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Filter media for basin infiltration: a case study

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ABSTRACT

This study presents a viable filter media for infiltration basins used by managed aquifer recharge (MAR) plants. Filter media properties for sand filters, such as rapid and slow sand filters, are well established. This article investigates suitable filter media based on operational experience and filter media recommendations for sand filters, which is applied to the Vomb water treatment plant (WTP), a MAR plant in south Sweden. The results from this case study showed that a filter media with an effective grain size (d_{10}) of 0.22–0.38 mm was likely viable based on the grain sizes of the natural glacifluvial deposits. The recommendation also included an optimal d_{10} range of 0.22–0.30 mm to increase the retention of particles in the filter media, rather than particles clogging and reducing the permeability of the aquifer. As a result of using filter media with lower d_{10}-values than the glacifluvial deposits, unsaturated conditions under the infiltration basins will also likely improve. Furthermore, the recommendations presented in this study include limits for certain natural occurring contaminants (such as arsenic and mercury), other grain size grading characteristics and mineral composition.

Key words: clogging, effective grain size, filter media, infiltration basins, managed aquifer recharge (MAR)

HIGHLIGHTS

- Descriptions of suitable filter media for managed aquifer recharge (MAR).
- Presents international recommendations for granular media properties and applies this in a case study at a MAR plant in Sweden.
- Results showed that a filter media with an effective grain size (d_{10}) of 0.22–0.38 mm was likely viable.
- Finer grain material and the d_{10} seems to be the dominant factor for predicting permeabilities of filter media.

INTRODUCTION

Managed aquifer recharge (MAR) is a common way of producing and storing groundwater worldwide (SWWA 2016; Sprenger *et al.* 2017; Stefan & Ansems 2018), where aquifers are recharged with surface water through infiltration basins. During infiltration and percolation, natural organic matter (NOM) and pathogens are removed to varying degrees in the unsaturated and saturated zones (WHO 2016; Sarma 2020; Hägg *et al.* 2021). Infiltration basins follow certain operational cycles, where the resistance increases in the basins due to the natural compaction of the sand and accumulation of organic and inorganic matter, and microorganisms (Jeong *et al.* 2018). As a result, infiltration basins require maintenance by emptying and scrapping the top layer of sand. Through this process, water treatment plants (WTPs) experience losses of natural sand material; therefore infiltration basins need additional sand to replace these losses. It is common that the natural sand material from the recharge field is used or that new sand is brought in from other natural glacifluvial deposit sources. In Sweden, it is very common that MAR-plants use sand that follow the Swedish recommendations on slow sand filtration (SFF) sand (Hägg *et al.* 2018). The specifications for filter media used for SSF vary internationally and is often applied for infiltration basins (Huisman & Wood 1974; Hansson 2000). However, the situation for MAR plants is very different from SSF, where the natural grain size variations in the recharge fields makes it difficult to apply SSF sand recommendations to infiltration basins. Very limited information is published for practitioners when it comes to guidelines and recommendations on sand quality for MAR plants. The purpose of this study was to identify a close to optimal sand quality for infiltration basins based on the natural geological conditions, and apply this reasoning in a case study at Vomb WTP, in south Sweden. The goal is to give practitioners tools and ideas on how to establish an optimal filter sand quality based on their requirements.

Properties of granular media

The function of filter sand is to have good hydraulic properties and high surface area for retention of organic matter and other contaminants. The hydraulic properties of the filter media is mainly governed by the sand grain size distribution, which is commonly described by grain sizes d_{10}, d_{60} and the uniformity constant (UC) (Brandt *et al.* 2016; Crittenden *et al.* 2017). d_{10} and d_{60} are size measures of the granular media determined by sieve analysis, where the sizes of which 10 and 60 percent of the media are finer, respectively. The concept of d_{10}, the effective size (ES), was proposed in 1890 because it gave a good measurement of hydraulic conductivity independent of the overall grain size distribution (Fair *et al.* 1971). Other grading characteristics, e.g. d_{20}, d_{60} and UC, have also been shown to affect hydraulic conductivity (Cabalar & Akbulut 2016). The effective size should be as low as possible to achieve adequate treatment and to avoid deep clogging (Huisman & Wood 1974). At the same time, too low effective size could result in inadequate permeability (Ellis & Wood 1985; Cheremisinoff 2019). UC is a measurement of the uniformity of the granular media and is given by the ratio of d_{60} and d_{10} ($UC=d_{60}/d_{10}$). The measurement is useful for filter media that undergoes backwashing to avoid stratification, such as rapid sand filters (Crittenden *et al.* 2017). For slow sand filters, UC is useful to ensure that the granular media is reasonably uniform with good porosity (Huisman & Wood 1974).

The function of infiltration basins is in many ways similar to SSF, why this could be suitable for MAR application. However, the recommendations for this filter sand varies internationally (Table 1).

Table 1 | Recommended granular media properties for sand used in slow sand filter

Source	d_{10} [mm]	UC [d_{60}/d_{10}]	Other recommendations
Huisman & Wood (1974)	0.15–0.35	<3	1.5<UC<2[a]. Washed sand
Schulz *et al.* (1992)	0.15–0.35	1.5–3	U_C<2[a]
Ellis & Wood (1985), Ellis (1987)	0.15–0.40	1.7–3	U_C<2.7[a]
Ten States Standard (2018)	0.15–0.30	≤2.5	Washed sand
Hazen (1913)	0.18–0.44	1.5–4.7	d_{10}=0.20–0.35[a]
Visscher (1988)	0.15–0.30	<5	U_C<3[a]
Hendricks (1991)	0.20–0.30	1.5–2	Possible: $d_{10}\geq0.3$ & UC>2. Washed sand
Seelaus *et al.* (1986)	0.20–0.30	1.5	Allowed for higher UC-values
Jabur & Mårtensson (1997)	0.20–0.40	<2.5	Washed sand
SWWA (2011)[b]	0.32–0.38	≤2.5	<1%>2 mm & <0.2 mm. Washed sand

[a]Preferred properties.
[b]Swedish recommended industry standard.

