the parasites but are of a size equal to bacteria. A $\log_{10}$-reduction was calculated by using the maximum detected effluent concentration for each model organism, $C_{max, column}$, which was divided with the minimum; $C_{min,pulse}$, and the maximum; $C_{max, pulse}$, concentration in the amended pulse concentration. Values <1 cfu or No/ml was treated as no detection=0. The relationships used were minimum reduction= $-\log_{10} (C_{max, column}/C_{min, pulse})$ and maximum reduction= $-\log_{10} (C_{max, column}/C_{max, pulse})$.

5.3.4 RAW WATER QUALITY AND HYDRO GEOLOGICAL CHARACTERIZATION OF SAND MATERIAL

The raw water from Delsjöarna was soft; 10 mg Ca /l , and had a temperature variation from 2° C in the winter to 20°C in the summer. The columns, however, were placed indoors and exposed to a constant temperature of 13 °C giving the water a similar temperature with only minor variations. Salinity (11 mS/m) and concentrations of metals were low. The concentration of faecal indicators was low. The turbidity was less than 1 FNU, pH was about 7.1 and alkalinity was approx. 0.25 mmol/l. The concentration of organic matter was 4 -7 mg/l O_2 for COD_{Mn}, 4 - 6 mg/l TOC and 0.092 - 0.202 ae/cm measured as UV- absorbance at 254 nm.

The material from Gråbo was found to originate from granite/gneiss with 40 % quartz and 27 % Na-silicates and with a clay content of 2-3%. The bulk density of the material was measured to be 1526 kg/m^3 with a total porosity of 41%. The specific yield (drainage porosity) was measured to 24 % and the theoretical specific surface was calculated to be $1.23 \times 10^5 - 2.51 \times 10^5$ m^2/m^3 (Rådmark and Svensson 2003). The grain size of d_{10} was between 0.044 mm and 0.074 mm and d_{60} between 0.210 and 0.500 mm, which gives d_{60}/d_{10} = 6-7.

The water transport time in the columns was 13-44 h for 1-4 m of unsaturated zone and 39 h for 2 m of saturated zone. The hydraulic conductivity was 0.4×10^{-4} to 1.5×10^{-4} m/s and the unsaturated water head was –25 cm. The analysis of the water transport time for both unsaturated and saturated conditions (Lundh *et al.,* 2006), suggests a rough estimation of the saturation of 56% of total porosity. A total porosity of 41 % would result in a saturation of 23 %.

5.4 RESULTS AND DISCUSSION

5.4.1 REDUCTION OF BACTERIOPHAGES

The results have been presented in Lundh *et al.* (2006). The average reduction, expressed as the filter factor, gained by analysing the inclination from 1 m to 4 m, was calculated to 0.73±0.4 $\log_{10}$/m

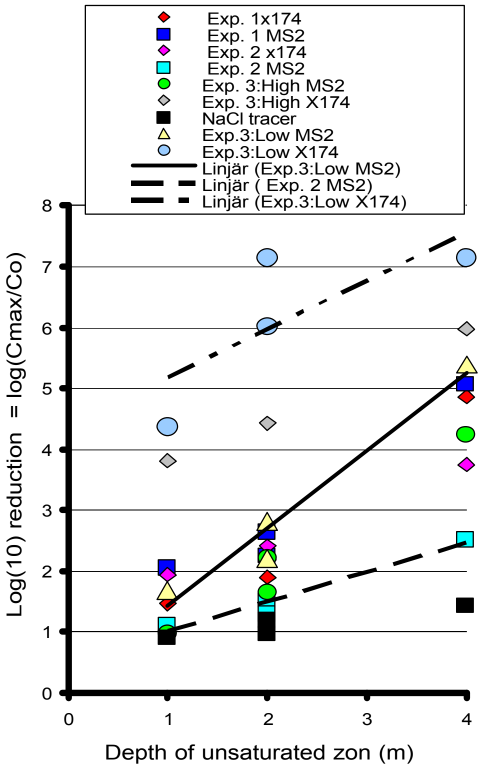


Figure 6 The log10-reduction of bacteriophages in relation to depth of unsaturated zone. C_0 is the maximum pulse concentration.

