UPGRADING EXISTING SOUTH AFRICAN FILTRATION PLANTS TO HIGH RATE FILTERS

Report to the
Water Research Commission

by

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Executive Summary

The capital cost of water treatment plants doubled from R1500/m^3 to R3500/m^3 between September 2005 and September 2008. It is anticipated that these costs could increase even further over the next few years, primarily due to the escalation of the price of steel and consequent civil construction costs. It is thus imperative that researchers and practitioners explore the options of minimising the capital costs of treatment plants without compromising public health.

Filtration is one of the most critical unit processes in the treatment process for the removal of microorganisms and other suspended matter, as it is the last physical barrier. Failure of the filtration unit can result in major failure of the whole treatment process, leading to the production of poor water quality. The design or upgrade of the filtration unit process should be kept simple to minimise capital costs. At the same time the efficiency of the filtration process should be optimised to reduce operating and maintenance costs.

There is a drive to increase the filtration rate of the filters to achieve higher filter loading rates in order to delay capital expenditure on new infrastructure. The possibility of upgrading filters to higher filtration rates should always be explored before deciding on adding additional filters to an existing process. The design of filters is based on technical expertise and operating experience. Pilot plant studies to establish the design limits of filters should be undertaken before implementing the upgrade to a high rate filtration plant. This report provides the practising engineer with a guide for the design and operation of pilot plants to establish the design parameters for the full scale upgrade of a water works. It also provides a literature review of the application of high rate filtration in the international arena. A survey of the South Africa filtration industry indicates that there is limited application of the technology which is contributing to the high unit capital costs of water treatment plants. Recommendations for the full scale design and operation are also included in the research report.

Operating filters at a higher rate reduces the capital cost of the construction of new filters or the uprating of existing filters. Engineers responsible for the design of filtration plants in South Africa have been very conservative in the selection of filtration rates, primarily due to the lack of historical water quality data and the short time period that is generally allowed for conceptual design and detailed process selection. These rates can be constrained by good planning which will provide process engineers with the requisite time frames of 3 to 5 years to undertake detailed investigations.

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1. Introduction

A common problem encountered at water treatment works is the need to increase the capacity of the treatment train while avoiding the construction of new facilities such as settling basins, extra single-layer filters, and storage reservoirs (Bablon *et al.*, 1988).

In the early part of the 20th century, slow sand filters, designed for filtration rates of 0.1 to 0.2 m/h, were initially replaced by rapid sand filters that operated at rates of 2.4 to 5.0 m/h and occupied much less space (Sindt et al., 1990). The 5.0 m/h rate became widely accepted in the USA as an upper limit for filtration. However, experience has shown that filters can be operated up to 25 m/h and in some cases higher without deterioration in filtrate quality provided there is adequate pre-treatment (Kawamura, 2001).

High rate filtration results in the least number of filters practicable at a lower capital cost (Nichols *et al.*, 2001) and designers have been moving away from building conventional porous media filters to filters operating at high rates (15-49 m/h), with deeper beds (up to 2.4 m), and coarser media (up to 2-3 mm) (Schneider *et al.*, 1999). The use of higher filtration rates removes some of the conservatism built into the design of conventional filters.

However, Ceronio and Haarhoff (1997) pointed out that a designer can only adopt a high filtration rate on the assurance of optimal pre-treatment. In practice this will require a high level of skill, on-line monitoring and automated chemical dosing systems. In South Africa the inherent difficulties in meeting these requirements has led to conservative filtration rates of less than 10 m/h and filtration rates of around 5 m/h are commonly encountered.

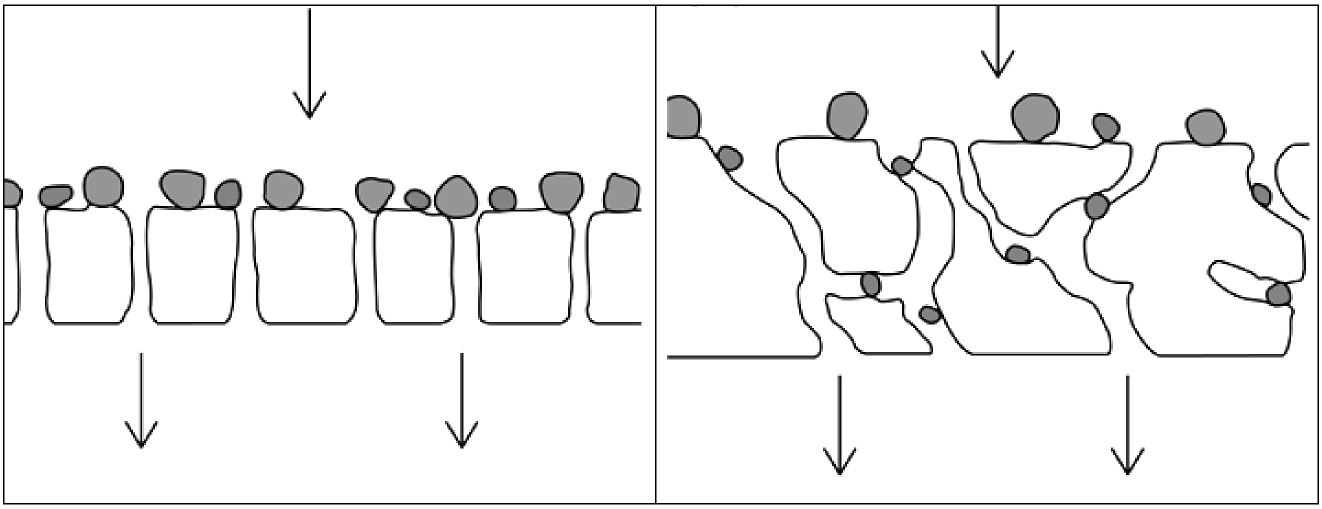
Nonetheless, given the increasing demand for treated drinking water and the financial constraints faced by Water Services Providers, many may be tempted to or should possibly consider the possibility of uprating existing filters or designing new filters specifically for high rate operation. In either case, it is important that both the designers and operating staff understand how both the filter design and operating conditions limit the maximum rate at which a given filter can be safely operated.

2. Literature Review

2.1. Filtration rates used in depth filtration

Filtration processes encompass a range of phenomena in which particles are separated from a fluid phase by attachment to a filter medium. In surface filtration or straining, particles are primarily removed and accumulate in a surface layer directly adjacent to the medium. Membrane processes, cake filtration and slow sand filtration fall into this category. In surface filtration, the pressure drop across the surface layer builds up rapidly as particles accumulate, limiting the rate at which these types of filters can operate. For example, slow sand filters typically operate at rates of less than 0.2 m/h (0.2 m^3/h of flow per m^2 of filter area). Membrane filters and cake filtration processes typically operate at higher rates than the alternatives identified above, but require higher applied pressures to do so.

By contrast, depth filtration utilizes a porous granular medium into which a significant number of particles will penetrate some distance (in the order of tens of centimetres) before depositing out on the surfaces of individual filter grains. As a result, the accumulation of particles within the filter media produces a lower rate of pressure drop increase than it would in surface filtration, allowing the filters to operate at higher rates with lower applied pressures. Conventional rapid filtration and modern high rate filtration used in both drinking water and wastewater treatment fall into this category. The difference between surface filtration and depth filtration is illustrated in Figure 1.



