Journal of Water Supply: Research and Technology—AQUA | 61.3 | 2012

Review of diagnostic tools to investigate the physical state of rapid granular filters

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ABSTRACT

This paper reviews diagnostic tools that can be used at waterworks to investigate the physical and operational state of rapid granular filters. Diagnostic tools can be of interest for the Water Safety Plans of WHO to monitor filters in a proactive manner. The review considers conventional and state of the art tools and tools currently in development or conception stage. The development status, usability and availability of each tool and procedure are discussed. Some conventional, simple and low-tech tools are available which can rapidly provide both qualitative and quantitative information. However, it is difficult to relate this information to guideline values or design criteria because the tools are often not documented and are most often used with past experience or rules of thumb. New tools such as the total dissolved gas probe, salt tracers and ammonium profiles are presented. Potential tools from the soil and groundwater field such as the hand penetrometer, time domain reflectometry and ground penetrating radar are suggested. The paper discusses how the filtration process can be optimized once a malfunction is recognized by the diagnostic tools, and finally, research and development needs are identified.

Key words | diagnostic tools, drinking water treatment, filters, troubleshooting, waterworks

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INTRODUCTION

Granular media filtration has been used for centuries in drinking water treatment to remove soluble and particle contaminants, and to prevent pathogens from entering the water distribution network. For a protected groundwater aquifer, filtration is often the essential treatment step that prevents iron, manganese and ammonium entering the distribution system. In the case of surface water treatment or groundwater under the influence of surface water, filtration removes particles and acts as a barrier against parasites such as *Giardia* and *Cryptosporidium*. These pathogens cannot be removed by chlorination and are a serious health threat. Therefore, it is very important that filtration efficiency is kept constant and reliable.

Although the construction and operation of rapid granular filters appears to be quite simple, several problems can occur in a waterworks and hinder the efficiency of the filtration process. The most common problems occurring in rapid granular filters are insufficient soluble or particulate removal, filter bed growth, filter bed compaction, and short filter runs. To optimize the use of filters, it is necessary to establish the causes and mechanisms of these problems. Diagnostic tools achieve this purpose by investigating the physical and operational state of the filter. They can first be used to observe the symptoms of the filter failures. Once a preliminary diagnosis is made based on these observations, appropriate diagnostic tools can be selected and a thorough analysis conducted. From the information obtained, the preliminary diagnosis can be revised and mitigation options prescribed. The diagnostic tools are used again to verify the efficiency of the solution applied. If the problem is not solved the whole process starts again (Figure 1).

Filters should be evaluated regularly as part of basic maintenance or to troubleshoot a failing filter. Diagnostic tools can be used to check that the filter is performing correctly, to collect data, and to improve the filtration

doi: 10.2166/aqua.2012.056

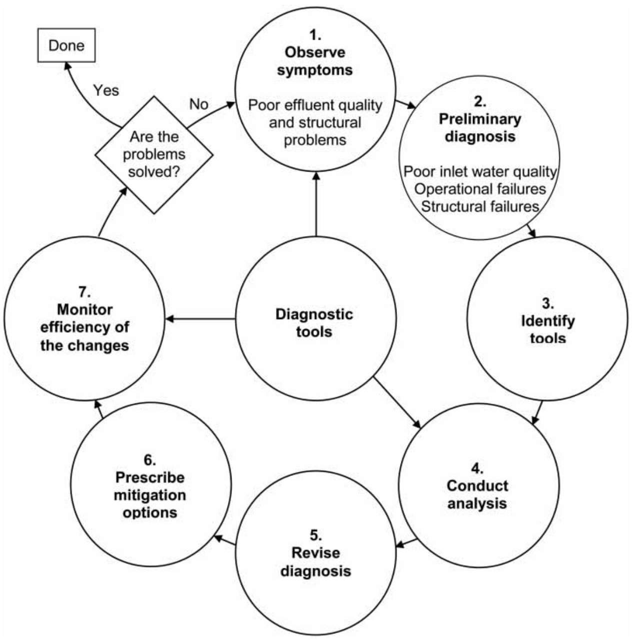

Figure 1 | Filter investigation flow chart diagram including the role of diagnostic tools.

process. Filter evaluation and troubleshooting is described in chapters of water treatment textbooks such as AWWA (2003), Cleasby (1990) and Kawamura (1991), and in specialized filtration books such as Beverly (2005), Logsdon (2008), Logsdon *et al*. (2002) and Nix & Taylor (2003). Beverly (2005) and Nix & Taylor (2003) detail very clearly the procedures required to carry out a filter evaluation at a waterworks as routine maintenance or as corrective action. They even provide the readers with a template for assessment reports. However, they only provide help on data collection and do not provide the values or criteria the information obtained should be compared with. They also do not describe how to respond to the information obtained. Moreover, the use of the tools for studying a specific problem or for optimizing filtration is not explained. No scientific articles consider comprehensive filter investigation and very few discuss the use of diagnostic tools (van Staden & Haarhoff 2004; Edwards & Scardina 2007; de Vet *et al*. 2009; Lopato *et al*. 2011a; Lopato 2011b). There is very little scientific research on the subject.

The aim of this article is to review all available diagnostic tools that can be used at a waterworks to investigate the physical state of rapid granular filters and obtain a better understanding of the filter performance and of the influence of the operating conditions. Most of the tools are only applicable to open-air gravitational filters, mono- or multimedia, and these filter types are the focus of this paper. In the review, the purpose, results obtained, documentation, usability, cost, and availability of each tool are addressed. The use of the tools for monitoring and optimization of the filter run and their potential as part of the Water Safety Plans of WHO to monitor filters in a proactive manner is discussed. Furthermore, the paper discusses how the filtration process can be optimized once a malfunction is identified by the diagnostic tools. Finally, research and development needs are discussed.

TOOLS REVIEW

The list starts with the more conventional tools, continues with newly developed tools, and ends with those which are only at the developmental stage. The estimates of time and costs required to conduct each procedure in this list are based on personal experience and data available from manufacturers.

All the tools reviewed are listed in Table 1. The table summarizes their main purpose, the information they can provide, their development status, their availability, and their cost.