(Figure 6). The filter factor was higher in experiment 1 (0.90-0.99 log$_{10}$/m) than in experiment 2 (0.32-0.46 log$_{10}$/m), which could be explained by the high concentrations of phages and organic matter (experiment 1), which might have occupied sorption locations in the sand, and possibly due to a difference in salinity. In both experiments 1 and 2 the filter factor for MS-2 was lower than for ΦX174.

The filter factor in experiment 3 was lower for ΦX174 (0.48 to 0.62 log$_{10}$/m) than for MS-2 (0.94 to 1.11 log$_{10}$/m) even though the total reduction was higher for ΦX174 (approx. 4 to 7 log$_{10}$) compared to MS-2 (approx. 1 to 5 log$_{10}$). The filter factor was based on the reduction between 1 and 4 m, which implies that ΦX174 was reduced efficiently in the first meter and thereafter to a lesser extent. MS-2 on the other hand, did not show the same initial reduction the first meter but seem to have had a more even reduction rate over the examined depths.

A hypothesis for the behaviour could be that the reduction of organisms in the experiment was caused by the organism's isoelectric point and real time concentration. MS-2, a relatively hydrophobic virus with a lower isoelectric point (3.9), making it more negative in charge, would be less attracted to a soil in neutral water, causing the soil also to be negative in charge, than ΦX174, which is a relatively hydrophilic virus with a higher isoelectric point (6.6), that is more neutral in charge in neutral water. The extensive initial removal of ΦX174 could be a result of this rationale. And a lower concentration would reduce the possibility of collision frequency between bacteriophages and grains, which could be the explanation to why MS-2 had a higher filter factor than ΦX174 after initial removal on the surface, as the phage would exist in higher concentration.

When applying a layer of IOCO-sand the reduction efficiency increased for both of the studied phages. In figure 2 it was possible to graphically determine a 5-6 log$_{10}$-reduction of ΦX174 and a 4-5 log$_{10}$-reduction of MS-2. This is a much higher efficiency than observed for the unsaturated cases, maybe except for the 4-m unsaturated case that had nearly the same efficiency for ΦX174.

5.4.2 REDUCTION OF BACTERIA

The number of bacteria was expectedly higher in the pre-treated wastewater than in the raw water from Delsjöarna and the variation was significant in the mixed pulse concentration. The content of coliforms was between 5,500 and 240,000 No/100 ml and the numbers of *E.coli* varied between 1,000 and 46,000 No/100 ml. Enterococci varied between 100 and 9,000 CFU/ 100 ml and *Cl.perfringens* between 180 and 520 CFU/100 ml (Figure 7).

Neither coliforms nor *E.coli* were detected in any effluent during experiment 4. For 2 m of unsaturated zone (K2) 1 CFU/100 ml Enterococci and 1-2 CFU/100 ml of *Cl.perfringens* was detected for 2 m and 4 m unsaturated zone and 2 m saturated zone. No bacterial parameter could be detected in any effluent from the IOCO-columns. Due to the low numbers of bacteria it was not possible to distinguish whether unsaturated condition was better than a saturated one or if 4 m of soil passage gave a higher efficiency than 1 m. Thus the log$_{10}$-reduction is related to a depth of 1-4 m of soil passage, regardless of saturation. The results indicate a removal of >5.4 log for coliforms, >4.7 log for E.coli, 2.0 to 4.0 log of Enterococci and 2.1 to 2.4 log of Cl.perfringens.