(a) (b)

Figure 1: Surface filtration (a) mainly retains particulate matter from the fluid on the surface of the filter, whereas depth filtration (b) retains particles on the surface and inside the filter.

As discussed in Section 1, rapid sand filters have traditionally been operated at rates of 2.4 to 5.0 m/h with 5.0 m/h becoming widely accepted in the USA as an upper limit for filtration (Sindt et al., 1990). However, over the last several decades, experience has shown that filters can be operated up to 25 m/h and in some cases at higher rates without deterioration in filtrate quality, provided there is adequate pre-treatment and appropriate adjustment to the filter media design (Kawamura, 2001; Nichols *et al.,* 2001). More recently, concerns about the potential breakthrough of pathogens such as *Cryptosporidium* have led to regulatory agencies in the developed world imposing tighter controls on the rates at which any given filtration plant will be permitted to operate.

South Africa does not currently have any regulated upper limit on filtration rate however, conventional gravity filters have typically been designed for rates less than 10 m/h (Haarhoff, 1997), whereas package plant filters, and in particular pressure filters are often designed for and operated at rates of up to 30 m/h.

2.2. Emphasis on pre-treatment

High rate filtration is the last barrier in removing suspended solids including bacteria, viruses, cysts and oocysts of protozoan and parasite eggs. Proper coagulation and flocculation is therefore absolutely essential to produce good filtered water. Filter performance is dictated by filter media selection, filtration rate and the effective use of filter aid polymers (Kawamura, 2001). Without optimal coagulation even the best facilities and operational procedures cannot ensure good filter performance (Bellamy *et al.*, 1993). If the best filtrate quality is desired, no attempt should be made to scrimp on coagulant dosages to save operating costs.

Chemical pre-treatment usually involves the use of metal salts or cationic polymers as primary coagulants. The coagulation process must produce a floc with a constant shear strength and surface properties (Moffett, 1968). Pre-treatment may also include oxidation of soluble forms of iron and manganese, or oxidation for the removal of algae and related taste and odours. The most common pre-treatment is aluminium sulphate (often incorrectly referred to as ‘alum’) flocculation and sedimentation with or without chlorination. For dual-media filters however, aluminium sulphate coagulation with short-time settling or without settling, and a small amount of polyelectrolyte addition just ahead of filtration are common (Kawamura, 1975).

2.2.1. Use of polymers

Filtration rates up to 10 m/h appear reasonable with conventional pre-treatment and alum as the only coagulant. Higher rates require the addition of polymeric filter aids to maintain filtrate quality (Sindt et al., 1990). Robeck *et al.* (1964) compared the performance of pilot filters at 5 to 15 m/h filtering alum coagulated water through single medium and dual media filters. Pre-treatment included the use of activated silica as a flocculant aid and a polyelectrolyte as a filter aid. It was concluded that with proper coagulation, the effluent turbidity and bacterial performance were as good at 15 m/h as at 10 or 5 m/h.

For high-rate filtration, the use of a cationic polymer with alum significantly improves floc settleability and subsequent filterability (Kawamura, 1996) and enables the filter bed to produce filter effluent with a turbidity of less than 0.1 NTU and low particle count, even at filtration rates of 15 to 20 m/h (Kawamura, 2001).

Nichols *et al.* (2001) explain the need for optimal pre-treatment and use of filter aid polymer. Due to the very high loading rates in the filters localised transitional flow conditions (Reynolds Number > 10) will exist in the spaces between the media particles. The turbulent eddies could be responsible for greater hydraulic shear forces on particles attached to the media surfaces, leading to increased particles detachment. During a filter run the media effectively increases in size and turbulence is increased. Hence, it is necessary to increase the efficiency of particle-particle adhesion by the use of a filter aid polymer. Nichols *et al.* (2001) reported that without the use of a filter aid, turbidity and particles rapidly entered the filter effluent (either due to breakthrough or particle detachment) and this occurred even when coagulation was optimized. The polymer apparently prevents a significant loss of particles from the media surface and delaying breakthrough.
The use of filter aids provides the benefit of increased water production and overshadows the increase in head loss gradients in the filter (Nichols *et al.*, 2001) and the additional capital and operational costs to the plant (Schneider *et al.*, 1999).

The prohibition of the use of synthetic polymers for potable water production in Japan has prevented the adoption of high-rate filtration to increase plant capacity in a country where site area is limited. Most Japanese water treatment works therefore operate filters of conventional rapid gravity design in the conservative range of 6 to 7.5 m/h (Kawamura and Trussell, 1991).

2.2.2. Pre-oxidation

The performance of rapid gravity filters operating in the contact filtration mode and employing pre-ozonation was investigated at filter flow rates up to 17 m/h (Chipps *et al.*, unpublished). Chlorophyll *a* and Coulter counter data showed that filtration without chemical dosing removed around 40-50% of algae and other particles between 4 and 80 μm diameter. Iron dosing improved removals to 60%. Ozone dosing on its own resulted in 70-80% removals but combined ozone and iron were required to achieve high quality filtrates with 90% removals.

2.2.3. Sedimentation

Assuming that adequate coagulation is feasible, the need for clarification needs to be assessed. The primary advantage of direct filtration (coagulation, flocculation and filtration only) is the elimination the capital and operating costs associated with clarification. Higher solids load on the filter will however shorten filter run times and increase the amount of product water required for filter washing. Sedimentation is recommended before rapid filtration when the turbidity exceeds 5 NTU (Kawamura, 1975; AWWA Committee Report, 1980). The higher storage capacity of dual- and mixed-media filters has however made filtration of water with higher turbidities practicable. Cleasby *et al*. (1984) argued that direct filtration could be used successfully for low algae concentrations and raw water turbidities of up to 12 NTU using aluminium sulphate only or 16 NTU using cationic polymer only. For high algae concentrations these authors recommended turbidity limits of 7 NTU with alum and 11 NTU with polymer.

2.2.4. Direct filtration

Typical aluminium sulphate doses for direct filtration are 5 to 10 mg/L. These are usually lower than the optimum dose determined by standard jar tests. This is because the goal in direct filtration is to produce small pinpoint floc which are barely visible but filter effectively (Sindt et al., 1990) whereas the goal in jar tests is to produce settleable floc. Kawamura (1975) suggested that proper aluminium sulphate dosing can only be established by pilot-scale studies or actual filter studies with turbidity monitors.

2.3. Design guidelines

The design engineer must document satisfactory performance of high-rate filtration from pilot plant studies before embarking on a full scale plant design (Monk, 1987; Bablon *et al.*, 1988). Pilot filtration plants are generally simple and inexpensive to set up (a column 500 mm in diameter is quite satisfactory). The impact of pre-treatment on the performance of high-rate filters has already been intimated and Kawamura (1975) stresses that the design of pre-treatment facilities should depend on the type of filter selected and these unit processes should not be designed separately. The pre-treatment processes must be designed and operated so that the high-rate filtration process can take advantage of the particle size conditioning. Wiesner *et al.* (1987) warns that when treating raw waters with low concentrations of small particles (<1 μm) at high filtration rates, inadequate consideration of flocculation may result in a filter influent that is more difficult and costly to treat than the un-flocculated water. The conditioned particles must be amenable to depth filtration.