Preliminary review of the filter

When performing a filter evaluation, it is important to start by collecting background data on the filter. Water composition and flow rate data are crucial to estimate how much and how well water is treated. Nix & Taylor (2003) recommend the use of four filter indices: performance over time, unit filter run volume, filter efficiency, and filter run time. The performance over time is measured in form of head loss or effluent turbidity over the filter run time, where the run time is the time between backwashes. The unit filter run volume is the volume of water treated per unit filter surface area and per filter run. The filter efficiency is the percentage of the volume of water treated per filter run compared to the total volume of water used per filter run. The filter run time analysis is an annual comparison of filter run times for all filters in a plant. It is also

Table 1 | Summary of the reviewed tools

Tool	Purpose	Information	Development status[a]	Usability[b]	Availability[c]	Cost/time	References
1. Preliminary review	Prepare filter evaluation.	Basic information on measured filter performance and design.	5	4	5	–/~3 d	Kawamura (1991); Nix & Taylor (2003); Beverly (2005)
2. Surface observation	Evaluate the uniformity and integrity of the filtration process.	Qualitative information on filter structural defects and on signs of improper backwash, uneven gravel layer, failed underdrain, poor inlet design and poor inlet water quality.	5	4	5	–/~2 h	Cleasby *et al.* (1975); Cleasby (1990); AWWA (2003); Nix & Taylor (2003); Beverly (2005); Logsdon (2008)
3. Backwash observation	Investigate the backwash process.	Qualitative information on media boiling, uneven distribution of backwash water or air, media loss, air release, hydraulic shocks, and floating scum.	5	5	5	–/<1 h	Cleasby (1990); AWQWA (2003); Nix & Taylor (2003); Beverly (2005); Logsdon (2008)
4. Expansion and backwash flow	Investigate the backwash process.	Expansion rate and the backwash water flow.	5	4	1–4	–/<1 h	Nix & Taylor (2003); Beverly (2005); Logsdon (2008)
5. Backwash water turbidity	Investigate the backwash process.	Quantitative data on backwash water turbidity versus time.	5	4	3	€ 3,000/ ~1 h	Kawamura (1991); Beverly (2005); Logsdon (2008)
6. Flow rate	Investigate filter flow control.	Effective flow rate.	5	4	4	–/< ½ h	Nix & Taylor (2003)
7. Turbidity monitoring	Monitor particle removal efficiency.	Precise and quantitative information on turbidity removal versus time.	5	4–5	3–4	€ 3,000/ ~10 d	Cleasby (1990); Kawamura (1991); AWWA (2003); Nix & Taylor (2003); Beverly (2005)
8. Head loss monitoring	Monitor head loss during a filter run.	Quantitative data on filter clogging.	5	3–4	1	–/~5 d	Kawamura (1991); Logsdon (2008)
9. Stick method	Investigate the uniformity of the filter bed.	Evenness of the gravel layer and qualitative information on the resistance of the filter bed.	5	3–4	3–4	–/~2 h	Cleasby (1990); Mayhugh *et al.* (1996); Nix & Taylor (2003); Beverly (2005); Logsdon (2008)

(*continued*)

Table 1 | continued

Tool	Purpose	Information	Development status[a]	Usability[b]	Availability[c]	Cost/time	References
10. Excavation	Inspect the gravel layer and the underdrain.	Qualitative information on gravel intermixing, gravel sizing, cracks, holes and clogging of the underdrain, and broken or clogged nozzles.	5	2	1–4	–/~1 d	Nix & Taylor (2003); Beverly (2005); Logsdon (2008)
11. Mud ball	Investigate the uniformity of the filter bed.	Volume of mud balls at different locations in the filter.	5	2	4	–/~5 h	Kawamura (1991); Nix & Taylor (2003)
12. Carbonate precipitation	Investigate the deposition of carbonate during filtration.	Volume and weight of the precipitates and coatings removed by acid washing in certain parts of the filter media.	5	2	3	–/~5 h	Nix & Taylor (2003)
13. Particle deposits and coatings	Investigate mineral deposits on the filter media.	Amount of deposits and amount and type of coatings in certain parts of the filter media.	5	2	3	–/~5 h	de Vet *et al.* (2009); van Staden & Haarhoff (2004)
14. Sieve testing – size distribution	Measure filter media characteristics.	Quantitative information on filter media effective size and uniformity coefficient.	5	2	3	–/~8 h	Nix & Taylor (2003); Logsdon (2008)
15. Turbidity profile in filter bed	Investigate particulates retained in the filter bed and backwash efficiency.	Quantitative information on retained particles in the filter before and after backwash.	5	2	3	–/~2 d	Kawamura (1991); Nix & Taylor (2003); Logsdon (2008)
16. Core sampler	Investigate the filter media condition (without disturbing the filtration process).	Core samples (undisturbed) that can be used to test for mud balls, particle deposits, coatings, media characteristics and turbidity.	5 (4)	2	1	–/~1 h	Kawamura (1991); Beverly (2005)
17. Ammonium profile	Investigate ammonium removal in the filter bed.	Ammonium depth profiles and qualitative information on ammonium removal heterogeneity.	4	2	1	–/~1 d	Johansen *et al.* (1999); Laurent *et al.* (2003); Tränckner *et al.* (2008); Lopato (2011)
18. Salt tracer	Investigate filter hydraulics.	Local pore velocities and dispersivities at different locations in the filter and on their evolution with filter run time.	4	2	1	–/1 d	Lopato *et al.* (2011)

19. Ammonium profile and salt tracer	Investigate ammonium removal in the filter bed.	Local nitrification rates and their evolution with time.	4	2	1	–/1 d	Lopato (2011)
20. Hand penetrometer	Investigate the uniformity of the filter bed.	Quantitative information on the leveling of the gravel layer, the layering and the resistance to penetration of the filter media.	2	3	2	€ 2,000 /~1 h	–
21. Sulfite tracer	Investigate air binding.	Quantitative information on the volume of gas present at different locations.	1	2	1	–/~1 d	Lopato *et al.* (2010)
22. TDR	Investigate air binding.	Quantitative information on the volume of gas present at different locations.	1	3	3	€ 3,000/ ~½ d	Noborio (2001); Jones *et al.* (2002); Topp & Ferré (2004); Rodgers *et al.* (2005)
23. Ground-penetrating radar	Investigate the filter bed structures.	Three-dimensional imaging of the filter bed.	1	3	3	–/–	Davis & Annan (1989)

[a]Development status is scaled from 1 to 5, from concept level, to prototype level, to tested in the laboratory, to tested in the field, to used at waterworks.
[b]Usability is scaled from 1 to 5. A high-tech, invasive, disruptive and slow tool is 1 and it gains one point for each positive criteria until it reaches 5 for a low-tech, non invasive, non disruptive and fast tool.
[c]Availability is scaled from 1 to 5, from the tool has to be built from scratch, it has to be adapted from another tool, it is an off-shelf product, it is available at the plant, and to no tools are required.

recommended that the physical and operating parameters of the plant be recorded (Beverly 2005). This information includes precise filter dimensions, filter media composition and age, and detailed filtration and backwashing procedures. It is also interesting to look at the historical data for the plant to find changes made in operational procedures, results from previous evaluations, and reports of past problems.

The preliminary review should yield quantitative information on the filter design and performance. It is important to locate poorly working filters and define their problems more precisely. It can also provide support information to assist in locating broken pipes or clogged nozzles later in an evaluation. An efficient filter should have a unit filter run volume above 400 m^3/m^2 and a filter efficiency above 95% (Kawamura 1991). Turbidity values should comply with local regulations. For groundwater treatment, removal of ammonium is a sign of efficient soluble contaminant removal. Iron and manganese removal can also be used as a mark of filtration efficiency.

