CLOGGING OF RECHARGE WELLS IN POROUS MEDIA

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1. BACKGROUND

Research makes clear (i.e. ANNEX 13 to the IEA Research Program on thermal storage) that clogging of recharge wells (ATES and ASR) by suspended solids is very common and, despite advances in infiltration well technology, remains a key determinant of infiltration well performance. The clogging potential of suspended solids in water is not just a function of concentration, but also of particle size and composition. Since 2000 in the Netherlands the MFI is used to estimate the clogging potential of water that has to be infiltrated using recharge wells. The MFI gives no detailed information about each individual particle, instead it gives a direct value of the clogging potential of the water. In 2000 a quantitative relation between clogging rate and MFI was developed. The relations has a theoretical-empirical base and it was derived by using published data of experiments performed by Olsthoorn (1982) and Pyne (1994). In the years between 2000 and 2005 the relation was used to design over 250 ATES-systems. During these years the relation has proven itself as reliable and as an useful tool to predict clogging rates of recharge wells satisfactory, especially considering the uncertainties in measured parameters like MFI and permeability. Further an easy, cheap (fast) and reliable apparatus was developed to measure the MFI of the water that has to be infiltrated.

2. OLSTHOORN'S INFILTRATION THEORY

According to Olsthoorn (1982) clogging caused by both straining and physical-chemical filtration can be described by the following equation:

$$\Delta h_v = \left(\frac{1}{\rho_w g}\right)\left(\frac{c\mu_d}{k_c}\right)v^2 t \qquad (1)$$

where Δh_v = increment of pressure caused by clogging [m_w]; ρ_w = density of the infiltrated water [kg/m^3]; g = gravity acceleration [m/s^2]; c = concentration of suspended matter in the infiltration water [kg/m^3]; μ_d = dynamic viscosity [Ns/m^2]; k_c = intrinsic hydraulic conductivity of the filter cake on the borehole wall [m^2]; v = infiltration rate on the borehole wall [m/s]; t = infiltration time [s].

3. MEMBRANE FILTER INDEX (or Modified Fouling Index)

One of the best parameters to predict the clogging potential of infiltration water, is the MFI. The MFI is a variation of the Silting Index (SI) and Silt Density Index (SDI). These indices were developed to characterize the fouling potential of reverse osmosis feed water on RO membranes. The SI and the SDI have week theoretical foundations and do not vary linearly with the concentration of colloidal and suspended solids in water. The MFI, on the other hand, has a strong theoretical foundation and exhibits a linear correlation with the concentration of colloidal and suspended solids in water (Hutchinson 1997).

The MFI is equal to the slope of the line that describes the inverse of the flow rate versus the amount of water that passes a membrane filter with 0.45 μm pores under a constant pressure drop for standard conditions and can be described with Equation 2 (Olsthoorn 1982):

$$MFI = \frac{\mu_d}{2pA_f^2}\frac{c}{k_c} \qquad (2)$$

where MFI = membrane filter index [s/l^2]; p = pressure loss [N/m^2]; A_f = area of the filter [m^2].

If an MFI of 1 s/l^2 is directly translated (with equation 1 and 2) into a clogging rate for an infiltration well under standard conditions ($A_f = 1.38\ 10^{-3}$ m^2 for a standard membrane filter; p = 2 10^5 Pa; $\mu_d = 1.3\ 10^{-3}$ Ns/m^2 and v = 1 m/h on the borehole wall, a 'common' value for infiltration wells), the calculated clogging rate of more than 2,000 m/yr is not compatible with measured clogging rates of around 0.1 m/yr in the field (Olsthoorn 1982). This demonstrates that a clogging rate derived with a filter with a pore size of 0.45 μm can not be translated directly into a clogging rate for an infiltration well. Olsthoorn (1982) found that the calculated clogging rates were more compatible to clogging rates for water flood wells in oil fields. Olsthoorn attributed the difference to the fact that the pore size of the receiving formation in an oil field is closer to that of the MFI-membrane than the pore size in groundwater environments.

The relation between the pore size of the membrane filter and the MFI has been measured by KIWA (1984) and by IF Technology (1998), see figure 1. This figure confirms that there is a relation between the MFI and the pore size. Both fits are based on a quadratic relation between the area of a pore and the MFI. This quadratic relation shows a very strong correlation with the measurements (R^2 = 0.99 and 1.00, respectively). The slope of each fit is about two (MFI = x (pore size)$^{-}$, _≈2).