When considering an upgrade to increase water treatment works' capacity the option of high-rate, dual-media filtration is attractive but the choices available are often restricted and complicated. The total depth of the existing filters determines the maximum height and the density of the media because of the expansion that is necessary during backwashing. The energy available for backwash determines the density of the two media comprising the dual-layer filter. The maximum head loss allowed for the dual-layer filters is the same as for the single-layer filters because of the hydraulic constraints of the plant (Bablon *et al.*, 1988).

The magnitude of the flow being filtered and the depth of each filter present a number of unique hydraulic problems that require special attention. There is a need to dissipate the kinetic energy in the inflow to the filter and maintain low velocities of water entering on top of the filter to prevent migration of the medium and control the rates of opening and closing the filter inlet to avoid impacting other filter rate-of-flow controllers (Nichols *et al.*, 2001). Bellamy *et al.* (1993) installed baffles in the filter boxes to deflect and slow the flow of settled water into the filters.

Air-scour backwash is an efficient means of maintaining a clean filter bed but there are a few case histories of significant mud accumulation in the lower part of deep filter beds despite of the use of air scouring wash, especially when polymers are used as coagulant, filter aid or both (Kawamura, 2001). The effectiveness of air scour rapidly decreases with time during an air scour cycle (Haarhoff and Malan, 1983) as most abrasion is caused as the first wave of air breaks through the bed. The bed thereafter compacts and the relative movement of particles decreases until it virtually ceases after 1-2 minutes, with the exception of the top 100 mm of the sand bed. An air scour cycle of longer than three minutes is of little value. Once the physical characteristics of the filter bed are identified, the proper backwash rate should be determined via pilot tests based on the grain size, specific gravity, and the high and low water temperature of the region. The backwash rate for the modern high rate filters in the USA is about 50 m/h at a water temperature of 20 °C (Kawamura, 2001).

Given that depth filtration is predominant, that the media is larger than conventional rapid gravity filters and that the filtration rate is higher, the ripening period is often longer (Monk, 1987). The result is the production of a greater volume of water before stable filter performance is attained. This initial quality problem can be addressed by filtering to waste, employing a slow initial filtration rate, polymer conditioning by filtration aids or the application of a small dose of polymer into the backwash water towards the end of the backwash cycle. The impact of filter ripening must therefore be addressed during the pilot plant test phase and incorporated into the filter design.

In addition to media head loss, hydraulic losses through collection and under drainage systems which may exceed one metre in high-rate dual-media filters must be provided for in the design (Kawamura, 1975). Kawamura (1975) also recommends that the minimum number of filters should be four to allow for shock loads when one unit is taken off line for backwashing. High-rate filters generally employ reverse graded dual- or multi-media beds that allow depth filtration. Bumping a filter already operating at high filtration rate can have a dramatic affect on filtered water quality from the release of entrapped solids.

2.4. Filter Media Selection

Kawamura (1975) summarised the ideal filter media as that of a size, material, and specific gravity so as to retain a maximum quantity of suspended solids, provide a good effluent quality, and be readily cleaned by a minimum amount of wash water. For high-rate filtration the two proven filter beds are standard dual media and coarse deep bed filters (Kawamura, 2001) with the recommendation that a thin (0.25m) sand layer at the bottom to act as a polishing barrier be considered.

The size of filter media affects the filter efficiency, bed use, and head loss development. Larger media has a lower removal efficiency (Moran *et al.*, 1993a; Nichols *et al.*, 2001).

In general, the quality of the filtered water is a function of the surface area of the media and of the pore size between the media grains (Kawamura, 2001). The efficiency with which influent particles are removed by the filter is roughly correlated to the total surface area of the grains.

The total collector surface per unit cross-sectional area of filter may be estimated from Equation 1 (Amirtharajah, 1978).

$$\sum A = \frac{6(1-\varepsilon)}{\psi}\left(\frac{l}{d}\right) \tag{1}$$

Where:

$\sum A$	Collector surface per cross sectional area
ε	Porosity
ψ	Sphericity
l	Bed height, m
d	Average grain size, m

The value of $\sum A$ typically $\cong 2800$ for conventional filters, however, greater bed depths are usually used in direct filtration.

Therefore, a bed of fine sand will tend to have higher removal efficiency than the same volume of coarse sand, since fine grains have a higher specific surface area. Conversely, a bed of coarse sand must be deeper than a bed of fine sand to be able to achieve the same removal efficiency. Kawamura (1975) states however that the use of fine media does not provide a reasonable length of filter run at filtration rates greater than about 7.5 m/h (180 m/day), mainly due to deposition of suspended matter in the top 5 cm of media. This can under certain conditions create negative head and in the upper layers of the filter bed, which is undesirable due to air binding, but also forms a compacted layer of mud-sand mixture at the top of the media. This is likely to contribute to mudball formation in filters without adequate auxiliary backwash.

Various combinations of media depth, l and media size, -d can be used in the design of a filter. Typical values of l and d_e (d_{10}) for various applications are shown in Figure 2 (Kawamura, 1975; Montgomery, 1985). The group of diagonal lines in Figure 2 was established based on a surface area of 2800 m^2 and various porosities that are typical of high rate filters. The *uniformity coefficients* of media in Figure 2.1 were 1.3-1.5. Kawamura (1975) indicates that some investigators have claimed that uniformity coefficients even smaller than 1.3 should be used.

Kawamura (2001) indicates that l / d ratio should differ depending on the filter configuration, application and size of the media used. When the size of the media exceeds 1.5 mm the space between the grains becomes large compared to regular filters and poor filter performance could result.