Surface observation

The purpose of this procedure is to evaluate the uniformity and integrity of the filtration process.

The procedure is described by AWWA (2003), Nix & Taylor (2003), Beverly (2005), and Logsdon (2008), and requires the draining of the water below the media surface. The surface of the filter should then be checked for mounding, craters, mud balls, cracks, ridges, sand separation from walls, algae, residual solids, and levelness of the media. The levelness of the media surface can be measured from the top of the filter box at 1.5 m intervals or in a grid pattern at 1.5 m intervals (Logsdon 2008). At the same time, the filter can be checked for structural damage such as fractured walls or rusting.

These visual observations provide qualitative information on filter structural defects, improper backwash, unevenness of the gravel layer, failed underdrain, poor inlet design, and poor inlet water quality (Cleasby 1990; AWWA 2003; Nix & Taylor 2003; Beverly 2005). Quantitative information on the thickness and height of the filter bed can be compared with historical data (Cleasby 1990). Heterogeneous backwashes create mounds in areas with low backwash velocity and depressions in areas with high backwash velocity (Beverly 2005). A poor inlet design can gouge a hole and create mounds in the filter bed if the starting water level is too low or if the incoming water flow is too fast. Heterogeneities affect both the surface of the filter media and the gravel layer. Higher initial water levels, baffles, splash plates or a perforated inlet box can be used to solve the problem (Beverly 2005). The direct relation between a well-operating filter and a clean and homogeneous filter surface is mentioned in the literature (Cleasby 1990; Kawamura 1991; AWWA 2003) but is not thoroughly documented. Visual observation was used by Cleasby *et al.* (1975) to evaluate the efficiency of different types of backwashing procedures. Agglomerates attached to the walls, mud balls and surface cracks were observed in the filter bed when backwashing was poor. The heavy mud ball accumulation caused higher initial head losses and shorter filter cycles. The cracks allowed deeper penetration of solids and reduced the development of head loss at the surface layer but increased it in the deeper layers (Cleasby *et al.* 1975).

Visual inspection of the filter surface is a simple and low-tech procedure which requires no specific tool and can be conducted by one or two plant operators or external consultants in less than an hour. Drainage of the filter below the media surface requires stopping the filtration process for some time but is not a major disruption. It is necessary to be able to be very close to the surface of the filter bed, for example by standing in the backwash water troughs or by standing on the filter on plywood panels.

Filter backwash observations

The purpose of this procedure is to investigate backwash performance (Nix & Taylor 2003; Beverly 2005; Logsdon 2008).

The filter backwash must be carefully observed. Any irregularity such as media boiling, uneven distribution of backwash water or air, media loss, air release, hydraulic shocks, and floating scum should be noted. Surface wash, if used, should be observed for clogged nozzles, vibration, unbalanced sweeps, non-uniform rotation and leakage (Logsdon 2008). It should be verified that the backwash is following the designed sequence. The sizing and levelness of the backwash water troughs should also be checked.

From this procedure, media loss due to too high backwash rates or structural defects in the backwash water troughs can easily be identified. Observed irregularities can reflect an improper backwash, unleveled gravel layer, failed underdrain, clogged nozzles, poor inlet design and bubble formation (Cleasby 1990; AWWA 2003; Nix & Taylor 2003; Beverly 2005).

Backwash observations are a simple, nondisruptive and low-tech procedure which require no specific tool and can be conducted by one or two plant operators or external consultants in less than an hour.

Filter fluidization, expansion and backwash water flow

If the filter backwash is to be further assessed, possible diagnostic tools are the evaluation of the filter bed fluidization during backwash (Logsdon 2008), its expansion (Nix & Taylor 2003; Beverly 2005), and the backwash water flow (Nix & Taylor 2003; Logsdon 2008).

To verify that the backwash water flow rate used fluidizes the filter bed, a long pole of approximately 3 cm in diameter is placed on top of the filter media before backwash. If the pole sinks into the bed as the backwash water flow rate is increased gradually, the bed is fluidized (Logsdon 2008). The expansion of the bed during backwash can be estimated by measuring the distance of the media surface from the top of the backwash water troughs before and during backwash. To measure this distance, a punch plate (a perforated metal sheet with regularly spaced holes) attached to a stick is lowered down in the filter until it rests on the filter media before backwash and during backwash (Beverly 2005). Another method is to use a pipe organ (Nix & Taylor 2003; Logsdon 2008). The pipe organ sampler is made of nine clear PVC pipes of 2–3 cm in diameter and of increasing heights (6–30 cm) fastened to the plate. Before backwash, the sampler is placed on the filter media and secured to the filter walls. The highest tube filled with filter media after backwash determines the extent of the filter expansion. The backwash water flow can be checked by measuring the rise of water in the filter versus time during backwash (Nix & Taylor 2003; Beverly 2005; Logsdon 2008).

These diagnostic procedures will provide information on whether the filter bed is fluidized during backwash, and provide quantitative values of the real expansion rate of the filter bed and the real backwash water flow. The values can then be checked against the recommended or design values. The fluidization necessary to provide proper cleaning and the optimum expansion rate during backwash was found to be 25% in dual media filters (Cleasby et al. 1975). In textbooks, typical recommended values for bed expansion are 20% for sand and 25% for anthracite (Nix & Taylor 2003), 20–30% (AWWA 2003), 15–30% (Cleasby 1990), or 22–30% (Beverly 2005). Filter bed expansion depends on backwash water flow, media size, media density and water temperature. Expansion has to be optimized for the larger sized media and backwash rate has to be increased in warm conditions (Logsdon 2008). At high temperatures, a higher rate is necessary to fluidize the filter bed as the water is less viscous. In the US, where filter media with 1 mm mean grain size is common, a full backwash water flow rate of 36–50 m/h is described as typical (Cleasby 1990) and sufficient to expand the filter bed (AWWA 2003), while 25 m/h is used as a low backwash water flow rate (AWWA 2003). Backwash water flow can be reduced due to leaking pipes or clogged nozzles (Schell & Bernhardt 1992).

These diagnostic procedures are simple, low-tech and non invasive. They do not require specialized tools and can be conducted by a plant operator or an external consultant if the filter bed is easily accessible.

Backwash water turbidity

The objective of this method is to investigate the backwash process.

Turbidity of the backwash water is measured manually every minute during the whole duration of the backwash so that the evolution of turbidity with time can be plotted. Turbidity meters can also be placed in the main backwash header or directly in the backwash water troughs to take automated measurements (Beverly 2005).

This diagnostic tool produces quantitative values of backwash water turbidity with time. Kawamura (1991) and Logsdon (2008) recommend that the backwash should end once the backwash water reaches a turbidity of 10–15 NTU to prevent long initial turbidity breakthrough. A shorter backwash would be insufficient and a longer backwash will washout the ripening layer causing turbidity spikes in the outlet water after the filter is put back into service. This procedure can be used to optimize the backwash time and preventing turbidity peaks in the outlet water (Nix & Taylor 2003; Logsdon 2008).