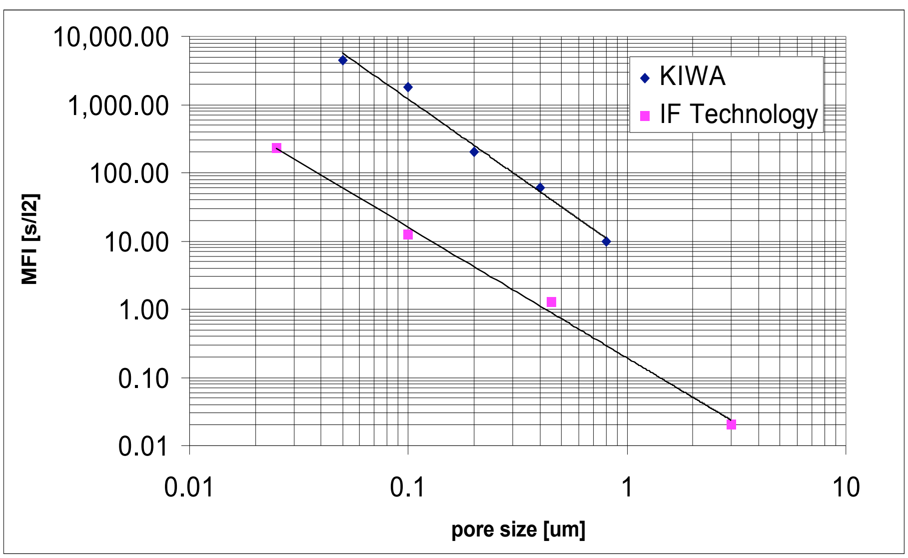


Figure 1: Measurements of the MFI with filters with different pore sizes, R^2 =0.99 (KIWA, 1984) and R^2 =1.00 (IF Technology, 2000).

The MFI measured with a standard membrane filter can now be translated into an MFI that is valid for other pore sizes (see Equation 3).

$$MFI_{cor} = MFI_{mea}\frac{A_{fp}}{A_p} \qquad (3)$$

where MFI_{cor} = corrected MFI; MFI_{mea} = measured MFI; A_{fp} = area of a pore of the applied filter; A_p = area of a pore for which the MFI must be corrected.

To calculate the ratio between the pore size of the aquifer and the pore size of the filter, it is necessary to estimate the pore size of the aquifer. According to Holtz & Kovacs (1981) the effective pore size is about a sixth of the median grain size of the sand (D_{50}).
In an aquifer with a D_{50} of 300 μm the effective pore size is then about 50 μm. A measured MFI of 1 s/l^2 (pore size 0.45 μm) will give a corrected MFI of 8.1 10^{-5} s/l^2 (Equation 3). The calculated clogging rate (for an MFI of 1 s/l^2 and v = 1 m/h) is now about 0.20 m/yr, which is a realistic value.

Equation 1, 2 and 4 can be combined and rewritten as:

$$\frac{\Delta h}{t} = \frac{2MFI_{mea}pA_f^2}{\rho_w g}\frac{t}{t_0}\frac{\mu}{\mu_0}\frac{A_{fp}}{A_p}v^2 \qquad (4)$$

The ratios t/t_0 and μ/μ_0 are added to make corrections for the amount of equivalent full load hours per year (t_0=8760 h) and temperature influences (μ_0 = viscosity at 10°C), and the ratio A_{fp}/A_p is added to translate a measured MFI to an MFI for the aquifer.

For practical use the D_{50} is translated into hydraulic conductivity k with a relation derived by Shepherd (1989):

$$k = 150\,(D_{50}\,10^3)^{1.65} \qquad (5)$$

with D_{50} in [m] and k in [m/d]. Equation 5 can be rewritten as:

$$D_{50} = 10^{-3}\left(\frac{k}{150}\right)^{0.6}$$

If the standard circumstances for the MFI measurement are substituted in (5), the equation can be simplified and rewritten to (t is replaced by u_{eq} and $\Delta h_v/t$ is replaced by v_v i.e. the clogging rate):

$$v_v = 2\cdot 10^{-6} MFI_{mea}u_{eq}\frac{v_b^2}{\left(\frac{k}{150}\right)^{1.2}} \qquad (6)$$

where u_{eq} = amount of equivalent full load hours per year [h] (m^3 infiltrated per year divided by max. flow rate in [m^3/h]); v_v = clogging rate [m_w /yr]; v_b = infiltration rate on the borehole wall [m/h].