Clogging in sand filters and infiltration basins

Clogging can occur in different places and for different reasons (Song *et al.* 2020), where retention of inorganic particles tends to occur deeper than organic particles (Hendricks 1991; Wang *et al.* 2018). The accumulation of organic matter and biofilm development is important for the function of sand filters, especially considering the comparably large pore size of clean SSF sand (about 60 μm) (WHO 2016). Many studies have investigated granular filter media capability to retain fine particles through full-scale and column tests (Siriwardene *et al.* 2007; Martin 2013; Du *et al.* 2018). Schuh (1990) showed in a field study that clay particles from turbid infiltrated water were found up to 38 cm of depth in the infiltration basin. Fine particles (<50 μm) have also been found to be retained in and penetrated through columns with fine sand (d_{50} = 0.5 mm) (Du *et al.* 2018). The same study showed the infiltration rates had a considerable impact on particle mobility.

Many articles describe the connection between mobilization and retention of particles and the grain size of the media and the particles. Crittenden *et al.* (2017) describes that a uniform media can retain particles that are down to 15% of the media's diameter, which means that a filter media with a grain size of 0.5 mm can retain particles bigger than 75 μm. Particles entering sand filters are also reported to be retained if the particle size is at least 20% of the filter media's d_{10}-value (Huisman & Olsthoorn 1983). In column trails with filter sand, the clogging phenomena is often described as either surface, mixed or inner clogging. In a column with fine to coarse sand, surface clogging occurred for 75 μm particles, mixed clogging for 40 μm particles, and particles below 13 μm were able to pass through the entire column (Du *et al.* 2014).

For infiltration basins, it is important that fine particles from the infiltration water (raw water) are retained in the surface and not transported into the aquifer. For this reason, microscreens are often used for pre-treatment for sand filters to reduce and mitigated clogging (Ljunggren 2006). Other pre-treatment methods for removal of algae, organic and inorganic matter include chemical flocculation, sedimentation and membrane filtration (Li *et al.* 2019; Hägg *et al.* 2020)The filter media used in infiltration can also be a source for fine particles that could cause clogging issues in the native material (Hansson 2000). The transport of clay particles in aquifers can occur over significant distance and result in reduced permeability (McDowell-Boyer *et al.* 1986; Akhtar *et al.* 2021). In Sweden, it has been reported that WTPs have chosen to use unwashed granular media in their basins, resulting in deep clogging due to fine particles in the sand (SWWA 2007). The importance of washing filter sand used in infiltration basins to remove fine particles cannot be understated, and has been set as recommendations in several rapports, handbooks, and articles (Huisman & Wood 1974; Visscher 1990; Hendricks 1991; Sundlöf & Kronqvist 1992; Jabur & Mårtensson 1997; Johansson 2003; Jönsson & Wikström 2003; Sternö 2005; JTI 2016; Ten States Standard 2018). The reported recommended standards for silt concentrations have been in the range of 0.5–1.0 g/L (Brandt *et al.* 2016), which is equivalent to about 0.03–0.06% by weight.

Mineral composition and contaminants

Granular media for filters need to be resistant to shear forces to avoid weathering (Ratnayaka *et al.* 2009), therefore the media should mainly consist of quartz and feldspar and free from mica mineral (Hansson 2000; SWWA 2011). Micas are considered weathering minerals due to their sheetlike structure (Fetter 2014) and easily break from mechanical stress (Göransson 2014), which is also an issue in road construction (Hellman 2013). For MAR plants, the issue of chemical and mechanical weathering mica minerals is the creation of clay particles (Höbeda 1987; Göransson 2014; Price & Velbel 2014; Johansson 2015), which can result in clogging.

Calcium and magnesium concentrations should be below 2% (calculated as carbonate) to avoid cavities in the filter media (Huisman & Wood 1974). The requirements for acid solubility for SSF sand varies. The Swedish standard is maximum 1% weight reduction after samples have been soaking in a 10% hydrochloric acid solution for 2–3 hours (SWWA 2011). Internationally, it is common to measure a 5% weight reduction over a 24-hour period in concentrated hydrochloric acid (40%) (Huisman & Wood 1974; Ten States Standard 2018). The recommendations for filter media is that it should be washed and free from any contaminants (Huisman & Wood 1974; Hansson 2000; SWWA 2011; Ten States Standard 2018). However, it is very difficult to find natural deposits without any traces of unwanted contaminants, e.g., chloride, arsenic, and iron. Useful information on soil contamination has been published by the Swedish Environmental Protection Agency (EPA), where the agency has set guidance limits on metal concentrations in potentially contaminated soil intended for sensitive land use (as mg/kg total solids), e.g., parks and residential areas (Swedish EPA 2016). It is recommended that a site-specific limit is developed for each site and the values for Vomb WTP with the general limits are noted in Table 2.