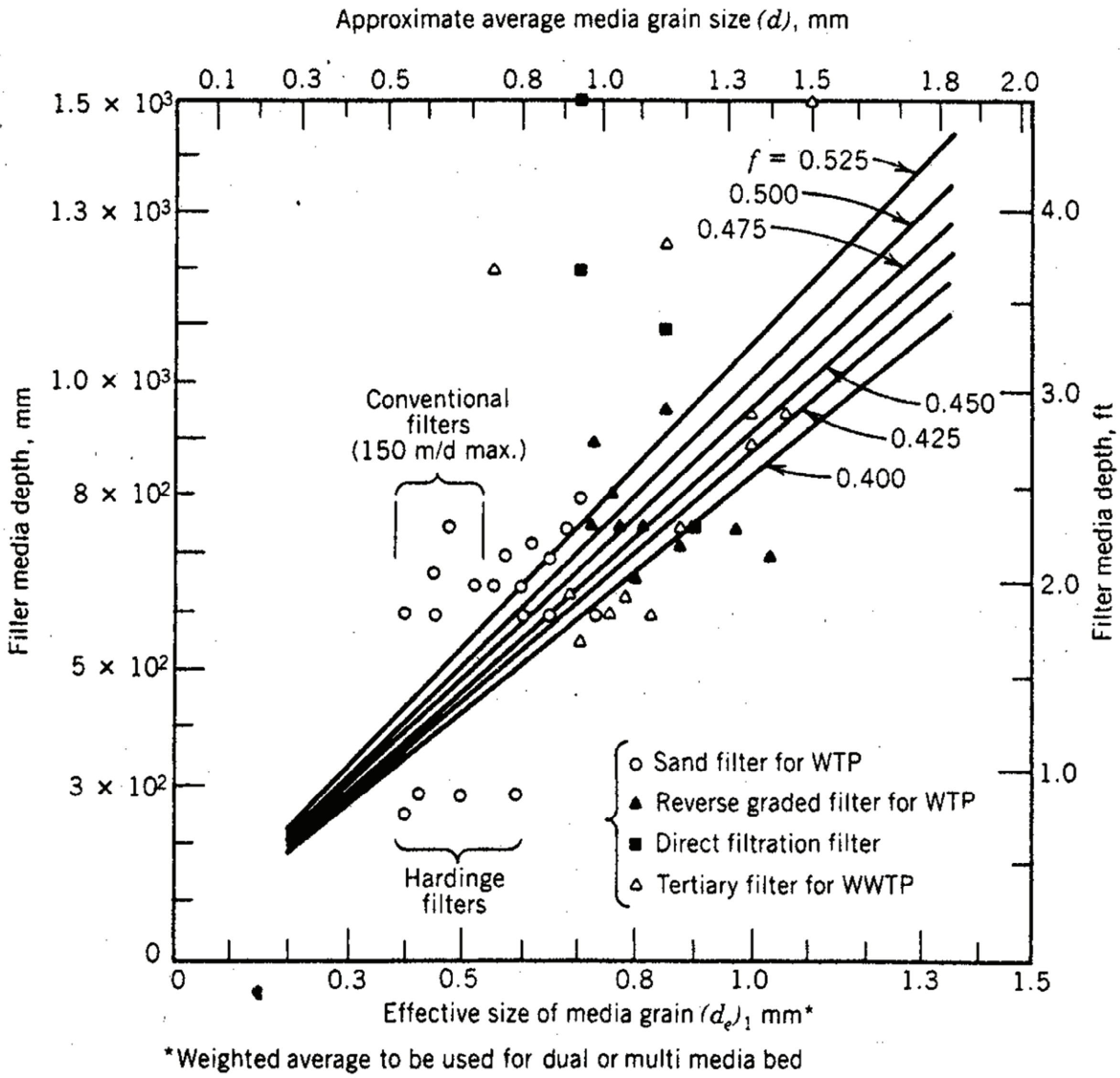


Figure 2: Relationship between depth and size of media (Montgomery 1985).

The general design guides for the ratio of *l* to *d* for filter beds are as follows:

l/d_e	> 1000	for rapid sand filters and basic dual media filters
	= 1250	for regular tri-media filters
	> 1300	for coarse media filters where *d* is 1.2-1.4 mm and *l* is less than 2 m
	>1500	for coarse media where *d* is greater than or equal to 1.5 mm

Bed depth is important to ensure adequate protection for the effluent (Moran *et al.*, 1993a) as particles appear to go through a repetitive process of capture and release.

Smaller uniformity coefficients of less than 1.4 result in slightly better filtrate quality and significantly longer filter run lengths (Kawamura, 2001). Rates of head loss development can be excessive, resulting in short filter runs if a medium with too large a uniformity coefficient is used (Bablon *et al.*, 1988).

The ratio of effective size of media is 2:3 (Bablon *et al.*, 1988) but where GAC and sand is utilized a ratio of between 4 and 5 between the coarsest GAC fraction and the finest sand fraction is to be used since GAC with a low uniformity coefficient is difficult to obtain.

In the case of dual and triple-media filter beds, the size of the media must be carefully matched. The size of grains and the specific gravity of each layer determine the potential loss of media, media mixing during backwash and level of fluidisation during backwash. To ensure that two different types of filter media grains gave the same settling velocity, the relationship described in Equation 2 should exist (Kawamura, 2001):

$$\frac{d_1}{d_2} = \left[\frac{s_2 - 1}{s_1 - 1}\right]^{0.667} \qquad (2)$$

Where d_1, d_2 = 10% passing size for media with specific gravity s_1 and s_2 respectively.

2.5. Filtration Rate

2.5.1. Effect on filtrate quality

Higher filtration velocities result in lower removal efficiencies but this can be offset by greater media depth (Moran *et al.*,1993a). Kau and Lawler (1995) found that equal removal can be expected in filters where the ratio of depths equals the ratio of filtration rates. It was also shown that similar efficiencies of removal can be expected when the ratio of media depth equals the ratio of media diameter. Penetration of particles into the filter bed is greater at higher filtration rates.

2.5.2. Effect of headloss development and water production

Whilst the head loss increases at a faster rate per hour at higher filtration rates, the production volume per unit time also increases (Sindt et al., 1990). Optimisation of filter operation depends therefore on the effect of filtration rate on filtrate quality, net production and costs. The unit filter run volume (UFRV) is the actual throughput of a filter during one filter run. Therefore depending on the volume of water required for backwashing, the net production of the plant can be calculated. (Sindt et al., 1990) indicates that whilst allowing a backwash volume of 4 to 8 m^3/m^2 per wash, the production will remain high provided the unit filter run volume exceeds 200 m^3/m^2 (i.e. 98% production efficiency). According to Kawamura (2001), 98% efficiency or greater reflects good plant performance while less than 95% water recovery indicates room for improvement, even for direct filtration processes.

Kawamura further suggests that the goal for conventional water treatment should be to achieve a unit filter run volume of 600 m^3/m^2, but only 200 m^3/m^2 is expected for direct filtration. A unit filter run volume of 200 m^3/m^2 translates to a filter run time of 42 hours at 5 m/h. Kawamura (1975) indicates that there are diminishing advantages in operating filters at rates higher than 25 m/h because of the frequency of filter washing, the quantity of backwash water required and the need for special supervision, filter aids and filter pre-conditioning (or both) and special consideration needed for the selection of media. The key issue therefore in considering the impact of high filtration rates on production is not the run length, but rather the gross production per run and the filtrate quality.

The greater depth and higher filtration rates resulted in a higher terminal head loss but a larger volume of water could be treated before breakthrough. The rate of head loss development is lower giving longer run times (Kau and Lawler, 1995).

During an investigation on the effect of filtration rate and filter depth on water production Nichols *et al.* (2001) increased the filtration rate on a DAF/Filtration train from 20 m/h to 30 m/h. The water production increased by 8-16%. However when the train was operated at higher filtration rates of 30 m/h and 40 m/h the water production through the filters decreased, indicating an optimum filtration rate of 30m/h existed for this system. The deeper filters (2.4 m) had somewhat higher water production (8-13%) than the shallower filters (1.8 m). Design engineers must therefore be aware of diminishing returns that can be obtained from increases in filtration rates (Kawamura, 1975). The optimum filtration rate is that which maximises net production without compromising on water quality targets.