The water that is infiltrated will not be distributed equally over the height of the aquifer but it is divided over the well screen in relation to the hydraulic conductivity of the aquifer. This means that layers with a high hydraulic conductivity are receiving more water than layers with a low hydraulic conductivity. The infiltration rate in layers with a high hydraulic conductivity is therefore higher than in layers with a low hydraulic conductivity, and because the clogging rate is quadratically related to the infiltration rate (and linear to the MFI), these layers with a high hydraulic conductivity will clog faster than layers with a low hydraulic conductivity.

This process will continue until all layers are receiving the same amount of water. So the clogging rate has to be corrected for the heterogeneity in the aquifer. This process will be illustrated by an example. The data used for this example are taken from an ATES-project in the Netherlands.

Total amount of infiltrated water/year:	500,000 m_
MFI:	1 s/l^2
Infiltration rate:	100 m_/h
Equivalent full load hours per year:	5,000 h
Diameter of the borehole:	1,125 mm
Transmissivity:	600 m2/d
Well screen length:	30 m

Table 1: Influence of hetrogeneities on the clogging rate

Section	k [m/d]	H [m]	Amount of water per section[1] [m^3]	V_v [m_w /yr]
a.	12	3	300,000	0.07
b.	50	4	166,667	0.21
c.	14	3	35,00	0.08
d.	22	6	110,000	0.11
e.	20	5	83,333	0.10
f.	10	9	75,000	0.06
			Weighted average	0.13
average	20	30	500,000	0.1

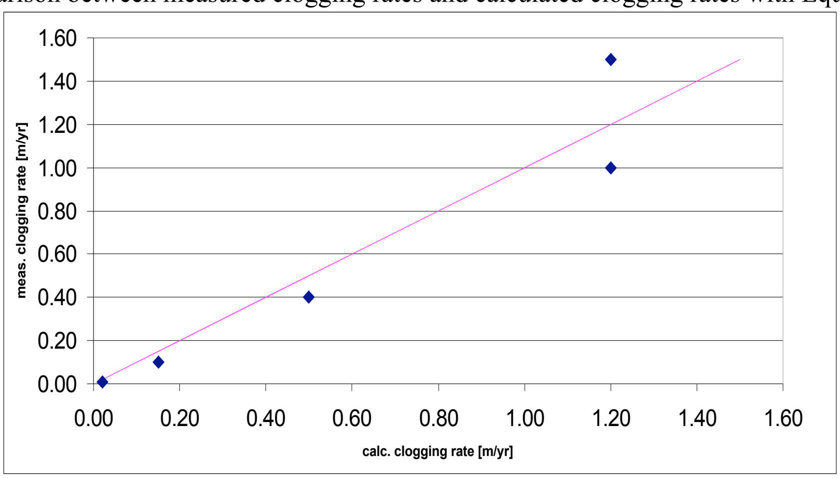
[1] ($Q_i = Q_{tot}\ k_i H_i / k_{ava} H_{tot}$)

This example makes clear that the clogging rate in a hetrogeneous aquifer is larger than in a homogeneous aquifer. In this case the clogging rate increases with 30 %.

4. THEORY VERSUS PRACTICE

Equation 6 has been used to predict the clogging rate of several existing infiltration wells. To verify the equation, a comparison has been made between calculated and measured clogging rates. The measurements have been gathered by IF Technology (2000) and by Pyne (1995). All data have been measured without changing the flow direction in the wells. So the measured clogging rates are not influenced by backflushing or flow reversals.

Figure 2: Comparison between measured clogging rates and calculated clogging rates with Equation 6; drawn line =



1:1, R^2 = 0.96 (data IF Technology, 2000).

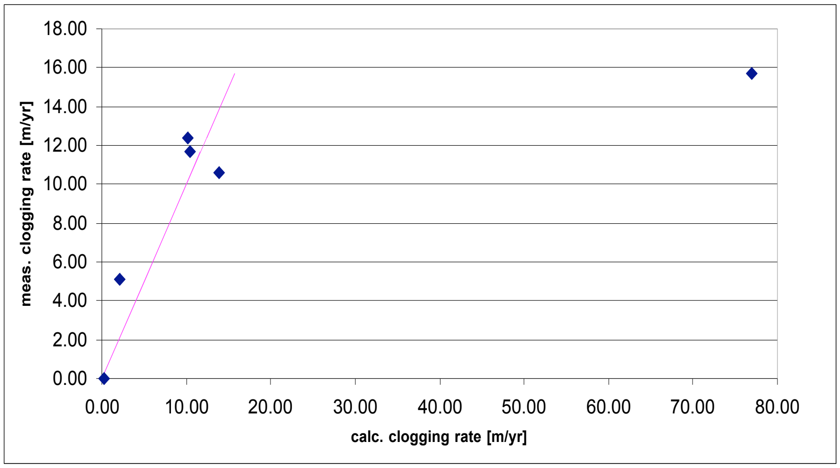


Figure 3: Comparison between measured clogging rates and calculated clogging rates with Equation 6; drawn line = 1:1, $R^2 = 0.68$ (data Pyne, 1995).