Other recommendations for SSF sand from the Swedish Water Works Association (SWWA) are the following:

- Turbidity (after wash) $\leq$4 FNU
- Acid solubility $\leq$1%
- Iron concentration $\leq$0.1%
- Humic substances $\leq$1,000 color (mg Pt/L)
- Chemical oxygen demand (COD_{Mn}) $\leq$0.3 mg/g.

MATERIALS AND METHODS

Study site

This study was conducted at Vomb WTP, an artificial groundwater recharge plant in southern Sweden (Figure 1). The WTP has 54 infiltration basins excavated in an recharge field of glacifluvial deposits (Pott *et al.* 2009) and uses Lake Vomb as a raw water source. About three-quarters of the basins are in operation and each basin is

Table 2 | Metal contaminant limits for Vomb WTP and the general limits for sensitive land use (Swedish EPA 2016)

Contaminant	Limits for Vomb WTP [mg/kg]	General limits [mg/kg]
Arsenic (As)	5	10
Barium (Ba)	100	200
Lead (Pb)	20	50
Cadmium (Cd)	0.2	0.8
Cobalt (Co)	8	15
Copper (Cu)	15	80
Chromium (Cr)	20	80
Mercury (Hg)	0.1	0.25
Nickel (Ni)	15	40
Vanadium (V)	40	100
Zinc (Zn)	70	250

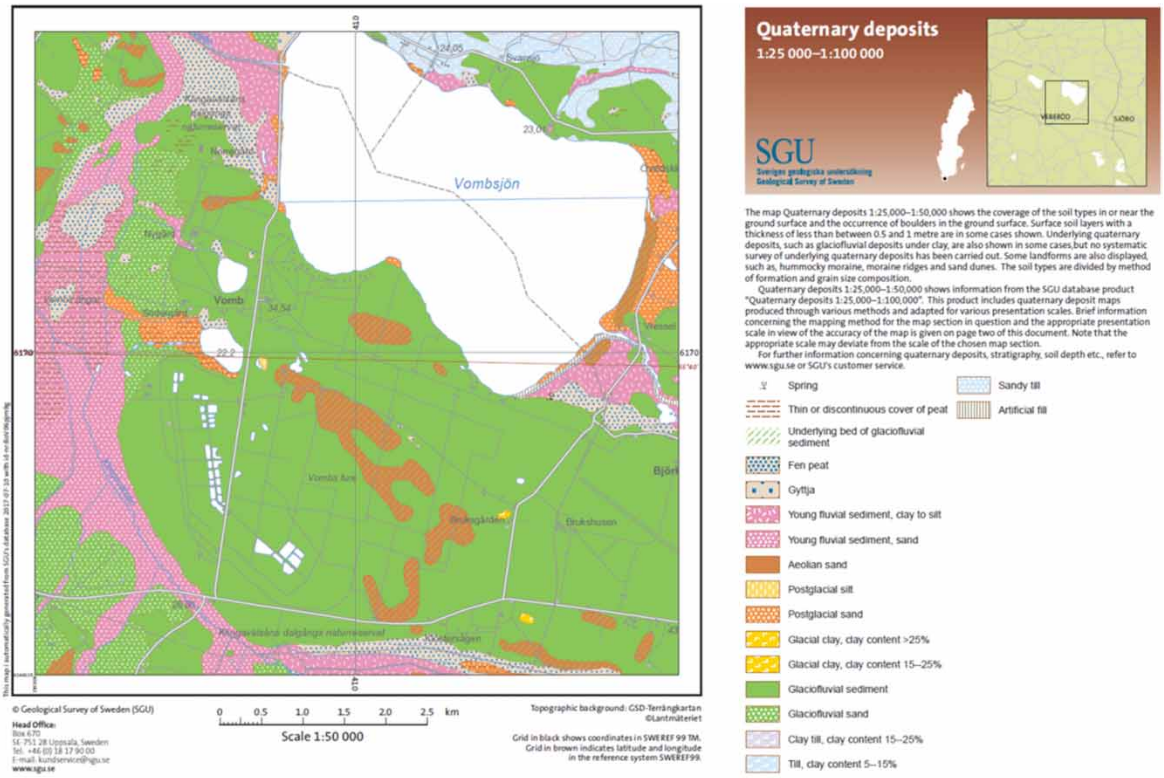

Figure 1 | Overview of the study area (Source: Geological Survey of Sweden, © Sveriges geologiska undersökning, www.sgu.se).

on average 10,000 m^2. Prior to infiltration, the raw water is pretreated by micro sieving (40 μm). The groundwater is recovered after about two months from 114 wells about 200 m from the basins The water is aerated and softened before adding monochloramine prior to distribution (Sydvatten AB 2015).

The infiltration basins follow certain seasonal and operational cycles, where newly renovated and refilled basins are taken into operation in late autumn-winter to ensure that the bottom of the basins are covered by water and a bioactive layer is created before the algal blooms in late summer (Li 2020). Once the development of the biofilm creates too much resistance (bioclogging), usually around 1–2 years, the basins are emptied and skimmed (about 5 cm of the top layer). The basins are then restarted and continue to be in operation until the resistance is too high. After a few years, once a basin has been skimmed about 2–5 times, the basin is renovated by excavating the top 50 cm of the basin. The sand is washed, mixed with stored native sand, and put back into the basin. After that, the newly renovated basin is ready to be returned to operation.

