Assessment of manganese removal from over 100 groundwater treatment plants
Jantinus H. Bruins, Dirk Vries, Branislav Petrusevski, Yness M. Slokar and Maria D. Kennedy

ABSTRACT

The aim of this study was to make an inventory of water quality and operational parameters which could affect manganese removal through aeration and rapid sand filtration and to establish correlations between these parameters and manganese removal efficiency. The focus of the overview was on manganese removal efficiency in the first aeration-filtration stage of conventional groundwater treatment plants (GWTPs). Data from selected full-scale GWTPs have been collected, and univariate and multivariate statistical analyses were conducted. Multivariate statistics indicated that multiple parameters including NH$_4^+$ removal efficiency, iron loading per filter run (FR) and pH of filtrate play a significant role in manganese removal, while other parameters (oxygen concentration in filtrate, filtration rate and empty bed contact time (EBCT)) were found to be of secondary importance. Univariate statistical assessment of the data suggests that very effective manganese removal can be achieved when all of the following conditions are met: NH$_4^+$ removal efficiency $>85$%, pH of filtrate $>7.1$, iron loading per FR $<2.7$ kg Fe/m$^2$, oxygen concentration in filtrate $>1$ mg O$_2$/L, filtration rate $<10.5$ m/h and EBCT $>11.5$ min.

Key words | aeration-filtration, conventional groundwater treatment plants, groundwater quality, inventory, manganese removal efficiency, operational parameters

INTRODUCTION

Groundwater is the predominant global source of water for drinking water production (United Nations Environment Programme (UNEP) 2000).

In addition to impurities such as iron, ammonia and methane, groundwater frequently contains elevated levels of dissolved manganese, which need to be lowered for both health and aesthetic reasons. Manganese is a naturally occurring metal that is a constituent of more than 30 manganese oxide/hydroxide minerals, which occur in a wide variety of geological settings (Post 1999). The occurrence and thermodynamic stability of different manganese species in groundwaters is dependent on different conditions like reduction-oxidation (redox) potential ($E_h$) or electron activity ($p_e$) and pH.

Due to the natural occurrence of manganese in sediments and soils, dissolved manganese (Mn$^{2+}$) can also be present in associated aqueous systems like groundwater, because of the low redox potential of anaerobic groundwater and the relative low pH. From Figure 1 it can be seen that in a reducing environment and at relatively low pH (conditions found in anaerobic groundwater), the most abundant and stable manganese species is Mn$^{2+}$.

The removal of manganese from groundwater is commonly achieved through aeration-rapid sand filtration. A typical example of a groundwater treatment plant (single filtration step with pre- and post-aeration) is shown in Figure 2. An aeration followed by a single filtration step is most commonly applied, but in some cases, e.g. groundwater with elevated levels of ammonia, iron and/or manganese, two filtration steps are required. In those cases, a second...
The aeration step is frequently included to correct the pH and increase the oxygen concentration in the (treated) water.

Physical-chemical and/or biological mechanisms were reported to be responsible for manganese removal (Graveland & Heertjes 1975; Vandenabeele et al. 1998). Despite extensive research carried out on manganese removal through aeration-rapid sand filtration, the mechanisms controlling the process are still not fully understood.

Conventional groundwater treatment is simple and very cost effective, but performance of an individual plant depends amongst others factors on the individual approach to various technological issues related to a given groundwater. Advantages of manganese removal on conventional aeration-rapid sand filtration could be seriously hampered by the following:

(a) Long ripening periods taking several weeks to more than a year to achieve effective manganese removal with virgin filter media (Huysman 2009).

(b) Manganese breakthrough after some years of operation, introducing the need for filter media replacement, associated with a long start-up period and additional costs for filter media disposal and replacement (Buamah et al. 2008). As an example in Figure 3 the manganese breakthrough is expressed after more than 12 years of proper operating and treating the same raw water quality.

(c) Insufficient manganese removal for some types of groundwater (e.g. groundwater containing high concentration of natural organic matter, that could cause complexation of Mn$^{2+}$).