2.6. Insight into Filter Breakthrough

Stricter potable water quality requirements have made an effluent turbidity of less than 0.1 NTU an accepted goal in many plants around the world. In meeting this goal filters are washed regardless of the magnitude of head loss when turbidity starts to break through the filter bed (Kawamura, 1975). In fact breakthrough often occurs long before terminal head loss occurs. Kawamura reports that breakthrough quite often starts when the headloss reaches about 1.2 m, but the turbidity only exceeds 1 NTU after about 2 m headloss. The fact that early breakthrough is hardly noticed depends on strict pre-treatment control. In the absence of good control, in some instances breakthrough can occur with less than 1 m headloss. Kawamura points out that breakthrough can occur at any time regardless of headloss because of (1) poor coagulation control and (2) hydraulic shocks. It was concluded that both conventional and reverse graded dual-media filters have a tendency toward turbidity breakthrough when headloss exceeds 1.3 m and many dual-media filtration plants set the terminal headloss in the vicinity of 1.5 m or within 48 hr of filter run, whichever comes first.

Floc particles attached to the filter media appear to undergo a process of detachment and subsequent reattachment in the lower sections of the filter (Moran *et al.*, 1993b) and during filter breakthrough there is an apparent preferential detachment of particles in the range of 3-20 µm, a size range within which *Cryptosporidium* oocysts and *Giardia* cysts fall. It is unclear, however, whether these particles came into the filter at that size or if they came into the filter as much as smaller particles, formed flocs on the surface of the media, and detached as flocs. The latter argument seems probable since Mackie and Bai (1992) had already established that the size distribution of a suspension changes with depth and time. Thus at any one time different parts of the filter are treating different suspensions and the suspension treated at any one depth will change with time. The size distribution of a suspension may affect the performance of a filter in terms of removal efficiency, headloss and breakthrough.

A step decrease in the influent concentration allowed direct investigation of detachment of previously retained particles and flocs (Moran *et al.*, 1993b) and concluded that detachment of previously retained particles or flocs is perhaps the dominant factor contributing to filter breakthrough; this was later supported by Kau and Lawler (1995).

2.7. Process Monitoring

The high hydraulic loading rates and reduced retention times utilized in modern water treatment plant clarification and filtration processes leave little margin for error in the event of an operational error or equipment failure that could lead to water quality failure (Nichols *et al.*, 2001).

Bellamy *et al.* (1993) recommended that each filter be equipped with a continuous monitoring turbidimeter, using turbidity as a surrogate for removal of cyst-sized particles. However particle size data reveal a relatively earlier breakthrough of particles in the 3-7 µm size range, which was not detectable from turbidity or suspended solids data (Moran *et al.*, 1993a; Schneider *et al.*, 1999).

Moran *et al.* (1993a) were unable to conclude that the use of particle counting techniques in monitoring for the removal of *Giardia*- and *Cryptosporidium*-sized particles would be accurate. Additional investigation of floc break-off is required to gain insight into the relationship between size distribution of particles in the filter feed and effluent. It is however clear that particle counting may be used as an indicator of filter performance, the trend being more important than the absolute value of the particle counts.

Additionally, Schneider *et al.* (1999) reported a 21% loss in production when the particle count endpoint criterion was used to determine a run length, instead of turbidity. Thus, the difference between the two endpoint criteria is of significant economic consideration.

The use of media interface turbidity monitoring is suggested by Kawamura (1975) as it will show signs of breakthrough before it actually takes place. The same principle can be applied to on-line particle counting and is likened to techniques used for breakthrough detection on ion exchange applications.

2.8. Options for Treatment Plants in Developing Communities

Most filtration plants in the developing world use sand as the filter media (Schulze and Okun, 1984). However, conversion to dual media can allow substantial increases in filtration rate (10 to 15 m/h) without sacrificing run time or filtrate quality. Dual media filters traditionally use sand as the fine layer and anthracite coal as the coarse layer, however, other types of non-conventional filter media made from indigenous materials have been tested in various parts of the world.

Unconventional coarse media including indigenous coals, crushed coconut shells, pea gravel, berry seeds and kernels from stone fruits such as apricots have all been found to be suitable for use in dual media filters. Crushed stone prepared from stone dust, a waste product of quarries using stone crushers, has been found to be a suitable alternative to conventional sand as a fine filter media (Rao, 1981).

2.9. Conclusions

Whilst it may seem expensive to use a filter aid polymer or a higher coagulant dose, to backwash a filter for a longer time or more frequently, to always wash a filter before it is returned to service, or to install continuous turbidimeters; these expenses are minor compared with those associated with an outbreak of waterborne disease. In the field of public health, providing effective prevention is a better alternative than bringing about a cure. This review highlights the following issues critical to the design, operation and monitoring of high-rate filters to ensure this goal of preventing public health incidents:

- Optimal coagulation is essential to ensure good filter performance and must produce a floc with a constant shear strength and surface properties.
- The use of pre-ozonation together with coagulation improves filter removal efficiency and there appears to be a synergistic effect.
- There is a need for the use of filter aid polymers to counter the higher turbulence shear forces within the filter bed to delay breakthrough. Restrictions on the use of a filter aid polymer (as in certain countries) will prevent the adoption of high-rate filtration.

- As part of the design of high-rate filters, pilot plant testing is essential to assess filtered water quality, media selection, backwash requirements, filter ripening pre-treatment requirements for depth filtration and clean bed and terminal head loss.
- Upgrade of existing filters to high-rate filters can be complicated by the available head, position of wash water troughs, depth of filter box, energy available for backwash.
- The velocity of water entering on top of the filter must be kept low to prevent media migration and scouring.
- The minimum number of filters should be four to allow for shock loads when one unit is taken off line for backwashing or maintenance.
- Larger media has lower removal efficiency.
- Bed depth is important to ensure adequate protection for the effluent.
- Smaller uniformity coefficients of less than 1.4 result in slightly better filtrate quality and significantly longer filter run lengths.
- The ratio of effective size of media should be 2:3.
- In the case of dual and triple-media filter beds, the size of the media must be carefully matched such that they have the same settling velocity
- Similar removal efficiencies can be expected when the ratio of depths equals the ratio of filtration rates or when the ratio of media depth equals the ratio of media diameter.
- Design engineers must be aware of diminishing returns that can be obtained from increases in filtration rates.
- Filter breakthrough often occurs before terminal head loss.
- Floc particles attached to the filter media appear to undergo a process of detachment and subsequent reattachment in the lower sections of the filter.
- There is an apparent preferential detachment of particles in the range of 3-20 µm, a size range within which *Cryptosporidium* oocysts and *Giardia* cysts fall, but it is likely that these particles came into the filter as much as smaller particles, formed flocs on the surface of the media, and detached as larger flocs.
- Detachment of previously retained particles or flocs is perhaps the dominant factor contributing to filter breakthrough.
- Whilst online monitoring of individual filters is regarded as essential, it is still unclear as to whether turbidity or particle counting or both should be employed. Turbidity monitoring when compared to particle counting appears insensitive to particle breakthrough. But there is no conclusive proof that particle counting can be used as a surrogate for pathogen removal. In fact using particle counting as a run length endpoint criterion results in significant production loss due to the earlier particle breakthrough.
- Media interface turbidity or particle counting can be considered as it will show signs of breakthrough before it actually takes place.
- High rate filtration requires the process to be monitored 24 hours per day or automated monitoring / control to be in place. Skilled operators would be required to operate such plants.

3. Survey of South African filtration plants

3.1. Survey objectives

A survey of treatment plants in South Africa was conducted to determine whether any of the plants could be classified as High Rate Filtration Plants. Of the 118 questionnaires sent out to various water treatment facilities in South Africa, 27 were completed and returned.