The figures show that the calculated clogging rates agree remarkably well with the measured clogging rates (R^2 = 0.96 and 0.68, respectively). The low correlation in Figure 3 is caused by one measured clogging rate that is much lower than the calculated one and has a very high MFI (79.2 s/l^2).

5. ECONOMICAL BENEFITS

The relation described in this article makes it is possible to predict the clogging behavior of infiltration wells under different circumstances. With this relation a well designer can make a trade off between well design (investment cost) and well maintenance (operational cost).

6. MFI-apparatus

To use the relation it is necessary to know the clogging potential of the water that has to be infiltrated. This clogging potential is described by the MFI. A good and fast method to measure this MFI is therefore needed. Over the last 2 years a fast, cheap and reliable method for MFI measurements was developed. The results of the measurements with this method have been compared with the results of more complex and more expensive measurement methods. These results were very promising. There are two reasons why the new method is cheaper and faster than the old method. In the first place the amount of water that passes the membrane is measured by weight instead of volume and in the second place a standard SDI apparatus is used instead of a custom built MFI apparatus.

7. DISCUSSION

The relation between calculated and measured clogging rates is surprisingly good, especially considering the fact that:

1 measured parameters such as the clogging rate, the hydraulic conductivity and the MFI may not be very accurate;

2 two empirical relations are used to relate the pore size to the hydraulic conductivity. These empirical relations are not very accurate and depend on local circumstances such as the clay content in the aquifer, the method of sorting of the sand, etc;

3 the material that is clogging the pores of 0.45 μm size may be different from the material clogging pores of 50 μm in size (although the very good relation between MFI and pore size suggests that the process is identical).

Given the uncertainties and the low number of data, it could be coincidence that the relation fits so good. But given the fact that two independent data sets have been used, that were measured under different circumstances (groundwater infiltration in the Netherlands and surface water infiltration in the USA), makes coincidence not very likely.

More than 1,000 recharge wells for Aquifer Thermal Energy Storage (ATES; see e.g. Doughty et al., 1982) have been realized in the Netherlands. The clogging rates presented in Figure 2 are based on measured clogging rates for six ATES projects in the Netherlands. Unfortunately, accurate data for clogging rates are not available for most of the ATES projects. For the projects where accurate data is available (about 30 projects), only 20% show signs of clogging. The other 80% of the projects do not clog at all. The cause of this difference is not clear. The theory presented in this paper makes it possible to predict the clogging rate when clogging occurs, but it can not predict whether clogging will occur or not. So, the remaining question is: what are the circumstances for clogging to occur.

Since the year 2000, recharge wells for ATES are designed according to the theory discussed in this paper. Wells designed since then are not very different from the wells designed before 2000, except that wells are now larger in diameter for low permeable aquifers and smaller for high permeable aquifers. In the past, the only clogging problems that have been encountered occurred in low permeable aquifers. We expect that use of the new theory will prevent these problems as well.

When infiltrating groundwater, as is the case with ATES, it is important to know the MFI of the groundwater that has to be infiltrated. MFI values of natural groundwater measured in the Netherlands vary from 0.5 to 5 s/l^2. It is not known what causes the range in MFI values encountered, but it is likely that this range is related to the chemical composition of the groundwater and the sediment properties of the aquifer. Design of production wells is different to the design of infiltration wells. As production of groundwater from an aquifer also induces filtration of the groundwater that passes the aquifer around the well, the MFI might be an important parameter to predict clogging of production wells as well. These aspects deserve further attention.

Another question that still remains is the influence of backflushing of the well and of flow reversal. Recharge wells that clog are often backflushed frequently. The clogging rate described in this paper is able to quantify the rate of clogging between two periods of backflushing. The amount of clogging materials that is removed during backflushing (or flow reversal), and the amount of clogging that remains, is still hard to assess.

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