Several researchers reported insufficient manganese removal due to water quality matrix and inappropriate process design and operational parameters. Amongst others, high concentrations of NH$_4^+$ (>2 mg/L) can have a negative influence on manganese removal (Gouzinis et al. 1998). In addition a low pH also negatively affects manganese adsorption (Buamah 2009) and manganese oxidation (Stumm & Morgan 1996). Without a catalyst, homogeneous manganese...
oxidation and subsequent removal by filtration is only achieved when pH is at least 8.6 (Graveland 1971). Finally, dissolved iron present in groundwater can affect manganese removal, because it can compete with Mn$^{2+}$ for adsorption sites (Po et al. 2004a, b). Therefore the main focus of this study was to improve the understanding of manganese removal in conventional groundwater treatment plants (GWTPs) based on aeration and (down flow) rapid sand filtration. Specifically the effect of groundwater quality, process design and operational parameters on manganese removal was assessed.

**MATERIALS AND METHODS**

Data presented in this paper are based on information gathered from over 100 GWTPs from the Netherlands (65), Belgium (34), Germany (6), Jordan (1) and Serbia (1). The data were mainly collected through questionnaire, or by visiting selected plants and interviewing key employees who have extensive operational experience. The focus of the inventory was on the plants that have a (down flow) single aeration-filtration treatment (with simultaneous removal of manganese, iron and ammonia) or on the first filtration step for plants that have multiple aeration-filtration steps. Therefore for GWTPs with multiple aeration-filtration steps, questions were aimed at the first filtration step only. Collected (water quality and process design) parameters were based on their importance for manganese removal, as suggested in the literature (Graveland 1971; Gouzinis et al. 1998; Buamah 2009) but were also dependent on data availability (e.g. redox potential is known to be of importance, but is seldom measured on a regular basis). Most of these plants included in the inventory have silica as filter media, in some cases in combination with anthracite as a double media filter. Plants run for at least 1 year, and so contain ‘aged’ (bio)layers (e.g. Fe and Mn oxides). The following data were collected or calculated.

Parameters with respect to the quality of anaerobic groundwater:

- concentration of ammonia, iron, manganese, hydrogen carbonate, calcium, phosphate, silica, methane, pH, dissolved or total organic carbon (DOC/TOC).

Parameters with respect to the water quality after the first filtration step:

- concentration of ammonia, iron, manganese, hydrogen carbonate, calcium, oxygen, pH;
- removal efficiency of manganese, ammonia and iron.

Parameters with respect to applied process design:

- iron and manganese loading (kg Fe and Mn/m$^2$/filter run);
- backwash (BW) criteria (head loss, time, volume);
- volume of filtrate produced between two consecutive backwashing cycles (m$^3$);
- filtration rate (m$^3$/m$^2$/h);
- empty bed contact time (EBCT) (minutes) ($t_{EB}$ in principal component analysis (PCA) analysis, Figure 4);
- filter area (m$^2$);
- filter bed depth (m) ($h_{FB}$ in PCA analysis, Figure 4);
- flow (m$^3$/h);
- filter configuration (gravity/pressure) and type of filtration (‘dry’ or ‘wet’, with water level below or above filter media, respectively).

Selected raw and treated water quality and plant design parameters were correlated to the performance of full-scale plants in terms of Mn$^{2+}$ removal. The focus was on the first filtration stage, in which Mn$^{2+}$ removal was often combined with the removal of ammonia, iron and sometimes methane. PCA and single correlation analysis of Mn$^{2+}$ removal efficiency as a function of selected water quality parameters and process design parameters were conducted, to determine the parameters of importance. For PCA, data were standardised by subtracting the data values by the process variable means, and dividing the resulting data values by the standard deviation of the corresponding variable. To check whether the data set is useful for PCA, the Kaiser-Meyer-Olkin (KMO) (Cerny & Kaiser 1977) and the Bartlett’s tests (Bartlett 1937) were performed. The KMO statistic assesses whether there is an underlying (latent) structure in the data. Low values of the KMO statistic, i.e. smaller than an index of 0.6, indicate that the correlations between pairs of variables cannot be explained by other variables, and that PCA or factor analysis may not be appropriate. The Bartlett’s test (Bartlett 1937) is used to
evaluate the homoscedasticity (equal variances across samples) of the data. A limit of 0.30 for the absolute value of the coefficient loading of a principal component is chosen to distinguish between moderate to high and low correlation.