METHODOLOGY

In this study, 114 samples from the infiltration basins were collected for sieve analysis (Table A1, supplementary material). The samples were taken at varies depths in the infiltration basins and were analysed at Vomb WTP. The sieve sizes were 2.00, 1.60, 1.25, 1.00, 0.80, 0.63, 0.50, 0.40, 0.315, 0.25, 0.20, 0.125 and 0.071 mm. The results were compared with literature data and operational experiences to create a filter media with viable properties for infiltration basins. With this information, sand with viable and optimal properties were suggested.

RESULTS AND DISCUSSION

Properties of the recharge field

The sand grain size distribution of the Vomb recharge field varied in different areas but also within each basin. This makes it difficult to determine an optimal sand grain distribution. However, operational experience of the hydraulic capacity of the infiltration basins can be used to get an indication of an approximate range. Figure 2 shows the size distribution of the basins that have too low and too high infiltration rates. Basins that obtain water coverage within weeks and can only receive low amounts of raw water (about 10 l/s) once full are considered to have a permeability which is too low. Basins that slowly, e.g. more than 6 months, or never obtain water coverage are considered to have a permeability that is too high.

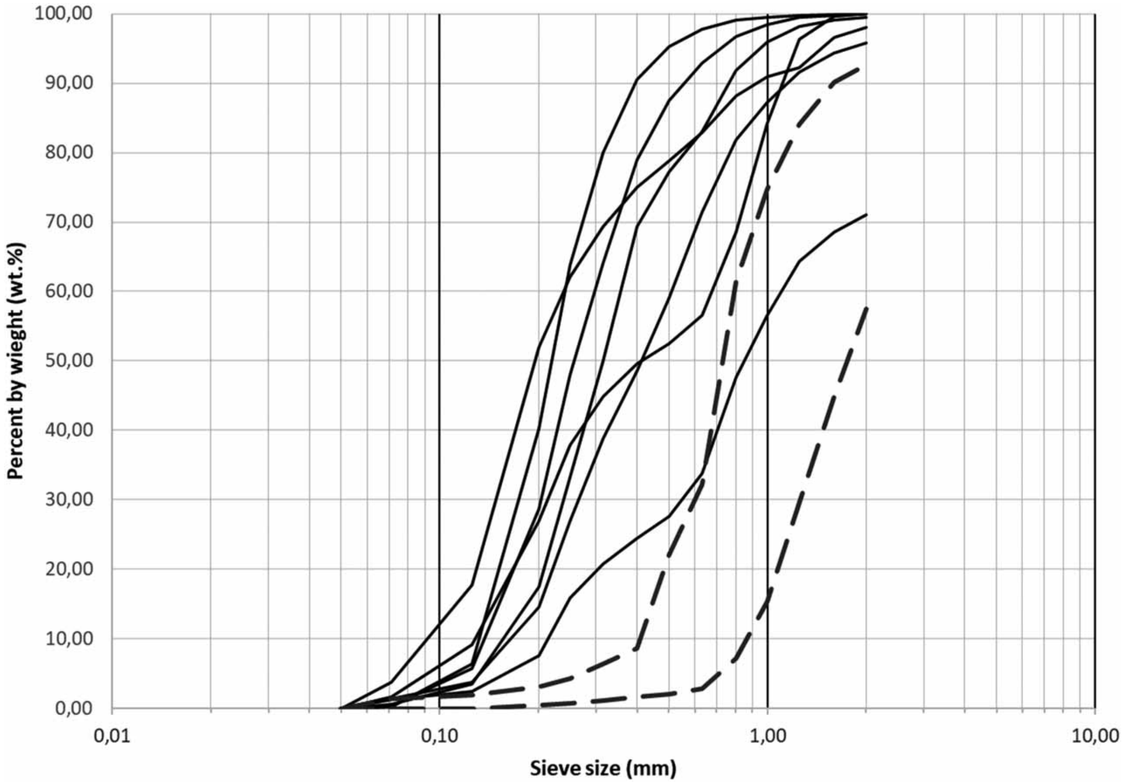

Figure 2 | Grain size distribution results from sieve analysis. The graph shows the basins that are reported to have too low (—) and too high (— —) permeability.

The distribution showed that the low and high flow rate basins had some overlap in the large fraction range and no overlap in the smaller fraction range. This result concurs with Fair *et al.* (1971) that stated that the effective size was the determinant factor for conductivity. Another way to illustrate the effect of grain sizes on infiltration rates can be done by calculating the hydraulic conductivity (Hazen 1911) and specific grain surface area (Crittenden *et al.* 2017) (Figure A1, supplementary material). The basins with a permeability that is too low also showed high total levels of fine grain sand (<0.2 mm) (Table 3). The UC and d_{60} do not seem to be a good indicator for basin permeability within this dataset, which is why the finer grain sizes might be more suitable for infiltration rate predictions. However, statistical verification would require a larger sample size. The 5 basins that showed too low hydraulic conductivity had an effective size, d_{10}, up to 0.21 mm. Out of the 54 basins, only two have showed too high infiltration rates, d_{10}=0.41 and 0.87 mm. Note that the basin with d_{10}=0.41 comes from one sieve sample 1.5 m below the surface and might not be the sand layer causing high infiltration rates.