3.2. Methodology

An existing database of treatment plants in South Africa (Swartz, 2000) was consulted to identify plants for the survey. A ten-page survey form was designed and posted to the selected plant managers. The returned forms were then reviewed to determine plants that needed more detailed investigation and where necessary, these plants were followed up with a site visit. An example of a completed form for the Biggasberg Water Works is shown in Table 1.

3.3. Data analysis

None of the plants surveyed used filter aids, as is common practice at American and French plants. Chemical pre-treatment is a critical unit process and the survey indicates that the plants are not optimised in terms of coagulation and flocculation. South African plants are also using polymeric coagulants as primary coagulants as opposed to using inorganic coagulants which can have better solids removal efficiencies.

The plants also rely on streaming current monitors for coagulant dose control. The system works well, however it has unfortunately generated a false sense of security for the process controllers, who in some cases are not capable of conducting jar tests for optimisation of coagulation.

Due to the high filtration rates, process controllers would need to implement faster response procedures for changes in raw water quality and it we would thus recommend that only impounded water be used as a source for high rate filtration.

3.4. Conclusions

The results indicated that only the following facilities were operating their filters above 5 m/h:

- Bethlehem 8-10 m/h
- Ladysmith 5-7 m/h
- Craigieburn 6-8 m/h
- Mtwalume 6-8 m/h
- Durban Water Recycling Plant 8-10 m/h

South African plants can be operated at higher filtration rates, however a major shortcoming would be the lack of trained process controllers to manage the treatment process which would require faster response times. Pre-treatment is a pre-requisite for the conversion to high rate filtration. It is recommended that plants convert to the use of inorganic coagulants to ensure higher removal of colloidal particles.

In terms of operation, jar tests for coagulant optimisation would need to be performed on a daily basis as opposed to the current monthly frequency. Process controllers with an M+2 (2 year post matric) technical qualification would be required to operate high rate filtration plants.

Table 1: Completed survey form – Biggasberg Water Works.

<table>
<tr><th colspan="3">GENERAL WORKS INFORMATION</th></tr>
<tr><td>Name of plant:</td><td colspan="2">Biggasberg
Uthukela / Umzinyathi</td></tr>
<tr><td>Owner:</td><td colspan="2"></td></tr>
<tr><td>Location:</td><td colspan="2">Dundee</td></tr>
<tr><td>Population served:</td><td colspan="2"></td></tr>
<tr><td>Shift coverage:</td><td colspan="2">4 operators + 4 assistants
(3 × 8 hr shifts per day, one operator per shift)</td></tr>
<tr><td>Operations staff training levels:</td><td colspan="2">Process Manager – DWAF, class 4
Operators – DWAF, class 3</td></tr>
<tr><td>Date of commissioning:
Previous upgrades, refurbishments:
Planned future expansions:</td><td colspan="2"></td></tr>
<tr><td colspan="3">RAW WATER</td></tr>
<tr><td>Raw water source:</td><td colspan="2">Buffels River (90% abstraction)
Upper Mpati Dam
Tom Wittington Dam
Verduk Dam</td></tr>
<tr><td>Raw water quality:
Winter
Summer
Time of visit (probably end of dry season
1-17 September 2002</td><td colspan="2">No temperature data given
21-86 NTU,
pH 7.71-9.09</td></tr>
<tr><td colspan="3">TREATMENT TRAIN</td></tr>
<tr><td colspan="3">Abstraction → cascade aeration → header dam → coagulation and pH adjustment, backwash return to rapid mixer → pre-chlorination→ settling→ rapid gravity filtration → post-chlorination → storage</td></tr>
<tr><td colspan="3">CAPACITY</td></tr>
<tr><td></td><td>Plant Flowrate</td><td>Filtration Rate</td></tr>
<tr><td>Design flow (average)
Design flow (maximum)
Current flow

Maximum flow (at which plant has been operated at)</td><td>15 ML/d

average 11 ML/d
range 8-12 ML/d
12 ML/d</td><td>2.8 m/h

2.1 m/h
1.5-2.3 m/h
2.3 m/h</td></tr>
</table>

Table 1: Completed survey form – Biggasberg Water Works, continued.

FILTER DESIGN AND OPERATION		
FILTER TYPE AND AREA		
Type Number Area per filter	Old – no brand 4 3.05 × 4.72 = 14.4 m^2	
Type Number Area per filter	Moore 4 8.16 × 5 = 40.8 m^2	
INSTALLATION, UPGRADES AND REFURBISHMENT		
Designer/supplier/contractor	Swans/V3 Consulting	
Future expansions/upgrades		
FILTER MEDIA		
Type Media size Media depth	Sand Samples for analysis Not available	
FILTER UNDERDRAIN		
RATE CONTROL		
Old – influent splitting, constant rate, variable level, effluent weir above bed surface Moore – constant rate, constant level, clack valves on inlet, level sensor + control valve on effluent		
HYDRAULICS		
 Design filtration rate Current maximum rate Current average rate Available head Hydraulic maximum filtration rate	Old Filters 2.8 m/h 2.3 m/h 2.1 m/h ~2 m	*Comments* Plant flow/total area Water level builds up above filter Need media size and depth to estimate
 Design filtration rate Current maximum rate Current average rate Available head Water level above media Hydraulic maximum filtration rate	Moore Filters 2.8 m/h 2.3 m/h 2.1 m/h < 0.35 m	*Comments* Plant flow/total area Need elevation of effluent discharge Will be very susceptible to air binding
FILTER RUN TIME		
Criteria for initiating backwash Typical run times Backwash water% of total production		
FILTER BACKWASH		
Old – Sequential air and water – calculate rates from pump curves Moore – Sequential air and water – calculate rates from pump curves Semi – Automatic backwash rate control		
FILTER START-UP		
Filter-to-waste Slow-start Polymers in backwash	No No No	*Comments*
FILTER AID		
Filter aid addition Minimum number of dosing points	No 3	*Comments*
MONITORING AND CONTROL		
PLANT OPERATING STRATEGY		

Table 1: Completed survey form – Biggasberg Water Works, continued.

FILTER DESIGN AND OPERATION		
Plant manager sets major process control strategies Management meetings – quarterly Operators make process control decisions Performance goals		
ON-LINE MONITORING CONTROL		
Variable	*Monitored*	*Controlled*
FLOW MEASUREMENT AND CONTROL		
Flow streams measured	Raw water Finished water (1 for each of 5 reservoirs) Backwash recycle	
COAGULATION MONITORING AND CONTROL		
Primary coagulant Sudfloc 3870 6-20 mg/L Alum or lime as required for pH control PAC – slug dose if required Manual dosing control There is a streaming current detector (Lechintech) but it is apparently not used because the optimal set point various a lot due to switch raw water sources – check Turbidity monitoring on filters and clarifiers pH monitoring (manual) – raw, settled, final – pH control of final water. Control point is settled water Jar and cascade tests – Jar test frequency? Best settled water turbidity?		
FILTER MONITORING AND CONTROL		
Parameter	*Frequency*	*Strategy / Comments*
Influent turbidity Effluent turbidity	Every 2 hours. Alternate odd and even every two hours.	Samples from each clarifier, i.e. every 4 hours for any given filter.
Influent pH	Same as turbidity.	
Effluent pH	Not measured.	pH of final water only, i.e. after chlorination.
Headloss	Not recorded.	Moore filters appear to have headloss indicators in control panels. Headloss in Old Filters can be determined from water level.
Length of run	Not recorded.	
Flow to individual filters	Not measured.	
PLANT PERFORMANCE		
Clarified water turbidity Filtrate turbidity Finished water free chlorine residual Finished water pH	*1-17 September 2002* info off logsheets	
FILTER PROBLEMS OBSERVED DURING SITE VISIT OR REPORTED BY OPERATIONS		
OTHER PROBLEMS		
FACTORS LIMITING MAXIMUM FILTRATION RATE (in order of decreasing importance)		
	Comments	*Possible corrective action*

Table 1: Completed survey form – Biggasberg Water Works, continued.