RESULTS AND DISCUSSION

Multivariate statistics and univariate correlations

Table 1 gives an overview of selected design and water quality parameters and correlation coefficients against manganese removal efficiency by a univariate and multivariate statistical method (PCA). The KMO measure of sampling adequacy shows that the data set yields a degree of common variance of 0.65, which can be considered as sufficient for PCA analysis. Furthermore, Bartlett’s test for dimensionality reveals that all the variables are necessary to explain non-random variations, in other words, they are correlated. The first two components of the PCA are shown on the left of Figure 4, while the number of components that account for the explained variance is shown on the right.

In general, vectors pointing in the same direction mean that the associated factors are (positively) correlated, while if pointing away from each other, an inversely proportional relationship exists. Additionally, loading vectors at right angles to each other indicate either a negligible or no interdependence. The variance of the variables in the data set is, by definition of PCA, covered by a summation of the principal components together with their loading coefficients. The part of the variance that is covered by principal components, is called the explained variance. The first component explains the largest part of the variance in the data.

Based on both PCA and single correlation analysis (Table 1 and Figure 4), NH₄⁺ removal efficiency, iron loading per filter run (FR), and pH strongly correlate with manganese removal efficiency. In contrast to NH₄⁺ removal efficiency and pH, the iron loading (and often also the iron concentration in raw water) was found to be inversely proportional to manganese and NH₄⁺ removal. Concentrations of dissolved calcium and hydrogen carbonate in raw water appear to have low correlation with manganese removal in single correlation studies, whereas PCA shows
that these parameters could have some influence, as shown in the loadings of the first component. Since the solubility of compounds is directly dependent on pH, it was expected that calcium and hydrogen carbonate will be (cor)related with pH, thus influencing the loadings of the first component. Furthermore, the PCA analysis showed a certain degree of correlation between all water quality and process parameters and manganese removal included in the inventory. This confirmed that manganese removal in the aeration-filtration treatment process is very complex and influenced by a large array of parameters. From the right-hand side of Figure 4 it follows that the second principal component explains another 15% of the variability in the data, while the third component covers an additional part of the variance, resulting in approximately 70% coverage when three components are used. Hence, the highest PCA loading coefficients of the second component (Table 1) indicate that, the influent manganese concentration, oxygen and phosphate might also play a role in manganese removal. A possible explanation for the negative (cor)relation between phosphate and manganese removal might be similar to that for the effect of phosphate on iron removal; heterogeneous Fe$^{2+}$ oxidation (rate) decreases with increasing phosphate concentration. The controlling mechanisms are not fully understood yet, but the oxidation rate may be influenced by colloid formation and their mobility, the charge of filter media, and pH of (raw) water (O’Melia & Crapps 1964; Wolthoorn et al. 2004). An additional explanation could be that phosphate competes with Mn$^{2+}$ for the same adsorption sites as observed for Fe$^{3+}$ adsorption on iron hydro-oxide surfaces. The PCA further reveals that the variability in data cannot easily be explained by only 2 factors, i.e. at least 4 components are needed to account for approximately 75% of the explained variance (Figure 4). Although the single correlation analysis does not confirm the effect of oxygen, organic matter (TOC/DOC) and phosphate, it is known from practice that these parameters may also have an effect on manganese removal efficiency. PCA shows that there is indeed an effect, although only significant in the second principal component for dissolved oxygen (Table 1), or even in the third for organic matter. It is important to keep in mind that PCA informs how many parameters are necessary to explain the data and which variables are most importantly related (to manganese removal), while the following assessment is based primarily on evaluating the correlation between two variables and analysing the ‘outliers’ by inspection of the other variables.