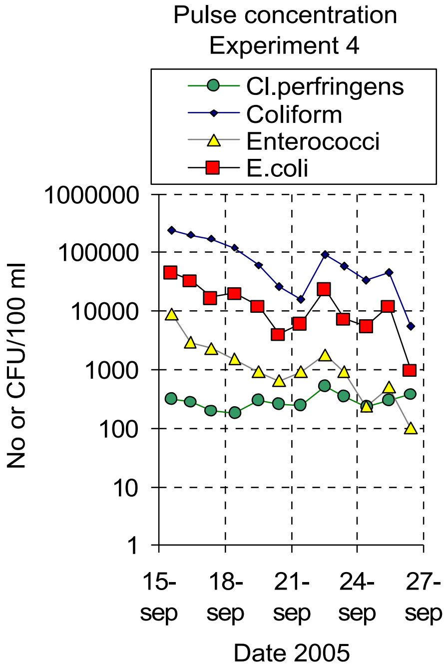


Figure 7 Pulse concentrations for all columns in experiment 4.

5.5 CONCLUSIONS

The microbiological barrier regarding virus was efficient in 4 m of unsaturated zone (3 $\log_{10}$). It was higher than disinfection with chlorine (2 $\log_{10}$) and as high as chemical precipitation (3-4 $\log_{10}$ for bacteria and virus). The efficiency was higher in unsaturated zone compared to saturated zone. IOCO-sand strongly enhanced the reduction of virus (in total 4-6 $\log_{10}$) and could be favourable in enhancing the reduction in a thinner layer of unsaturated zone.

The microbiological barrier efficiency regarding bacteria was sufficient in 4 m of unsaturated zone ($\geq$2.4 $\log_{10}$). It was similar to disinfection with chlorine (2 $\log_{10}$) and slightly lower than chemical precipitation (3-4 $\log_{10}$ for bacteria and virus). There was no obvious difference in efficiency between an unsaturated and a saturated condition.

6 STUDY 3 - LITERATURE SURVEY

6.1 INTRODUCTION

The preceding studies described in this paper have shown that there was a high removal of indicator organisms in the investigated plant and that a large part of the removal occured early in the subsoil transport of the water. The studies showed that an infiltration of water according to MAR practice, removed several logs of virus and bacteria the first 4 meters but that the removal declined with time/distance, which was shown by the removal of bacteriophages.

The objective of the literature survey was to investigate the latest research on the reduction/removal of pathogens in managed aquifer recharge to identify what factors are important for the performance. Another objective was an attempt to define a relationship with an applicable parameter that could be used as secure approach when designing a MAR plant.

6.2 METHOD

Electronic databases (Elsevier, ScienceDirect, ProQuest, Springer Link, etc) were used to find recent and relevant studies. Data was compiled and essential information was drawn from the studies. Diagrams were produced based on the collected data.

The reference list on the literature that was studied in the literature survey can be found in Engblom&Lundh, 2006, that can be downloaded from The Swedish Water & Wastewater Association's (SWWA) website: http://www.svensktvatten.se/web/VA-Forskrapporter.aspx.

6.3 SUMMARY

The literature survey showed that several parameters were interacting in the removal performance e.g. (Table 5 Characteristics influencing the removal/die off of pathogens in MARTable 5):

Table 5 Characteristics influencing the removal/die off of pathogens in MAR

Microorganism	Water	Soil	Operation
Concentration	pH	Particle size	Retention time
Type of organism	Temperature	Porosity	Transport distance
Size of organism	Organic content	Mineral composition	Groundwater velocity
Charge of organism	Ion content	Grain surface charge	Saturation
Hydrophobicity	Ion composition	Hydrophobicity	Biological scaling
Other microorganisms			

It is not within the scope of this paper to discuss the mechanism for each factor. In fact, when looking at designing a MAR plant it is probably not particularly efficient to try to investigate each and all of the factors in the above table. Parameters that are practical from a designing and controlling point of view would be factors such as groundwater velocity, retention time in the aquifer and the distance to abstraction wells. Thus the removal of microorganisms was related to the distance between abstraction well and infiltration pond, and furthermore to a rough estimation of the groundwater velocity (Figure 8), from the studies available.

The literature survey strengthened the observation that the reduction is initially high and then decreases with distance. It also showed that a minimum distance of 40-80 meters between the infiltration pond and the abstraction well, should provide a 4-6 $\log_{10}$ removal of viruses, even for "faster" groundwater flows. .