FILTER DESIGN AND OPERATION		
Moore filters – very low water above media	Susceptible to air binding. Not an issue for Old Filters. Current filtration rates very conservative by international standards for rapid filtration. Could possibly double rate in Old Filters.	
Plant design capacity	Need to look at maximum flows in pipes and channels.	
Abstraction from river – rapid variations in raw water quality, plus low sampling frequency and manual coagulation control.	The header dam acts as an equalisation tank but capacity unknown and must be silting up.	Increase sampling frequency. On-line instrumentation.
OTHER ISSUES		
MAINTENANCE		
Item	*Frequency*	*Comments*
Flow meters	Breakdown	Calibration
General	Breakdown	No routine maintenance schedule
Emergency maintenance program	None. Operators contact maintenance directly	
Work area	Workshop available	
Spare parts inventory	None – buy on demand	
Outside support	Uthekela	
DOCUMENTATION		
Maintenance and operations manual	None	
Documentation of work complete	Job card	
STANDBY EQUIPMENT		
All pumps and dosing equipment		
Alternate power supply – Diesel generator		
ADEQUACY OF DISINFECTION		
Retention time	Get reservoir volumes	
Monitoring	Free chlorine residual in reservoirs, DPD 1, every 2 hours	
Control	Manual, flow proportioning available but not used	
Problems observed or reported	None	
Alarms	Chlorine leak only	

Comments on filling out forms:
Maintenance – increasing rates require faster response to problems.
Pre-emptive maintenance is advisable.
Adequacy of disinfection – if poor disinfection, filtrate rates should be more conservative.

4. Pilot plant design and operation

4.1. Introduction

The objectives of conducting the pilot plant studies were as follows:

- To determine the effect of filtration rate and media size on filtrate quality
- To determine the effect of filtration rate and media size on
  - Rate of headloss development
  - Determine evidence of air binding
  - Turbidity breakthrough
  - Determine maximum practical operating rate

A pilot plant was constructed and initially installed at the Durban Heights Water Treatment Works in order to test the effect of increasing filtration rate on filter performance as well as to experiment with different media designs. The pilot plant was later moved to a second operational site, viz. Craigieburn Water Works to evaluate high rate filtration using river water as a source.

4.1.1. Pilot Plant Design

The optimum dimensions of the pilot filters depend on the size of the media used. Since higher filtration rates mean higher headlosses and rates of headloss development, coarser media sizes are typically used to ensure reasonable filter run lengths and water recoveries. The Durban Heights and Craigieburn plants employ sand with an effective size of 0.8-1 mm. The pilot plant was designed to use media sizes ranging between 0.8 and 3.5 mm.

The minimum recommended filter diameter, D, is:

$$D = 50 \times d \qquad (3)$$

Where d is the media size.

Twenty-five percent of the filter area is influenced by wall effects at this minimum diameter. If the maximum media size to be evaluated is 2 mm then the minimum filter diameter which should be used is 100 mm.

The pilot filter diameter was however also constrained by the desired filter nozzle density. The nozzle density in a pilot filter should ideally be the same as in the full scale filter it is intended to simulate. South African designers usually specify a nozzle density of 50 per m^2 for filter design. One filter nozzle in cylindrical filter column of diameter 150 mm corresponds to a nozzle density of 56.6 per m^2 which is close enough to the recommendation. The pilot filter diameter was therefore specified as 150 mm.

The recommended depth of filter media depends on the media size as larger media grains have less collector area per unit volume bed than smaller grains. According to Kawamura (1991), the relationship between bed depth, *l*, and effective media size should be as shown in Table 2:

Table 2: Relationship between filter depth and media size (Kawamura, 1991).

Bed depth, *l*	**Effective media size, *d***
$l \geq 1000d$	$d < 1.0$ mm
$l \geq 1250d$	1.0 mm $< d < 1.5$ mm
$l \geq 1250d - 1500d$	1.5 mm $< d < 2.0$ mm

In practice this will limit the maximum sand size which can be used in an existing filter. However, the pilot filters have been designed to accommodate the deepest filter bed of interest.

Ideally the height of the backwash trough and filter influent in the pilot filter should be identical to the full scale filter. However, if different media sizes and bed depths are to be considered, then the required height of pilot filter will depend on the maximum filter bed depth during backwashing. The backwash trough should be located at least 0.5 m above the surface of the bed to avoid media losses.

Combined air and water wash is recommended for high rate deep bed filtration to ensure maximum cleaning efficiency throughout the bed. Typical backwash rates for combined air and water backwash are given in Table 3 below:

Table 3: Typical backwash rates for 1-2 mm media.

Backwash type	**Typical range of rates** ($m^3/m^2/h$)
Air	37-73
Water	15-18
Water only rinse	15-36

The filter bed tends to contract during combined air and water wash while the rinse water rates are below the minimum fluidisation velocities of the media. Negative wall effects from bed expansion was thus neglected during backwashing as they would be negligible

Minimum distance from filter floor to backwash trough = fixed bed height (*l*) + 0.5 m

For a 2 mm effective size sand bed the total required height to the backwash pipe could be 3.5 m whereas for 0.8 mm sand it might only be 1.3 m. Furthermore, in some filters, the filter pipe or channel is below the backwash trough whereas in other filters, including those at Durban Heights, the backwash troughs are above the influent.

4.1.2. Filter Column Construction

The pilot filters were constructed in 0.5 m long flanged segments which were bolted together to achieve the desired filter height for various media designs. One segment per filter column was modified to include the influent pipe and backwash trough and another segment was modified to form the underdrain. For example, the pilot filter for a 0.8 m bed of 0.8 mm sand was constructed from four segments (including the top and the underdrain) whereas the filter column for a 2.5 m bed of 2 mm sand consisted of eight segments in total. The pilot filter floors consist of a PVC plate with a single filter nozzle screwed into the middle. The filter nozzle is the same type as that used in the Durban Heights filters. The lowest segment of the filter is fitted with a 63 mm flange through which the filter media can be removed.

4.1.3. Rate and Level Control

The pilot plant is currently installed in the lower chamber of the sand filters. Influent for the filters is drawn from the clarified water channel / filter influent channel 2.5 to 3.5 m above the operating level of the pilot filters. A siphon is employed to transport water from the clarified water channel into a constant level tank. It has proven nearly impossible to maintain a reasonably constant flow through the siphon due to the accumulation of gas bubbles in the line. This problem has been overcome by reducing the pipe diameter to increase the velocities in the pipe and hence reduce chances of gas accumulation.