<table>
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<tr>
<th>Parameter /concentration</th>
<th>Parameter</th>
<th>Unit</th>
<th>Correlation with Mn removal 1st component</th>
<th>2nd component</th>
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<tr>
<td></td>
<td>Fe$^{2+}$</td>
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<td></td>
<td>HCO$_3^-$</td>
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In the following sections, the parameters with a predominant effect on manganese removal efficiency are discussed in more detail.

**NH₄⁺ removal efficiency**

Figure 5 shows the correlation between manganese and NH₄⁺ removal efficiencies for the treatment plants included in the inventory. Analysis of the data set (Figure 5) suggests that for a majority of GWTPs, complete manganese removal is not achieved when NH₄⁺ removal efficiency is less than 85%. A few GWTPs still did not achieve complete manganese removal even when NH₄⁺ removal was very effective. Closer inspection reveals that each of the outliers had at least one parameter with values that were unfavourable for effective manganese removal, i.e. pH in filtrate <7.1 or the filtration rate >10.5 m/h and/or EBCT <11.5 min (both parameters discussed further in the paper).

The strong correlation between NH₄⁺ and manganese removal, is also observed in practice. Very similar trends for NH₄⁺ and manganese removal are specifically observed during the ripening period of new filter media (Figure 6(a)). In addition, results from the full-scale rapid sand filter suggest that complete manganese removal occurs only at a certain depth of a filter, when NH₄⁺ removal is almost complete or NH₄⁺ is not present anymore (Figure 6(b)).

Several papers confirm that NH₄⁺ removal and manganese removal are related. Scherer & Wichmann (2000) and Flemming et al. (2004), suggested that a negative effect of NH₄⁺ on manganese removal is a consequence of poor Mn²⁺ oxidation due to the low redox potential of the groundwater in the presence of NH₄⁺. As a result, high concentrations of NH₄⁺ (>2 mg/L) in (raw) groundwater hinder efficient and complete manganese removal in conventional one-stage aeration-filtration systems (Gouzinis et al. 1998). The observed correlation between NH₄⁺ and manganese removal efficiencies may be also related to biological processes, i.e. the oxidation of NH₄⁺ by nitrifying bacteria. Several mechanisms may contribute:

- Oxidation of Mn²⁺ by nitrifying bacteria (e.g. Nitrosomonas sp.), although from an energetic point of view this is unlikely (Vandenabeele et al. 1995).
- Adsorption of positively charged dissolved Mn²⁺ on negatively charged organic compounds, e.g. extracellular
polymeric substances (EPS) excreted by nitrifying bacteria (Vandenabeele et al. 1999).

- Local reduction of the zero point of charge (pH\textsubscript{ZP}) or zeta potential of the filter media to a more negative value, due to a pH decrease on micro scale, induced by the nitrification reaction; more negatively charged filter media surface will considerably increase the attraction of positively charged Mn\textsuperscript{2+}.

- Increase of the redox potential due to the nitrification reactions resulting in enhanced Mn\textsuperscript{2+} oxidation.

However, additional research is required to further clarify mechanisms responsible for the effect of NH\textsubscript{4}\textsuperscript{+} (removal efficiency) on manganese removal.

### Effect of iron loading

Iron loading, defined as the amount of iron removed in a filter during one filter run, appears to negatively affect manganese removal (Table 1 and Figure 7).