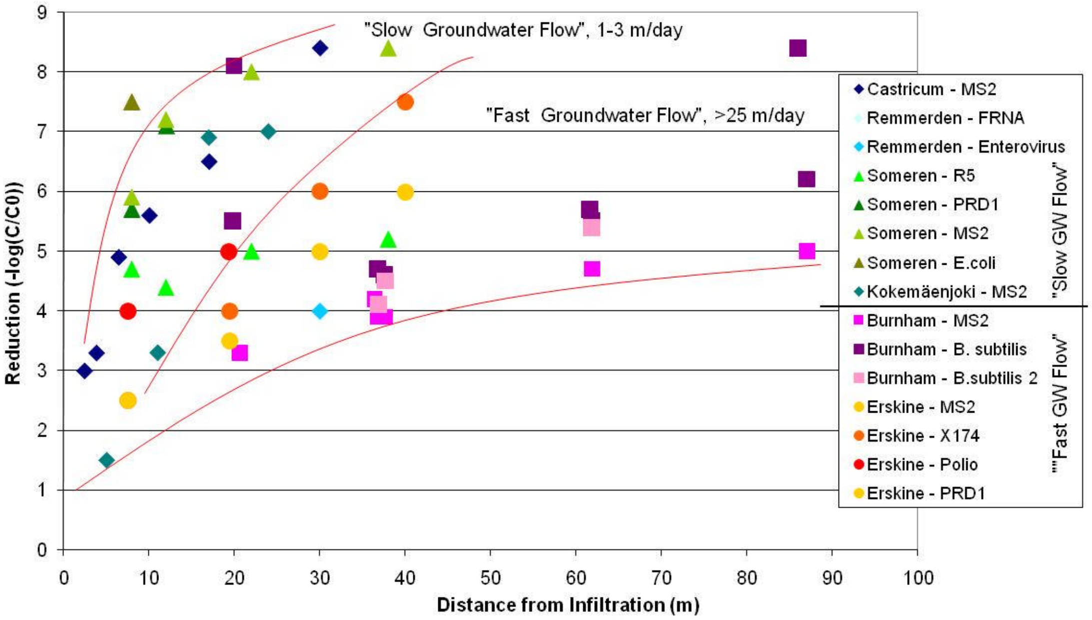


Figure 8 *Log-reduction of certain bacteria and virus versus the distance between the infiltration and the sampled well.*

7 CONCLUSIVE SUMMARY

The method of Managed Aquifer Recharge by basin infiltration was shown to have a high pathogen removal capacity in regard to bacteria and viruses. The microbiological barrier regarding virus was efficient in 4 m of unsaturated zone, 3 $\log_{10}$, comparable with both disinfection with chlorine and chemical precipitation For viruses the efficiency was higher in unsaturated zone compared to saturated zone and IOCO-sand strongly enhanced the reduction of virus and could be favourable in enhancing the reduction in a thinner layer of unsaturated zone.

The microbiological barrier efficiency regarding bacteria was sufficient in 4 m of unsaturated zone, $\geq 2.4 \log_{10}$, comparable to disinfection with chlorine and chemical precipitation. However, there was no obvious difference in efficiency between an unsaturated and a saturated condition. The study was limited by the fact that maximum removal efficiency was not observed due to a too low influent bacteria concentration.

Protozoa was not specifically investigated but them being larger than bacteria, implies that also protozoa should be effectively removed. However, heterogeneity in the soil and the protozoan high survival suggests that this should not be taken for granted.

Results from international studies also give evidence that the pathogen removal capacity is high for basin infiltration. Compiled and compared they seemingly display a secure distance of 40-80m between the infiltration and the abstraction well, a distance that would suffice for a 4 to 6 log removal. The required removal is dependent on the raw water pathogen concentration, but a 4-6 $\log_{10}$ removal is a performance target for a concentration of 1-100 viruses (pfu) per litre in the raw water (WHO), a typical value for waters such in Sweden and probably in New Zealand.

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