Flow rate

This diagnostic tool aims at investigating filter flow control at a waterworks (Nix & Taylor 2003).

The flow rate can be estimated by measuring the velocity at which the water level decreases in a functioning filter once the influent valve is closed. This value can then be compared to the designed flow rate value and the measured value by the flow meter. This tool is useful for filters which are operated under controlled flow or which have individual flow meters. Flow control is common in waterworks to prevent rapid fluctuations and to ensure proper distribution of the flow between the filters (Cleasby 1990). Maximum filtration rates are often regulated at the county or state level in the United States (Kawamura 1991; Nix & Taylor 2003).

A sudden increase in flow rate has been shown to result in a flushing of filter material (Kim & Lawler 2006; Han et al. 2009), causing increases in turbidity (Ahmad et al. 1998), *Giardia* cyst concentration (Logsdon et al. 1981), and head loss (Han et al. 2009). This effect is more marked when the head loss in the filter is high (Logsdon 2008; Han et al. 2009). Therefore ensuring proper filter flow control is very important.

Turbidity monitoring

The aim of this diagnostic tool is to monitor particle removal efficiency of a filter continuously (Cleasby 1990; Kawamura 1991; AWWA 2003; Nix & Taylor 2003; Beverly 2005).

Turbidity is continuously monitored at the outlet of the filter with an online turbidity meter and the data can be transferred to a computer for analysis. If no meter is installed, samples can be collected from the outlet pipe and analyzed for turbidity in the field or in the laboratory.

This tool provides precise and quantitative information via curves of turbidity versus filter run time. Particle counters are more sensitive to small changes in plant performance than turbidity monitoring (Lechevallier & Norton 1992), are a better indicator of the presence of bacterial cells and fibers smaller than 0.4 μm in diameter (Logsdon & Symons 1977) and have been reported to work well in waterworks (Bouchier 1998). However, turbidity meters are cheaper than particle counters. Also, as the technology is simple, they tend to be very reliable. Moreover, effluent filter turbidity has been shown to be an appropriate way to estimate filter ripening period (O'Leary *et al*. 2003), and filtration efficiency as turbidity breakthroughs coincide with increases in virus, asbestos fibers, and *Giardia* cyst concentrations (Logsdon *et al*. 1981, 1985). Turbidity removal has also been shown to be a good indicator of *Giardia* and *Cryptosporidium* removal (Lechevallier & Norton 1992). Online turbidity monitoring at each filter effluent is required by the United States Environmental Protection Agency for waterworks serving more than 10,000 people and is normal practice in the United Kingdom. Turbidity must be below 0.5 NTU 95% of the time at each filter outlet and below 0.3 NTU 95% of the time in combined filter effluent (US EPA 1998). Continuous online turbidity measurement is also recommended as part of the basic filter monitoring equipment to observe turbidity breakthrough and to control filter run time (Cleasby 1990; Kawamura 1991; Bellamy *et al*. 1993; AWWA 2003; Nix & Taylor 2003; Beverly 2005; Degrémont Suez 2007).

Head loss monitoring

The aim of this diagnostic tool is to monitor head loss during the filter run.

A pressure gauge is placed at the filter outlet to monitor head loss continuously. Piezometers to measure head are installed at four depths along the filter bed to measure the head loss profile. The piezometers can be screened and connected to glass tubes to create a piezometer board (Kawamura 1991; Logsdon 2008). The board can even be filmed and the image displayed in the control room for easier monitoring of head loss (Kawamura 1991).

This tool will provide continuous and quantitative information on the total head loss during a filter run and the head loss profile at one location in the filter bed. The total head loss can be monitored with time and can also help determine if the filter run is ended at the right time. Total head loss depends on the filter media, filtration rate, water temperature, and clogging. It is one of the main tools to determine filter clogging in a quantitative manner and one of the best methods to determine when to end the filter run (Cleasby 1990; Kawamura 1991; Degrémont Suez 2007; Logsdon 2008). Filters are generally designed to accommodate a head loss of 2.5–3 m but the effluent turbidity will start increasing when the net head loss rises above 1.8 m (Kawamura 1991). Total head loss values just after backwash can be recorded, collected and standardized for temperature and filtration rate. Increase with filter age may indicate changes in the filter media, such as accumulation of deposits (Logsdon 2008). A head loss profile can be used to investigate where head loss occurs in the filter bed. If head losses result in negative pressure in the filter bed, air bubbles may form in the media creating air binding (Scardina & Edwards 2004). Bubbles will further increase head loss.

Stick method

Stick methods are conventional tools that are used to investigate the uniformity of the filter bed and the depth of the gravel layer.

A stick can be a simple broom stick, a metal rod with a handlebar or a stick attached to a punch plate that is pushed into the filter (Cleasby 1990; Mayhugh *et al*. 1996; Nix & Taylor 2003; Beverly 2005; Logsdon 2008). To measure the depth of the gravel layer, the punch plate is pushed down in the filter during backwash until it lies on the gravel layer. The broom stick and the metal rod can be used at any time of the filter run. They are pushed into the filter bed until they meet a higher resistance, indicating that they hit the gravel layer. Another sign of the presence of the gravel layer is the change in tone produced by the metal rod handlebar when the rod strikes the gravel layer. The stick method can also be used to check if some parts of the filter have developed very high resistance during the filter run, indicating the presence of agglomerates (Mayhugh *et al*. 1996). Nix & Taylor (2003) recommend taking a measurement in 25 locations in the filter.

This method provides quantitative information on the depth of the gravel layer and qualitative information on the resistance of the filter bed. There is no documentation on

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what constitutes an uneven gravel layer. According to Nix & Taylor (2003), a gravel layer in good condition should be almost flat with irregularities of a maximum height of 2.5 cm. Beverly (2005) and Logsdon (2008) suggest that irregularities are a serious problem if they are more than a third of the gravel layer thickness. The evenness of the gravel layer helps to ensure homogeneous filtration and backwash processes. An incorrect installation, improper backwash (high rate or sudden start), poor inlet design, and clogged underdrain can cause the gravel layer to fail (Cleasby 1990; AWWA 2003; Nix & Taylor 2003; Beverly 2005; Logsdon 2008).

These diagnostic tools are quite simple to use if there is easy access to the filter bed. The broom stick is the easiest method as it does not require specialist equipment and it can be conducted at anytime in the filter run, but it may be difficult for the operator to feel the difference between the bottom of the filter and the fine gravel layer (Cleasby 1990). For the rod method, the results depend on the ability of the operator to hear the change in tone (Beverly 2005). When using a punch plate, it is necessary to be sure that the filter is fluidized all the way down to the gravel layer. The rod method also requires that the media is fluidized for the duration of the analysis.

Excavation

The aim of this diagnostic tool is to inspect the gravel layer and the underdrain (Nix & Taylor 2003; Beverly 2005; Logsdon 2008).