Table 3 | d_{10}-value (min/max/median), UC value, percent coarse and fine grains (>2.0 mm and <0.2 mm) and percent silt and clay particles (<0.0071 mm) found in Vomb recharge field

Parameter	Vomb recharge field	Low infiltration rates	High infiltration rates
d_{10}	0.095–0.87 mm (median=0.39)	0.095–0.21 mm (median=0.16 mm)	0.41 & 0.87 mm
d_{60}	0.46–0.95 mm (median=0.77)	0.24–1.1 mm (median=0.35)	0.79 & 2.10 mm
UC	1.1–5.2 (median=2.3)	1.8–5.2 (median=2.5)	1.93 & 2.4
>2.0 mm median	4.6%	0.5%	7.4 & 42.5
<0.2 mm median	2.6%	26.9%	3.1 & 0.4
<0.0071	0.4%	1.2%	0 & 1.3%

90 samples from 27 infiltration basins were collected for sieve analysis, where 5 basins showed low infiltration rates and 2 showed too high infiltration rates.

The grain size distribution of the glacifluvial deposits at Vomb WTP consists of finer material than many other recharge fields used in Sweden. Samples from filter media taken from basins at Swedish MAR plants showed an effective size range of 0.27–0.43 mm (Hansson 2000), which is why SSF sand with the Swedish standard is likely more viable for these WTPs.

Optimal sand for Vomb WTP

The sand properties for the basins need to be based on the literature data and experiences from other MAR plants, and applied to the natural conditions in the recharge field. The optimal method would be to adapt the grain sizes of the filter media for each basin. However, this is not possible for practical reasons. Instead, the goal is to find a filter media with acceptable grain size distributions for the whole recharge field. According to the WHO, the filter media for MAR should have equal or slightly coarser grain size distribution than SSF sand, which would assumably imply $d_{10} \geq 0.15$ mm. Furthermore, in sand filters, each sand layer should have less than 4 times the effective size (d_{10}) of the sand layer above it. If applied to Vomb WTP, the effective size of the filter media used in the basins should be $d_{10} > 0.21$ mm, based on the coarsest native glacifluvial deposits ($d_{10} = 0.87$ mm). Based on operational experience, the basins with too low infiltration rates have an effective size of $d_{10} \leq 0.21$ mm. This gives a good indication that new filter media for Vomb WTP should have an effective size of $d_{10} \geq 0,22$ mm. The upper limit for the effective size is more difficult to establish because of the wide range of grain sizes in the recharge field. A starting point that could be applied is that the filter media should be finer than the native sand media to avoid clogging in the aquifer (Huisman & Wood 1974). To set the upper d_{10} limit as high as possible to avoid limiting the access from suppliers and at the same time make sure that the sand would be adequate for a majority of the basins. A d_{10} value higher than the median effective size of the field was chosen for this reason. In this case, $d_{10} \leq 0.38$ mm, which is equivalent to the coarsest Swedish recommendation for SSF sand (Table 1). An optimal range has also been set to d_{10} 0.22–0.30 mm, making it more suitable for all infiltration basins, increasing the protection of the aquifer from clogging and reducing high infiltration rate in the early stages of newly started basins.

The uniformity coefficient (UC) does not seem to have a significant impact on permeability according to the literature and collected data. However, the recommendation from the WHO is that the UC value should be within a similar range of the surrounding sand layers. The collected UC values are very broad, around 1.1–5.2, and a majority of the UC recommendations are mostly around 1.5–3 with a couple of exceptions extending it to about 5. Thus, a suitable choice is likely around 1.5–3, which is also relatively close to the median UC-value of the glacifluvial deposits (UC=2.3). An acceptable alternative is possibly to allow for UC values up to 5. The coarser material only inflates the cost of the filter media and does not have any meaningful impact on water treatment, therefore these grain sizes should be limited. The Swedish recommendation on filter media used for SSF also include an upper cut-off for grain sizes above 2.0 mm, which is omitted in the international recommendations. It is possible that the effective grain sizes and UC values are sufficient, and that this recommendation is unnecessary. However, the natural glacifluvial deposits have a broad grain size distribution and the grain size cut-off is needed to determine sieve sizes when maintaining and washing the sand supply. The median value for the coarser grain sizes (>2.0 mm) in the recharge field 4.6%, which would result in some losses if this cut-off was chosen. The purpose of adding filter media in MAR, as in the case for Vomb WTP, is also to ensure adequate distance to the water table and thereby achieving sufficient unsaturated zones. For these reasons, an argument can be made that the upper grain size limit could be extended to 3.0 mm with a potential minor loss in treatment efficiency. However, these losses are estimated to be insignificant due to the long retention times before groundwater extraction, so the upper cut-off limit of $\leq$1% for grain sizes over 3 mm will be chosen. If higher treatment efficiencies are desirable, a 2.0 mm upper cut-off limit could be set to $\leq$1%. Based on site-specific conditions and considerations, the upper cut-off limit could vary.

The d_{10} value will be the controlling factor for the finer fractions of the media, and therefore no value will be set for fractions <0.2 mm. The fine silt and clay fractions (<0.0071 mm) are very important to limit to avoid deep clogging and reduced permeability of the aquifer. As reported by the SWWA, MAR plants have experienced lowered permeability in their recharge fields due to particles originating from unwashed filter media. The recommendation for SSF sand containing silt particles was 0.03 and 0.06 wt. %. For practical reasons, this limit will be set to 0.1% with an optimal value of 0.05%. An infiltration basin at Vomb WTP needs around 15,000 tons of sand, which means that this limit still allows up to 15 tons of silt and clay particles.