From Figure 7 it seems that complete manganese removal cannot be achieved with an iron loading above approximately 2.7 kg Fe/m\textsuperscript{2} per filter run. Although iron oxides can adsorb Mn\textsuperscript{2+}, and can consequently also act as a catalyst for manganese removal (Buamah 2009), iron (hydr)oxide can also cover active sites on filter media available for Mn\textsuperscript{2+} adsorption (Buamah et al. 2009). In addition, Fe\textsuperscript{2+} ions can compete with Mn\textsuperscript{2+} ions for adsorption sites (Po et al. 2004a, b). As a consequence, better manganese removal is typically achieved when either iron is removed prior to manganese removal, or when iron loading per FR is lower. The latter can be achieved by reducing the amount of water filtered between two backwash cycles by, for example, reducing the FR length. Data from the conducted inventory also suggest that complete manganese removal in a single aeration-filtration treatment can be achieved also for groundwater with very high iron content (up to approximately 15 mg/L) when iron loading per FR is reduced to <2.7 kg/m\textsuperscript{2} (Figure 7). Iron loading can also be influenced by the prevailing iron removal mechanism. The achieved iron loading is typically much lower when iron is removed through oxidation-floc formation in comparison to adsorptive and/or biological iron removal. Iron removal through oxidation and floc formation is characterised by accumulation of iron (hydr) oxide flocs in the upper part of the filter bed or in the anthracite part of dual media filters, and associated faster head loss increase, and the need for frequent backwashing, specifically when fine sand size fraction is used. Consequently, iron removal predominantly through floc formation results in relatively lower iron loading and has potentially a larger adsorption/oxidation area for Mn\textsuperscript{2+} adsorption. At the same time, more frequent backwashing cycles could negatively influence the development of the catalytic layer on the filter media.

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**Figure 7** Manganese removal efficiency as a function of the iron loading per FR (kg Fe/m\textsuperscript{2}) and the iron concentration (mg/L) in raw groundwater.
A closer look at the inventory data revealed that each of the outliers that showed poor manganese removal at low iron loadings had at least one other parameter that is critical for manganese removal including:

- pH < 7.1 (discussed under ‘Effect of (filtrate) pH’)
- NH₄⁺ removal efficiency < 85% or
- filtration rate > 10.5 m/h and/or EBCT < 11.5 min (discussed under ‘Effect of filtration rate’ and ‘Effect of contact time and filter bed depth’).

**Effect of (filtrate) pH**

Both PCA and single correlation analysis of the inventory data show that pH has a large effect on manganese removal efficiency (Figure 8).

The data presented in Figure 8 show that 7.1 is the limiting pH value, below which complete manganese removal was not achieved on any of the plants included in the inventory, with the exception of one specific groundwater treatment plant where complete manganese removal is achieved at a somewhat lower filtrate pH of 6.8. Closer data inspection of this specific plant revealed that the aerated water had a pH > 7.1, and that pH was strongly reduced in the filter bed, probably due to the oxidation of Fe²⁺ (15 mg/L), which resulted in the release of protons. NH₄⁺ which can also lower pH is hardly present in raw water (0.1–0.25 mg/L). It is very likely that the pH upper part of the filter bed was around 7.1, which was sufficient for effective manganese removal, although in this zone iron might compete with manganese for adsorption sites. More research is, however, needed to explain efficient manganese removal achieved at pH < 7.1 in this plant. Also in the literature complete (biological) manganese removal at low pH of 6.5 is reported (Burger et al. 2008). However, it should be mentioned that the raw water quality used in the study of Burger et al. (2008) differs significantly from the raw groundwater quality of plants included in this study (extremely low alkalinity, absence of iron and ammonia, high redox potential). Data shown in Figure 8 strongly indicate that increasing pH, in general, improves manganese removal. Higher pH will strongly enhance adsorption of Mn²⁺ (Buamah 2009), and will support heterogeneous and autocatalytic manganese adsorption and oxidation. At low pH values, it is known from practice and reported in the literature that physicochemical manganese removal seems to be impossible in traditional aeration-filtration treatment plants. Ramstedt et al. (2002) showed that γMnOOH (manganite) starts to dissolve significantly at pH below 6, causing leaching of Mn²⁺ from the adsorbent into the filtrate. Hastings & Emerson (1986) and Klewicki & Morgan (1999) described these dissolution processes as disproportion reactions (Equations (1) and (2))

\[
\text{Mn}_3\text{O}_4 + 2\text{H}^+ \leftrightarrow 2\text{MnOOH} + \text{Mn}^{2+} \quad (1)
\]

\[
2\text{MnOOH} + 2\text{H}^+ \leftrightarrow \text{MnO}_2 + \text{Mn}^{2+} + 2\text{H}_2\text{O} \quad (2)
\]