Inspecting the gravel layer or the underdrain involves removing the filter media to reach the bottom of the filter and be able to visualize the gravel layer or the underdrain. If only a part of the filter bottom needs to be inspected, a box of height greater than the height of the filter media and of width determined by the area needing inspection can be pushed in the filter during backwash to delimit the part of the filter which has to be dug up, leaving the rest of the filter in place. The walls of the box must be able to withstand the pressure from the surrounding media (Logsdon 2008). If the box is made of clear plastic, it will provide a valuable view of the media. The media must be put back in place correctly and the filter backwashed and disinfected. During excavation, heterogeneities in the filter bed should also be evaluated.

This inspection will allow checking for filter media heterogeneities and layer intermixing, as shown in Figure 2, but the method is mostly used to detect an uneven gravel layer, and broken or clogged underdrain, and nozzles.

Mud balls

This diagnostic tool is aimed at investigating the uniformity of the filter bed by determining the frequency of mud balls in the filter (Nix & Taylor 2003). Mud balls are pieces of filter media adhering together often in a spherical shape.

Filter media samples are collected from the first 15 cm of the filter bed. The volume of mud balls present in each sample is compared to the sample volume.

This procedure provides the volume of mud balls at different locations in the filter and can be extrapolated to a volume of mud balls in the whole filter. Improper backwashing, an uneven gravel layer or failed underdrain can cause gravel movements leading to the formation of mud balls (Cleasby 1990). Mud balls are also indicative of an excess of coagulants (Beverly 2005) or flocculants in pretreatment. According to Kawamura (1991), if the filter bed is in poor condition, percentage volume of mud balls is greater than 1%. If the volume of mud balls is greater than 5%, the filter media should be replaced. Surface washing has been shown to prevent the formation of mud balls more efficiently than air-scour backwash (Kawamura 1991).

Figure 2 | Picture of filter media from a second stage rapid sand filter at a Danish groundwater treatment plant. Layers of sand of different colors and grain sizes are mixed, without the expected horizontal stratification.

Carbonate precipitation

The purpose of this procedure is to investigate carbonate deposition on the filter media.

To conduct this procedure, filter media samples are collected from the first 15 cm of the filter bed (Nix & Taylor 2003). The samples are thoroughly washed, dried and weighed. The samples are then washed with 50% hydrochloric acid solution to remove all carbonate precipitates. The difference in weight and volume between the initial samples and the acid washed samples is measured.

This procedure provides quantitative information on the volume and weight of the precipitates and coatings removed by acid washing. There is no certainty that only carbonate precipitates will be removed by this procedure. The difference in weight could also be due to other mineral deposits such as iron, manganese or aluminum oxides. If the raw water contains manganese or iron below limits of detection, and if alum or iron salts are not used for coagulation, it can be safe to assume that the precipitates on the filter grains are carbonate. High carbonate precipitation is a sign of a poor recarbonation process or unstable water with regard to carbonate content. Precipitation on the filter grains change the size, shape, and density of the grains and might affect the efficiency of the backwash and the mixing with other media layers (Logsdon 2008). No documentation was found in the literature on how much carbonate precipitate should be a concern.

Particle deposits and coating

The aim of this diagnostic tool is to investigate particle deposits and coatings in the filter media.

van Staden & Haarhoff (2004) describe a reproducible method to measure particle deposits in a filter media. A homogenized 60 mL sample of filter media is dried and weighed. It is stirred at slow speed for one minute with a magnetic stirrer in 100 mL distilled water. The supernatant solution is then drained off in a beaker and this step is repeated four times. The wash water is filtered through a glass fiber filter and the deposits are weighed to determine the total suspended solids. The deposits can be further analyzed according to Standard Methods (2005) to determine the fraction of nonsoluble solids and nonvolatile solids. de Vet *et al.* (2009) investigated the coatings on the filter media after removing the deposits. The filter media sample is dried and mixed in 4 M hydrochloric acid with 2 g/L oxalic acid until dissolution of the coatings. The amount of coating is estimated. The calcium, iron, magnesium and manganese concentration in the acid solution are measured by ICP-MS.

This procedure provides quantitative information on the amount of deposits and the amount and type of coatings in a certain part of the filter bed. Iron and manganese oxides are common mineral deposits in a plant treating iron and manganese rich water (Cleasby 1990). Large amounts of coatings can be linked to improper backwashing with low filter bed expansion (de Vet *et al.* 2009). Iron coatings on filter grains have also been shown to decrease nitrification efficiency (de Vet *et al.* 2009).

Sieve testing – size distribution of the granular medium

This diagnostic tool aims at measuring filter media characteristics.

For this procedure, filter media samples of 100–200 g (Logsdon 2008) are collected from the first 15 cm of the filter bed (Nix & Taylor 2003). The samples are washed with water and dried. Each sample is sieved following Standard Methods for sieve analysis of fine and coarse aggregates (ASTM Standard C136 2006) to determine the effective size, uniformity coefficient, and grain size distribution curve.

This tool provides information on the size distribution of the media and it should be approximately normally distributed. If the distribution is distorted it can be a sign of layer intermixing (Logsdon 2008). This tool also provides quantitative information on filter media effective size and uniformity coefficient which can be compared with the initial characteristics. The uniformity coefficient is typically around 1.4–1.5 (Logsdon 2008). An increased or high effective size can be a sign that the finest filter grains are lost or that the media is heavily coated. Rapid granular filters usually lose 1–2% of sand or 5–7% of anthracite per year (Kawamura 1991). Media loss can be due to air binding, an excessive backwash rate, too long surface wash, low wash troughs or leakage through the underdrain. Up to 20% of the original depth is a tolerable loss; above this value the filtration efficiency will greatly decrease (Kawamura 1991). The same procedure can be carried out after the sample has been acid washed to estimate the effect of coating on the filter medium effective size and uniformity. A common design approach is that the ratio of filter bed depth to effective grain size must be greater than 1,000 (Nix & Taylor 2003; Lawler & Nason 2006). This value was determined empirically from many well functioning rapid granular filters which had values above 850 and often above 1,000 (Kawamura 1991).

Turbidity profile in filter bed

The aim of this diagnostic tool is to estimate the amount of particulates retained in the filter bed and to determine the backwash efficiency.

For this procedure, filter media samples are taken from the drained filter before and after backwash (Nix & Taylor 2003). Samples are collected using a core sampler at 5 cm intervals until reaching 90 cm. The method described under the section Particle deposits and coating can be used here. The turbidity of the wash water is then measured with a turbidity meter. This procedure is repeated for each sample. A turbidity depth profile can then be plotted before and after backwash.

This tool provides quantitative information on the amount of retained particles in the filter before and after backwash. An average of 30–60 NTU after backwash is recommended (Kawamura 1991; Nix & Taylor 2003; Logsdon 2008) and a turbidity value over 120 NTU should be of concern (Kawamura 1991). There should also be a clear decrease in turbidity after backwash, indicating the efficiency of the process. Instead of turbidity, iron oxide concentration or particle counting could be used to investigate the retained particle depth profile.