The mineral composition and the limits for contaminants for filter media in rapid and slow sand filters in Sweden differs from international recommendations, and there are no reasons why these recommendations should be less strict for filter media used in MAR plants. It is clear that filter media should mainly consist of quartz and free from mica minerals and contaminants. The measurements for acid solubility differ in Sweden compared to international standards, and it is not clear how they relate to one another. However, both methods aim to quantify magnesium and calcium concentrations. For the purpose of this study, the Swedish standard will be used. The recommendations from the SWWA (SWWA 2011) and the Swedish EPA for the remaining contaminants for the filter media will be used (Table 4). To ensure that the filter media is washed with fresh water and that chloride concentrations does not increase in the recharge field, a calculated value has been presented. Higher levels of chloride, between 50 and 100 mg Cl^-/L, can be found in several coastal areas in Sweden (HaV 2018), and has been used as the limit in this study. Based on a field capacity (the water volume that stays attached to the grains) of 25% for the filter media (Fetter 2014) and washing water with an chloride concentration of 50 mg/L, the resulting maximum chloride concentration on the media is 6.9 mg Cl^-/kg.

CONCLUSIONS

This study investigated suitable filter media properties for infiltration basins used for MAR, and applied this reasoning in a case study at Vomb WTF, a MAR plant in south Sweden. The filter media recommendations focused on protecting the aquifer from contamination and deep clogging and ensuring that clogging particles are retained in the upper layers of the filter media. Also, choosing filter media with lower permeability than the natural deposits improves the unsaturated conditions for infiltration basins in the early operational stages before physical and biological clogging occurs. This was achieved by choosing a filter media that was finer than the natural glacifluvial material and coarser than the media found in infiltration basins with low permeabilities. The effective grain size (d_{10}) range was coarser than the international recommendations for SSF sand, which concurs with the recommendations from WHO for filter media used in MAR. Based on the results, the finer grain material (<0.2 mm) and the effective size (d_{10}) seem to be the dominant factors for predicting permeabilities of filter media. The coarser grain sizes do not contribute to higher treatment efficiencies, therefore limiting these fractions are preferred for filter media for SSFs. However, the conditions for MAR-plants are different and it is possible to extend the upper grain size limit depending on site-specific considerations.

Future studies: crushed rock as an alternative filter media

The supply of crushed rock is vast, which makes it a sustainable alternative to natural sand material. The material has been used as filter media for wastewater treatment (JTI 2016) and media for coarse filtration of corrosive liquids (Cheremisinoff 2001). There have also been bench-scale experiments that investigated the viability of crushed rock for drinking water supply (Sternö 2005; da Silva *et al.* 2021). However, there is very little published

Table 4 | Filter media quality and property recommendations for Vomb WW

General limitations		
• Washed natural sand (with freshwater). • Mainly consist of quartz and feldspar. • Free from mica minerals. • Sourced from contaminant free areas.		
Grain size distribution	**Limit**	**Optimal**
d_{10}	0.22–0.38 mm	0.22–0.30 mm
UC [d_{60}/d_{10}]	1.5–5	1.5–3
<0.071 mm	≤0.1%	≤0.05%
Coarse grains (≤1%)	>3.0 mm	>2.0 mm
Chemical parameters	**Limit**	
Turbidity (after wash)	≤4 FNU	
Acid solubility	≤1%	
Humic substances	≤1,000 mg Pt/L	
Chemical oxygen demand (COD_{Mn})	≤0.3 mg/g	
Contaminants	**Limit (mg/ kg dry weight)**	
Arsenic (As)	≤5	
Barium (Ba)	≤100	
Lead (Pb)	≤20	
Iron (Fe)	≤1,000	
Cadmium (Cd)	≤0.2	
Chloride (Cl^-)	≤7	
Cobalt (Co)	≤8	
Copper (Cu)	≤15	
Chromium (Cr)	≤20	
Mercury (Hg)	≤0.1	
Nickel (Ni)	≤15	
Vanadium (V)	≤40	
Zinc (Zn)	≤70	

on it being used full scale. Because the grain surface structure differs from that of natural sand, there are several uncertainties related to its properties; the main being, the material's resistance to mechanical weathering and the changes in hydraulic properties once compacted. Other considerations include the development of the biofilm on the grains, the capacity to retain organic matter and the effect of mixing native natural sand on its hydraulic properties. However, there are no reasons why this material could not be utilized as filter media for water production, provided that the material fulfils the requirements.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Akhtar, M. S., Nakashima, Y. & Nishigaki, M. 2021 Clogging mechanisms and preventive measures in artificial recharge systems. *Journal of Groundwater Science and Engineering* **9**(3), 181–201.

Brandt, M. J., Johnson, K. M., Elphinston, A. J. & Ratnayaka, D. D. 2016 *Twort's Water Supply*. Butterworth-Heinemann. Chapter 9 - Water filtration. Pages 367-406. (Oxford, United Kingdom).

Cabalar, A. F. & Akbulut, N. 2016 Evaluation of actual and estimated hydraulic conductivity of sands with different gradation and shape. *SpringerPlus* **5**(1), 820.

Cheremisinoff, N. P. 2001 *Handbook of Water and Wastewater Treatment Technologies*. Butterworth-Heinemann, Oxford, UK.

Cheremisinoff, P. N. 2019 *Handbook of Water and Wastewater Treatment Technology*. Routledge, London, UK.

Crittenden, J. C., Rhodes Trussell, R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. 2017 *MHW's Water Treatment Principles and Design*, 3rd edn. John Wiley & Sons Inc, Hoboken, NJ, USA.

da Silva, B. M. R., Bastos, R. K. X. & Bastos, P. K. X. 2021 Comparison of crushed rock sand and natural river sand as filter media for rapid filtration. *Water Supply* **21**(1), 401–411.