From Figure 8 it is also clear that manganese removal is very effective at pH values between 7.1 and 8.0. Graveland (1971) and Graveland & Heerijes (1975) reported that there was no substantial oxidation of Mn²⁺ with oxygen in water (homogeneous oxidation) at pH < 8.6 when no catalyst is present. Hence, it is reasonable to expect that the mechanism responsible for manganese removal in treatment plants included in this study is either (i) biological or (ii) a heterogeneous and autocatalytic manganese adsorption and oxidation that takes place on the surface (e.g. MnO₂) of the filter media (Katsoyiannis & Zouboulis 2004). Figure 8 depicts that manganese removal was less effective on a number of plants included in the inventory where the filtrate
pH was higher than 7.1. Close inspection of the data for these plants revealed that at least one of the following parameters limited manganese removal efficiency:

- NH₄⁺ removal efficiency <85% or
- iron loading per FR >2.7 kg Fe/m² or
- filtration rate >10.5 m/h and/or EBCT <11.5 min (discussed under ‘Effect of filtration rate’ and ‘Effect of contact time and filter bed depth’).

**Other parameters**

According to the single correlation analysis (Table 1), the rest of the variables included in this study did not show a significant correlation with the efficiency of manganese removal. However, PCA demonstrates that some parameters (e.g. filtration rate, EBCT and to a lesser extent oxygen and phosphate) may influence manganese removal (Table 1 and Figure 4). When plotting a number of parameters such as filtration rate, EBCT, and oxygen concentration, against manganese removal efficiency, some trends may indeed be deduced. The effect of these three parameters is discussed in the following paragraphs.

**Effect of filtration rate (m/h)**

In Figure 9, the manganese removal efficiency obtained on the plants included in the study is plotted as a function of applied filtration rate.

![Figure 9](https://iwaponline.com/aqua/article-pdf/63/4/268/400876/268.pdf)

**Figure 9** | Manganese removal efficiency as a function of the filtration rate (m/h).

Based on the results from the inventory, complete manganese removal was achieved only in treatment plants that operate at filtration rates of up to 10.5 m/h. Ineffective manganese removal was, however, observed at several treatment plants that operate at filtration rates significantly lower than <10.5 m/h. These outliers are most likely due to:

- poor NH₄⁺ removal efficiency (<85%) or
- high iron loading (>2.7 kg Fe/m²/filter run) or
- low (filtrate) pH (<7.1) or
- short EBCT (<11.5 min) (discussed further under ‘Effect of contact time and filter bed depth’).

Lower filtration rates provide longer contact time in the filter bed, and consequently more time for manganese adsorption and oxidation.

**Effect of contact time and filter bed depth**

Figure 10 shows manganese removal efficiency as a function of the EBCT for GWTPs included in the study. It can be seen that only plants that apply an EBCT of 11.5 min or more achieved complete manganese removal.

Results from the inventory also show that an EBCT longer than 11.5 min does not guarantee complete manganese removal. Detailed analysis of plants that apply an EBCT >11.5 min and have ineffective manganese removal showed that again one or more earlier identified water quality parameters and/or process conditions were probably responsible for poor manganese removal.
A parameter directly related to EBCT is bed height of the filter media. No significant statistical correlation between bed height and manganese removal efficiency was found (Table 1).

Assuming that a groundwater treatment plant is operating at a maximum acceptable filtration rate of 10.5 m/h, a filter bed of approximately 2.0 m is required to provide a minimal required EBCT of 11.5 min that will allow an effective manganese removal. Selected data from the inventory, however, demonstrate that a relatively shallow filter bed height of 0.9 m might be sufficient to obtain complete Mn$^{2+}$ removal, if the other parameters of relevance for manganese removal are optimal (e.g. high pH, low iron loading, low filtration rate, long EBCT).

**Effect of oxygen concentration**

Only five GWTPs included in the inventory had dissolved oxygen <1 mg/L. None of these plants achieved effective manganese removal (Figure 11).

It is known from the literature that manganese removal is negatively affected by the absence of, or low concentration of, dissolved oxygen (Stumm & Morgan 1996). Lack of oxygen creates a reducing environment, i.e. Mn$^{2+}$ cannot be oxidised, and already formed manganese oxides will start leaching Mn$^{2+}$. Consequently, a minimal concentration of dissolved oxygen in water is required to prevent manganese oxide reduction, and to support manganese removal by adsorption and oxidation.