Core sampler

The aim of this diagnostic tool is to investigate the filter media without disturbing the filtration process.

Common soft-bottom sediment or soils core samplers fail to take undisturbed cores from saturated filter beds because rapid granular filter beds are made of loose coarse material making coring a difficult task. A thin-walled galvanized pipe 1.5 m long and 3.8 cm in diameter can be used to take cores in drained filters (Kawamura 1991). Core samples can also be taken in drained filters by excavation at one location while being careful to enlarge the size of the hole as the hole gets deeper to prevent the sides from collapsing (Kawamura 1991). Beverly (2005) suggests the use of a clear PVC pipe 5 cm in diameter with a flexible flap and a wire support grid at the bottom to collect core samples of the filter bed while it is being backwashed at low rate. However, this method is not exact as it might not capture all the media. To be able to take cores in functioning filters, a core sampler was developed by the authors (Lopato 2011).

This tool can be used to collect undisturbed core samples which can then be used to investigate the filter media for mud balls, particle deposits, coatings, size distribution and turbidity versus depth. Intermixing of the different media layers can also be visualized. The intermixing zones should be approximately 10–15 cm deep to provide a smooth transition from one media type to the next one below and prevent a sudden increase in head loss (Beverly 2005). A wider intermixing zone will provoke an accumulation of particles at the interface because of the lower porosity caused by the different grain sizes (Kawamura 1991). A high degree of intermixing can be caused by improperly sized media, by media with high uniformity coefficients, or by a backwash sequence terminating abruptly (Logsdon 2008).

Total dissolved gas probe

This diagnostic tool aims at investigating sources of gas supersaturation and the potential for bubble formation in the water treatment train. Air binding is recognized as a common problem in rapid granular filters in handbooks (Cleasby 1990; Kawamura 1991; AWWA 2003; Beverly 2005; Logsdon 2008), but no tools or methods are proposed to investigate the causes of the problem. Dissolved gas supersaturation in the water can be caused by excessive aeration intensity, air entrainment in pipes, underground tank or negative pressures in the filter and can lead to air bubble formation during filtration (Kawamura 1991; Logsdon 2008). The bubbles formed in the filter can reduce water porosity, increase filter head loss, remove filter media by 'burping' and be measured as turbidity in the outlet (Hach Co. 1997). In pilot scale experiments conducted by Scardina & Edwards (2002) with 0.05 atm supersaturated inlet water, the effluent flow to the filter was decreased by 50% after 24 h. Bubble formation in filters can be reduced by increasing submergence, decreasing the flow rate or by using a higher porosity media (Scardina & Edwards 2004).

A total dissolved gas probe is used to measure gas supersaturation at different points of the water treatment train. An increase of supersaturation after a certain step of the water treatment process identifies the source of supersaturation, while a reduction of total dissolved gases after filtration is a proof of bubble formation in the filter media (Scardina & Edwards 2002). From gas supersaturation measurements, the amount of air bubbles forming per liter of treated water can be predicted (Scardina & Edwards 2001).

This diagnostic tool provides quantitative measurements of the total dissolved gas in water. The probe provides a direct measure of dissolved gases in solution at a hollow cylindrical silicon membrane. Several minutes are sometimes required for an accurate reading of a water sample, bubbles forming in the probe can interfere with the reading, and supersaturation can be overestimated when measured at depth with certain probes (Scardina & Edwards 2002). Edwards & Scardina (2007) used the total dissolved gas probe in six case studies to successfully determine the cause of gas supersaturation. This tool should be part of the basic toolbox of waterworks where air binding is a frequent problem.

Ammonium profile

The purpose of this diagnostic tool is to investigate ammonium removal in the filter bed (Johansen *et al*. 1999; Laurent *et al*. 2003; Tränckner *et al*. 2008; Lopato 2011). Nitrification is a symptom of the physical state of the filter as ammonium removal is a good indicator of filtration efficiency.

Ammonium profiles can be measured by taking water samples at different depths in the filter bed by inserting a probe vertically and sampling the water every few centimeters. The samples can then be analyzed with an ammonium field test such as a photometer with adequate accuracy and detection limit. The sampling can be conducted in different locations in the filter and at different times (Lopato 2011).

This diagnostic tool provides ammonium depth profiles and qualitative information on ammonium removal evolution in space and time. Ammonium profiling is a common tool when studying nitrification but it is rarely used in waterworks to investigate ammonium removal. However, insufficient ammonium removal is often a problem in waterworks treating groundwater. Ammonium profiles provide a scientific approach to the problem, investigating how nitrification evolves with filter run time and with space.

This diagnostic tool is simple but time-consuming. It requires a sampling probe, a pump, and easy access to the filter bed. The measurements can be conducted while the filter is in use and they do not disrupt the filtration process. They require a skilled technician for one to several days depending on the amount of depth profiles measured.

Salt tracer

The aim of this diagnostic tool is to investigate filter hydraulics (Lopato *et al*. 2011).

Various nonreactive tracers are available. Salt is safe and easy to monitor. The tracer solution is pumped into the filter media through a needle inserted at the top of the filter bed. A sample probe is inserted at a specified angle and depth so that its opening is directly below the injection point in the granular filer. Water is pumped from the sampling probe. If salt is chosen, conductivity measurements can be carried out using a conductivity probe located in a flow through cell connected to the outlet of the sampling probe. Tracer experiments can be performed at different locations in the filter and at different times during the filter run. The resulting breakthrough curves are corrected for the delay time due to the tubing connections. The data can be modeled using the analytical solution of Leij *et al.* of the advection-dispersion equation (equation 3T, Leij *et al*. 1991). The pore-velocity and the longitudinal and transversal dispersivities can be estimated.

This diagnostic tool provides quantitative information on local pore velocities and dispersivities at different locations in the filter and on their evolution with filter run time. These velocities can be compared to the filter discharge. It also provides qualitative information on heterogeneity and hydraulic conditions in the filter and its evolution in time without disturbing the filtration process (Lopato *et al.* 2011). It has been shown that heterogeneity in rapid sand filters has practical implications for filter plant operation; it can decrease contaminant removal efficiency (Lopato *et al.* 2011).

This procedure requires specialized sampling probes, a peristaltic pump, a conductivity meter, and access to the filter bed. In order to compare the measured pore velocity values with the filter discharge, flow meter measurements at the inlet or outlet of the filter are necessary. The procedure requires a trained technician to conduct the experiments and the analysis of the breakthrough curves. The injection and sampling system can be installed without interrupting the filtration process. They can be left in the filter bed for the duration of the filter run. Eight tracer experiments can be conducted per day.

Ammonium profile and salt tracer combined

The aim of this diagnostic tool is to investigate ammonium removal in the filter bed.

This tool is a combination of the nonreactive tracer experiment and the ammonium depth profile presented previously. By conducting both analyses at the same time and location, the pore velocity value and the ammonium concentrations with depth can be estimated and used to determine the nitrification kinetics (Lopato 2011).