Du, X., Fang, Y., Wang, Z., Hou, J. & Ye, X. 2014 The prediction methods for potential suspended solids clogging types during managed aquifer recharge. *Water* **6**(4), 961–975.

Du, X., Ye, X. & Zhang, X. 2018 Clogging of saturated porous media by silt-sized suspended solids under varying physical conditions during managed aquifer recharge. *Hydrological Processes* **32**(14), 2254–2262.

Ellis, K. V. 1987 Slow sand filtration. *WEDC Journal of Developing World Water* **2**, 196–198.

Ellis, K. V. & Wood, W. E. 1985 Slow sand filtration. *Critical Reviews in Environmental Science and Technology* **15**(4), 315–354.

Fair, G. M., Geyer, J. C. & Okun, D. A. 1971 *Elements of Water Supply and Wastewater Disposal*.

Fetter, C. W. 2014 *Applied hydrogeology*. Essex Pearson Education cop. 2014. Available from: http://ludwig.lub.lu.se/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat01310a&AN=lovisa.003480002&site=eds-live&scope=site.

Göransson, M. 2014 'Kritiska egenskaper hos bergmaterial och alternativa material', *Minbas*.

Hägg, K., Persson, K. M., Persson, T. & Zhao, Q. 2018 *Artificial Recharge Plants for Drinking Water Supply – Groundwork for A Manual for Operation*. The Swedish Water & Wastewater Association, Stockholm SWWA, (2018–11).

Hägg, K., Persson, T., Söderman, O. & Persson, K. M. 2020 Ultrafiltration membranes in managed aquifer recharge systems. *Water Supply* **20**(4), 1534–1545.

Hägg, K., Chan, S., Persson, T. & Persson, K. M. 2021 Source water quality requirements for artificial groundwater recharge. *Water Practice and Technology* **16**(4), 1510–1514.

Hansson, G. 2000 *Artificial Groundwater Recharge – A Method Used in Swedish Drinking Water Supply*. The Swedish Water & Wastewater Association, Stockholm SWWA, (2005–05).

HaV 2018 *Chloride in Groundwater, Swedish Agency for Marine and Water Management*. Available from: https://www.havochvatten.se/data-kartor-och-rapporter/data-och-statistik/officiell-statistik/officiell-statistik – havs–och-vattenmiljo/klorid-i-grundvatten.html (accessed 3 June 2021).

Hazen, A. 1911 Discussion: dams on sand foundations. *Transactions, American Society of Civil Engineers* **73**(11), 25.

Hazen, A. 1913 *The Filtration of Public Water Supplies*, 3rd edn. J. Wiley & sons.

Hellman, F. 2013 *Glimmer i bergmaterial för vägbyggnation: en kunskapsöversikt*. VTI, Linköping, Sweden.

Hendricks, D. W. 1991 *Manual of Design for Slow Sand Filtration*. Amer Water Works Assn, Denver, Colorado, United States.

Höbeda, P. 1987 *Glimmer i vägmaterial : Inverkan på egenskaper och analysmetoder för glimmerhalt, VTI meddelande*. Swedish National Road and Transport Research Institute: Statens Väg- och Trafikinstitut., VTI meddelande 527. Available from: http://vti.diva-portal.org/smash/get/diva2:671540/FULLTEXT01.pdf.

Huisman, L. & Olsthoorn, T. N. 1983 *Artificial Groundwater Recharge*. Pitman Advanced Publishing Program, London.

Huisman, L. & Wood, W. E. 1974 *Slow Sand Filtration*. World Health organization (WHO). Available from: https://www.who.int/water_sanitation_health/publications/ssf9241540370.pdf.

Jabur, H. S. & Mårtensson, J. 1997 *Optimering av långsamfilter*. The Swedish Water & Wastewater Association, SWWA, Stockholm.

Jeong, H. Y., Jun, S.-C., Cheon, J.-Y. & Park, M. 2018 A review on clogging mechanisms and managements in aquifer storage and recovery (ASR) applications. *Geosciences Journal* **22**(4), 667–679.

Johansson, P. O. 2003 Filtermaterial för vattenbehandling. *Minbas rapport område* **2**, 17.

Johansson, Å. 2015 *Bergarter: bildning och bestämning*. Available from: https://www.nrm.se/download/18.3536e06e14f3b657a68c6210/1445522220997/Bergartsbroschyr.pdf.

Jönsson, R. & Wikström, A.-S. 2003 *Vattenbehandling genom återinfiltration i filterbäddar med skikt av krossad kalksten*. The Swedish Water & Wastewater Association, SWWA, Stockholm.

JTI 2016 *Informationsblad–Rekommendationer för bergkross som filtermaterial i markbäddar*. JTI–Institutet för jordbruks-och miljöteknik, Stockholm.

Li, J. 2020 *Managing Eutrophic Waters in Artificial Recharge Plants : Cyanotoxin Risk in Swedish Freshwaters*. Department of Water Resources Engineering, Lund Institute of Technology, Lund University. Available from: http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edsswe&AN=edsswe.oai.lup.lub.lu.se.25759a85.0a41.4ce2.9098.446b98d030af&site=eds-live&scope=site.

Li, J., Hägg, K. & Persson, K. M. 2019 The impact of lake water quality on the performance of mature artificial recharge ponds. *Water (Switzerland)* **11**(10), 1–17.