Apart from a minimum value of dissolved oxygen concentration required to achieve effective manganese removal, no other distinct relationship between manganese removal efficiency and the oxygen level in filtrate was observed from univariate correlation analysis. Operation of GWTPs with high to very high dissolved oxygen concentrations does not necessarily lead to complete manganese removal. This observation is backed up by the relatively high loading coefficient in the second principal component obtained by PCA (see Table 1), indicating that oxygen levels only play an indirect role in manganese removal. More detailed assessment of the data from plants where manganese removal was ineffective with dissolved oxygen in filtrate >1 mg/L revealed that one or more of the earlier identified critical water quality or process parameters may explain poor manganese removal.

In groundwater, manganese is typically present in low concentrations and exhibits low oxygen demand (0.29 mg O$_2$ per mg Mn). However, although the oxygen requirement for oxidation of dissolved manganese is very limited, groundwater entering the filters should have a high dissolved oxygen concentration to enable oxidation of dissolved iron (0.14 mg O$_2$ per mg Fe$^{2+}$), NH$_4^+$ (3.6 mg O$_2$ per mg of NH$_4^+$), and in some cases methane (4.0 mg O$_2$ per mg CH$_4$) and hydrogen sulphide (1.9 mg O$_2$ per mg H$_2$S), since these compounds are typically oxidised prior to manganese, if not removed during the aeration (CH$_4$ and H$_2$S).

**Effect of filtration type (gravity or pressure)**

The type of manganese removal filters applied (gravity or pressure filters) was not included in the statistical analysis. Additional assessment of available data revealed that the type of filters applied, could have an important impact on the manganese removal efficiency. In Figure 12, the effect of some selected water quality and process parameters on manganese removal efficiency is given, taking into account the type of filters applied.

The results of the inventory show that a large number of GWTPs utilising gravity filters achieved complete manganese removal, while none of the plants having pressure filters achieved that. It should be noted that pressure filters typically operate at a significantly higher filtration rate.
(Figure 12(d)), which results in higher iron loading and shorter contact time (Figure 12(b)). However, also pressure filters that were operated at a filtration rate < 10.5 m/h, did not achieve complete manganese removal possibly due to a somewhat lower pH (Figure 12(c)) that could be caused by pressure aeration and (related) lack of CO₂ degassing.

CONCLUSIONS

The manganese removal efficiency of (the first stage) of aeration-rapid sand filtration in GWTPs was assessed. The results from the conducted statistical analysis and assessment of data collected confirmed that manganese removal in the conventional aeration-rapid sand filtration treatment plants is complex and simultaneously influenced by several water quality and process parameters. Close inspection of the collected data from a large number of GWTPs and conducted statistical analysis (univariate correlations and PCA) show that manganese removal efficiency is influenced by several parameters simultaneously, including both water quality matrix and several (operational) design parameters. The results of the PCA show that at least four components are necessary to explain at least 75% of the total variance in the data. Furthermore, the PCA reveals that iron loading, NH₄⁺ removal efficiency and pH in filtrate play a major role in manganese removal, while oxygen in the filtrate, and phosphate, manganese and NH₄⁺ concentrations in raw water were found to influence manganese removal to a smaller degree.

Univariate statistics and assessment of available data indicate that very effective manganese removal efficiency in the first aeration-filtration stage can be achieved under the following conditions:

- NH₄⁺ removal efficiency: >85%
- iron loading per filter run: <2.7 kg Fe/m²
- pH of filtrate: >7.1
- filtration rate: <10.5 m/h
- EBCT: >11.5 min
- oxygen in filtrate: ≥1 mg/L.
The results of this study might be a helpful tool for engineers to design a traditional aeration-filtration treatment scheme for proper manganese removal. In addition results emerging from univariate statistics and assessment of available data from full-scale plants could be of help in making a decision as to whether manganese removal could be combined with removal of iron and ammonium in a single filtration step.

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