This tool provides quantitative information on local nitrification rate constants and orders and their evolution with time. Nitrification kinetics can have important implications on filter operation. It also gives qualitative information on the heterogeneity of ammonium removal in the filter (Lopato 2011).

Hand penetrometer

The aim of this diagnostic tool is to investigate the uniformity of the filter bed.

Hand penetrometers are usually used to determine the resistance to penetration of a soil and are operated manually. They consist of a cone, a probing rod with strain gauges and a pressure gauge. The penetrometer is pushed in the media at a constant rate. During penetration, the forces on the cone are measured and read on a pressure gauge. As the filter media is very loose and less resistant than most soil, a very large cone is necessary to make meaningful measurements in the first layers of the filter bed. It was determined that a cone with a base area of 5 cm^2 was not large enough to take measurements in sand layers with grain sizes ranging from 3 to 14 mm in a first stage rapid sand filter (unpublished results). This method could be improved by using a cone with a larger base area.

This tool can provide quantitative information on the location of the gravel layer and is more precise than the stick method reported previously. It can also provide information on the layering of the filter media and on the presence of zones of higher resistance.

Sulfite tracer

The sulfite tracer diagnostic tool can be used to investigate air binding in the filter bed (Lopato *et al.* 2010).

The tool employs a reactive sodium sulfite tracer that can be injected and monitored in the filter. Sodium sulfite is a salt, an oxygen scavenger and a base. Sulfite consumes the oxygen present in trapped air bubbles to form sulfate. The tracer solution is pumped in the filter media through a needle inserted at the top of the filter bed. A sample probe is inserted at a specific angle and depth directly below the injection point in the granular filter. Water is pumped out of the sampling probe and the conductivity and dissolved oxygen are measured to obtain two different breakthrough curves. As the tracer passes through the filter bed, the oxygen present is consumed. The tracer is injected until no oxygen is measured at the outlet. The conductivity curve gives information on hydraulic conditions while retardation of the oxygen curve is due to the presence of air bubbles in the media. The degree of retardation can be related to the amount of oxygen present through sulfite oxidation equation (Lopato *et al.* 2010).

Time domain reflectometry

Time domain reflectometry (TDR) can be used to investigate air binding in the filter bed.

A TDR probe measures bulk electrical conductivity using electromagnetic waves and is used to measure moisture content in soil, often for agricultural purposes

(Noborio 2001; Jones *et al.* 2002). Probes are made of two or three steel or brass rods and are connected to a pulse generator and an oscilloscope to measure the reflected waves. Rods can be of different sizes depending on the required resolution. The time difference between the transmitted and reflected waves can be related to water content through Topp's equation (Topp & Ferré 2004). The water content is averaged over the length of the rods.

TDR probes have an accuracy of up to 0.01 m^3 air/m^3 (Evett *et al.* 2005), and they have an excellent temporal resolution (Noborio 2001). Continuous measurement is possible through automation and multiplexing. This procedure could provide quantitative information on the presence and evolution of gas bubbles with time and space in the filter bed.

The use of a TDR probe in rapid granular filters for this purpose was not found in the literature. It has been used in stratified sand filter columns treating synthetic dairy parlor washings to monitor variations in the sand volumetric water content (Rodgers *et al.* 2005). Experiments are necessary to determine if this method can be applied in rapid granular filters.

Ground-penetrating radar

Ground-penetrating radar can be used to investigate filter bed structures.

Ground-penetrating radar is a noninvasive electromagnetic technique mainly used to investigate the subsurface structure of soil (Davis & Annan 1989). Electromagnetic waves are directed into the ground and reflected back to a receiving antenna which records time delays and signal strength. Signal reflections occur at interfaces between different dielectrical permittivities caused by a variation of the subsurface features (water content, rock type, fractures). The resolution of the method increases, and depth of investigation decreases, with shorter wavelength. In soils studies, the method has been used at depths between 1 and 5,400 m but is typically around tens of meters. The detectability of subsurface structures depends on their size, shape, and orientation relative to the antenna, contrast with the host medium, as well as radiofrequency noise and interferences.

This technology is not known to have been used for filter investigation. If proper depth of investigation, resolution and detectability can be obtained, it can be used to obtain a three-dimensional image of the filter bed in a noninvasive manner.

DISCUSSION

The inventory, presented in this paper, shows that there is a large range of diagnostic tools available for investigating the physical and operational condition of filters. The diversity of available tools reflects the difficulty of operating granular filtration processes and the necessity of filter evaluations (Nix & Taylor 2003). In this section, the proper use of these tools to monitor and optimize the filtration process is discussed. Finally, possible research and development topics are identified.

Prerequisites for filter investigations

Filter evaluation campaigns should always start with a preliminary review of the available data (Nix & Taylor 2003). Historical information, documentation of the filter design, and filter performance data can be very scarce and difficult to access. Rapid granular filters can remain in service for more than 30 years, making it difficult to locate schematics and initial designs for filter control values. Even if meters are in place and in order, the data measured might not be collected and saved properly so it can be easily retrieved when needed. Therefore, efforts should be made to keep a database of all analyses, evaluations and measurements, as recommended by Beverly (2005).

Moreover, as the investigation of the granular medium of the filter is an essential part of filter monitoring and evaluation, it is important to provide easy access to the filter bed when designing a filter. In the state of California, the use of pressurized filters is discouraged because of the difficulty of observing the filter bed (Kawamura 1991).

Choice of tools

A preliminary review and visual observations methods will enable the identification of visible filter malfunctions (structural defects, media loss, upset backwash, heterogeneity, poor removal, short filter run, etc.) but often it will not be sufficient to determine the causes of a filter problem. Further analyses are necessary as shown in Figure 1. Table 2 presents the problems that can be diagnosed by a preliminary review and visual observations of the filter. For each problem, the tools necessary to determine its causes are listed. Once the causes are discovered, they can be related to the mitigation options. This can be used in a Water Safety Plan according to the principles of WHO (Davison et al. 2005) in order to help choosing the proper corrective actions. This plan requires efficient monitoring of the state of the different components of the water supply system, including the water treatment steps. Diagnostic tools can also be used in a proactive manner for monitoring the condition of a filter. They can provide an early warning of deteriorating filter performance and can also suggest ways to intervene and further investigate problems.

Identification of research and development topics

Determining the exact cause of problems occurring in filters is often difficult because the link between the observed heterogeneities and the cause of failures is not clear. For example, the effect of the inlet design on filter heterogeneity should be studied. As mentioned earlier, the way the water is transported to the filter can cause depressions and mounds on the filter bed. It may also lead to heterogeneous particle settling at the surface of the filter media.

In addition, many design criteria and guideline values for filter diagnostic tools are qualitative or determined empirically (Table 3). Documentation of diagnostic tools for evaluation and troubleshooting of filters are limited to handbooks and a few research papers. Filter benchmarking is available for backwash methods, flow rate control, turbidity and head loss monitoring but is very limited for filter media evaluation. Further research is necessary to establish quantitative data on the physical state of a well-functioning filter in order to set up values and criteria for an acceptable filter medium. For example, it is important to determine the acceptable amounts of mud balls, deposits, coatings, and biomass in a filter bed. What form should a typical ammonium, manganese, iron, or turbidity profile have? How much media loss is acceptable?