Ljunggren, M. 2006 Micro screening in wastewater treatment-an overview. *Vatten* **62**(2), 171.

Martin, R. 2013 *Clogging Issues Associated with Managed Aquifer Recharge Methods*. IAH Commission on Managing Aquifer Recharge Reading.

McDowell-Boyer, L. M., Hunt, J. R. & Sitar, N. 1986 Particle transport through porous media. *Water Resources Research* **22**(13), 1901–1921.

Pott, B.-M., Cronberg, N., Annadotter, H., Johnsson, S. & Cronberg, G. 2009 *Effect of Nitrate Addition on Algae Bloom*. The Swedish Water & Wastewater Association, SWWA, Stockholm, (2009–14).

Price, J. R. & Velbel, M. A. 2014 Rates of biotite weathering, and clay mineral transformation and neoformation, determined from watershed geochemical mass-balance methods for the Coweeta Hydrologic Laboratory, Southern Blue Ridge Mountains, North Carolina, USA. *Aquatic Geochemistry* **20**(2), 203–224.

Ratnayaka, D. D., Brandt, M. J., Johnson, K. M., 2009 CHAPTER 8 – water filtration granular media filtration. In: (Ratnayaka, D. D., Brandt, M. J. & Johnson, K. M. B. T.-W. S., eds). Sixth E. (eds). Butterworth-Heinemann, Boston, Water Supply, pp. 315–350.

Sarma, J., 2020 Chapter 6 – Filtration and chemical treatment of waterborne pathogens. In: (Vara Prasad, M. N. & Grobelak, A. B. T.-W. P., eds). Butterworth-Heinemann, Waterborne Pathogens, Oxford, United Kingdom, pp. 105–122.

Schuh, W. M. 1990 Seasonal variation of clogging of an artificial recharge basin in a northern climate. *Journal of Hydrology* **121**(1), 193–215.

Schulz, C. R., Okun, D. A., Donaldson, D. & Austin, J. 1992 *Surface Water Treatment for Communities in Developing Countries*.

Seelaus, T. J., Hendricks, D. W. & Janonis, B. A. 1986 Design and operation of a slow sand filter. *Journal (American Water Works Association)* **78**(12), 35–41. Available from: http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=edsjsr&AN=edsjsr.41290467&site=eds-live&scope=site.

Siriwardene, N. R., Deletic, A. & Fletcher, T. D. 2007 Clogging of stormwater gravel infiltration systems and filters: insights from a laboratory study. *Water Research* **41**(7), 1433–1440.

Song, W., Liu, X., Zheng, T. & Yang, J. 2020 A review of recharge and clogging in sandstone aquifer. *Geothermics* **87**, 101857.

Sprenger, C., Hartog, N., Hernández, M., Vilanova, E., Grützmacher, G., Scheibler, F. & Hannappel, S. 2017 Inventory of managed aquifer recharge sites in Europe: historical development, current situation and perspectives. *Hydrogeology Journal* **25**(6), 1909–1922.

Stefan, C. & Ansems, N. 2018 Web-based global inventory of managed aquifer recharge applications. *Sustainable Water Resources Management* **4**(2), 153–162.

Sternö, E. 2005 'Bergkross som filtermaterial vid vattenbehandling'. MinBaS rapport.

Sundlöf, B. & Kronqvist, L. 1992 *Artificial Groundwater Recharge – State of the Art – Evaluation of Twenty Swedish Plants*. The Swedish Water & Wastewater Association, Stockholm, SWWA, (1992–13).

Swedish EPA 2016 *Riktvärden för förorenad mark*. Available from: https://www.naturvardsverket.se/globalassets/media/publikationer-pdf/5900/978-91-620-5976-7.pdf.

SWWA 2016 The Swedish Water & Wastewater Association, SWWA. Available from: http://www.svensktvatten.se/Vattentjanster/Dricksvatten/Ravatten/ (accessed 12 July 2017).

SWWA 2007 *Dricksvattenteknik 2 – Grundvatten*. The Swedish Water & Wastewater Association, Stockholm, SWWA.

SWWA 2011 *Dricksvattenteknik 3 – Ytvatten*. The Swedish Water & Wastewater Association, Stockholm, SWWA.

Sydvatten AB 2015 *Sydvatten – Collaborating for Public Welfare*. Available from: https://sydvatten.se/wp-content/uploads/2016/02/Sydvatten-in-English.pdf.

Ten States Standard 2018 *Recommended Standards For Water Works*. Available from: https://www.health.state.mn.us/communities/environment/water/tenstates/standards.html.

Visscher, J. T. 1988 'Water Treatment by Slow Sand Filtration: Considerations for Design, Operation and Maintenance', Slow Sand Filtration: Recent Developments in Water Treatment Technology. John Wiley and Sons, New York New York. 1988. pp. 1–10. 5 fig. 7 ref.

Visscher, J. T. 1990 Slow sand filtration: design, operation, and maintenance. *Journal-American Water Works Association* **82**(6), 67–71.

Wang, Y., Huo, M., Li, Q., Fan, W., Yang, J. & Cui, X. 2018 Comparison of clogging induced by organic and inorganic suspended particles in a porous medium: implications for choosing physical clogging indicators. *Journal of Soils and Sediments* **18**(9), 2980–2994.

WHO 2016 *Assessing Microbial Safety of Drinking Water: Improving Approaches and Methods*. WHO, Geneva, Switzerland.

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