All the tools described in this review relate to the physical and operational state of filters, but it is also important to study the microbial communities (ammonia-, nitrite-, iron-, manganese-, methane-, hydrogensulfide-, and organic matter oxidizers) present in filters in order to determine what the biological fingerprint of a balanced filter looks like. This may help identifying abnormal filter conditions and thereby supplementing the information obtained by other diagnostic tools. Such a study should include several well functioning filters to obtain a general overview of filter behavior.

It is also necessary to develop standard methods for investigation of filters. For example van Staden & Haarhoff (2004) developed a standard method for measuring turbidity in the filter bed. Methods for choosing sample location and number of samples needed for filter media analysis are also needed. Sampling locations should account for the size of the filter and for the visible and expected heterogeneity of the filter bed. Nix & Taylor (2003) suggest sampling five locations to quantify mud balls, carbonate precipitation, and to determine grain size. Only three are considered to be necessary to investigate turbidity profiles.

To establish a Water Safety Plan at a waterworks, control measures, appropriate means of monitoring and critical limits are needed for each water production step (Davison et al. 2005). By introducing the use of diagnostic tools to Water Safety Plans, new monitoring measures with specific critical limits can be established that can provide an early warning of deteriorating filter performance. Diagnostic tools can be used as monitoring methods if threshold values or critical limits are defined. Moreover, standard methods for use of the diagnostic tools, as done by van Staden & Haarhoff (2004) for turbidity measurements in the filter bed, should be developed so they can be used in a reproducible manner.

Moreover, new tools should be developed to help waterworks operators to investigate filters easily. Geophysical methods for investigation and modeling of subsurface physical properties and conditions are well advanced. Neutron scattering, TDR, X-ray computed tomography, nuclear magnetic resonance, and ground penetrating radar are some of the tools used to investigate soil water content. The best possible diagnostic tool should provide a precise three-dimensional picture of the filter bed showing mud balls, sand stones, biomass, air bubbles and grain size distribution in the filter media without disturbing the filtration process. Ground penetrating radar sounds promising as it is used to

Table 2 | Tools recommended for investigating problems discovered after preliminary review and visual observations of the filter

Visible problems	**Heterogeneous backwash**	**Surface heterogeneity**	**Low particulate removal**	**Low removal of soluble contaminants**	**Filter bed growth**	**Filter bed compaction**	**Short filter run**
Tools recommended	9 & 21. Stick method or hand penetrometer	4. Expansion and backwash flow	4. Expansion and backwash flow	4. Expansion and backwash flow	4. Expansion and backwash flow	4. Expansion and backwash flow	4. Expansion and backwash flow
	10. Excavation	5. Backwash water turbidity	5. Backwash water turbidity	5. Backwash water turbidity	5. Backwash water turbidity	5. Backwash water turbidity	5. Backwash water turbidity
	17. Total dissolved gas probe	6. Flow rate	6. Flow rate	6. Flow rate	9 & 21. Stick method or hand penetrometer	8. Head loss monitoring	7. Turbidity monitoring
		9 & 21. Stick method or hand penetrometer	7. Turbidity monitoring	11–16. Core sampler analysis (mud balls, deposits, sieve, turbidity)	11–16. Core sampler analysis (mud balls, deposits, sieve, turbidity)	9 & 21. Stick method or hand method or hand penetrometer	8. Head loss
		10. Excavation	9 & 21. Stick method or hand penetrometer	20. Ammonia profile and salt tracer	17. Total dissolved gas probe	11–16. Core sampler analysis (mud balls, deposits, sieve, turbidity)	11–16. Core sampler analysis (mud balls, deposits, sieve, turbidity)
		11–16. Core sampler analysis (mud balls, deposits, sieve, turbidity)	11–16. Core sampler analysis (mud balls, deposits, sieve, turbidity)				9 & 21. Stick method or hand method or hand penetrometer
		17. Total dissolved gas probe	19. Salt tracer				17. Total dissolved gas probe

Table 3 | Guideline values for various parameters investigated during filter evaluation gathered from literature

Investigated parameters	Guideline values	References
Unit filter run volume	>400 m^3/m^2	Kawamura (1991)
Filter efficiency	>95%	Kawamura (1991)
Effluent turbidity	<0.5 NTU 95% of the time	US EPA (1998)
Total head loss	<1.8 m	Kawamura (1991)
Expansion during backwash	15–30%	Cleasby (1990)
Backwash water end turbidity	10–15 NTU	Kawamura (1991)
Flow rate increase	3–5% increase per minute	Logsdon *et al.* (2002)
Gravel layer irregularities	<2.5 cm or 1/3 of total height	Nix & Taylor (2003); Beverly (2005)
Volume of mud balls	<1% of core sample	Kawamura (1991)
Media loss	<20% of the original depth	Kawamura (1991)
Filter media grain size	Ratio of filter bed depth to effective grain size <1,000	Nix & Taylor (2003); Lawler & Nason (2006)
Filter media uniformity coefficient	1.4–1.5	Logsdon (2008)
Turbidity depth profile after backwash	30–60 NTU	Kawamura (1991); Nix and Taylor (2003)

investigate the subsurface structure (Davis & Annan 1989). The use of TDR probes and sulfite tracers to monitor air content in the filter bed should also be investigated.

CONCLUSIONS

- Considerable interest is being shown for diagnostic tools which will be necessary for water suppliers who wish to adopt the Water Safety Plans of WHO. These tools can be used by water companies in a proactive manner because they can detect potentially dangerous situations.
- Simple and low level technology tools such as preliminary review, surface observation, backwash observation, expansion and backwash flow investigation, backwash water turbidity investigation, flow rate investigation, and turbidity monitoring are available to evaluate the physical state of filters. They rapidly provide significant qualitative and quantitative information.
- Recommended values, indices or designed criteria are often not documented, and instead rely on the experience of people in the field.
- New tools such as the total dissolved gas probe, salt tracers and ammonium profiles should be used in waterworks where they can provide quantitative information on the state of the filter bed.
- Additional tools could be developed to provide a better insight and easier evaluation of filters. Tools from the soil and groundwater field such as the hand penetrometer, the TDR and the ground penetrating radar should be researched because of the similarity of the applications. Biological and chemical tools should be developed to investigate the microbial communities and the chemical state of filters.
- In order to be able to use most of the diagnostic tools, filter design should provide easy and hygienic access to the surface of filters.

ACKNOWLEDGEMENTS

This study was supported in part by Grontmij and the Urban Water Tech Research School. We are grateful to Nicholas Thomson (Grontmij) for helpful comments. We thank Bent Skov for his design of the core sampler.

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First received 4 August 2011; accepted in revised form 10 February 2012