Maintaining a constant water level in the filter columns proved to be a problem and the design was modified to operate as constant rate filter with influent rate controller. And constant water level. The constant level tank was designed to be flexible enough to allow the filter to operate at different outlet water levels. The constant level tank has an overflow facility allowing excess water to be discharged to waste. Despite these modifications, there was still a tendency for gas to accumulate in the lines feeding the filters from the constant level tanks. In some cases, this has led to a drop in operating level of the filters, which complicated the interpretation of the results.

Filter influent flows directly from the filter influent channel of the water treatment plant into the pilot filters, through a constant level holding tank. The filtration rate strategy employed on this investigation was the downstream control system. Since it was desired to maintain a constant filtration rate, a means to dissipate a large amount of headloss at the beginning of the filter run, decreasing as the run progresses was to be established. This was achieved by the installation of a needle float valve.

The filtration rate for each pilot filter was controlled using a simple flow rate control device shown in Figure . The filtrate pipe discharges into a small tank at a rate controlled by a float needle valve. Water flows out of the tank at a constant rate manually set using the manually controlled outlet valve at the beginning of the filter run. A needle valve is used on the outlet to allow the flow to be accurately set.

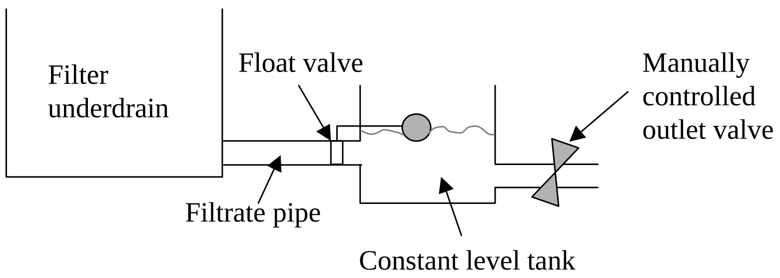


Figure 3: Filtration rate controller.

The manually controlled outlet valve is the valve used to set the desired experimental filtration rate. The float needle valve is employed to ensure constant flow leaving the filter columns. At the beginning of the filter run the float needle valve is almost closed due to the high level in the constant level tank. However, as the run progresses the filter clog's up and the water level drops in the holding tank. To ensure constant outflow the float needle valve drops thereby allowing headloss to be moved across to the filter bed. Terminal headloss is reached when the float needle valve is completely open.

A magnetic flow meter was employed to measure the flow rate of water into the columns. Water flows from the constant level holding tank, in which the siphon discharges, into the filter columns.

The filtration rate for each pilot filter was controlled using a simple flow rate control device shown above under the Rate Control Strategy section. The filtrate collects in the under drainpipe and discharges into a small constant level tank at a rate controlled by a float needle valve. Water flows out of the constant level tank at a constant rate manually set, using the effluent valve, at the beginning of the filter run. A needle valve is used on the outlet to allow the flow to be accurately set.

4.2. Instrumentation

4.2.1. Flow measurement

A magnetic flow meter was employed for the measurement of the flow into the filter columns. Each column had its own magnetic flow meter which was set to display the flow is l/sec and the accumulated volume in litres, through the flow meter. For each filter run an account of how much water was charged into the column could be obtained which simplified the water balance across the plant. This also helps in displaying the amount of filtered water relative to the filtration rate. A calibration curve of the flow in l/sec and the voltage displayed on the data logger was developed and improved upon every time a new run was carried out.

4.2.2. Headloss measurement

Headloss development is measured by using manometer tubes located along the length of the filter column. The total headloss across the filter bed is measured by a differential pressure cell, connected to the manometer ports located along the length of the filter bed. The manometer ports used for the differential pressure cell are the first port located above the sand bed, which gives an indication of the headloss available, and the last port located at the underdrain.

The spacing between the manometer ports is 5 cm. For the course media (1.4 and 1.7 mm) bed filter the spacing is 10 cm. The first manometer is above the filter bed and the last port is at the bottom of the column below the filter nozzle. The difference between the port above the filter bed and the port below the filter nozzle gives the total headloss across the filter bed. The calibration of the differential pressure cell is carried out by making use of the available piezometer board connected to the manometer ports. The difference in the manometer ports is related to the voltage displayed by the data logger. This implies that for every difference in height between the ports a different voltage will be displayed by the data logger.

4.2.3. On-line turbidity measurement

An on-line turbidity meter is employed throughout the experiment to record the filtrate turbidity. A submersible pump placed in the bottom constant level tank feeds the on-line turbidity meter. The meter is connected to a data logger which records output from the meter at five-minute intervals. Optimum operation of the online meter is maintained by regular calibration of the meter using the Formazin standard and the calibration kit as per manufacturer’s instructions. A calibration curve has been developed that relates the turbidity output reading to the voltage reading displayed by the data logger.

4.2.4. Data logger

The data collected throughout the operation of the pilot plant was recorded via Rustrak Scout data logger. It has four channels that operate in a voltage range of zero (0)-10 volts using direct current. A 250-ohm resistor is connected across the outputs of the instruments to covert the current signal to a voltage output for data logging purposes. A calibration curve was developed for each instrument connected to the data logger to convert the signal to the required engineering units of the instrument, e.g. for DP cell the voltage is related to the mmH_2O or Pa.

4.2.5. Pilot plant flowrates and pumping requirements

For the 0.15 m diameter pilot filters, the volumetric flowrates during filtration are tabulated in Table . The auxiliary pipe work valves and fittings were sized to accommodate the above range of flowrates. The four pilot filters share a common backwash pump and compressor. The backwash flowrates are manually controlled. The design air and water flowrates are tabulated in Table 5. The details of the plant's construction are given in Table 6.

Table 4: Volumetric filtration rates versus filtration velocity for 0.15 m column.

Filtration rate (m/h)	Flowrate (l/hr)
5	88
10	177
15	265
20	353
25	442
30	530

Table 5: Summary of pilot plant design.

Air	650-1300 standard l/h
Water	270-650 l/h

4.3. Commissioning and trouble shooting

Two sand filter pilot plant columns were installed at the Durban Heights Water treatment works. The pilot plant was situated about 5 metres below the full scale clarifiers, feeding the pilot filters, to avoid pumping clarified water into the sand filter columns. A schematic flow diagram is presented in Figure 4.

4.3.1. Gas accumulation in the influent line

Throughout the commissioning phase, the gas accumulation in the influent line gave rise to a number of operational problems. It was observed that gas was accumulating in the lines as the filter run progressed and was reducing the inflow rate. Increasing the velocity in the inflow pipe by reducing its diameter resulted in reduced air accumulation and improved filter control.

4.3.2. Installation of movable constant level holding tank

Maintaining the water level above the sand was another challenge that was encountered during commissioning. The water level was observed to be greatly influenced by the initial filtration rate employed. It was observed that a ramping upon the flow rate gradually resulted in stable operation.

Table 6: Pilot plant construction details.

Details of construction	
Number of filter columns	4
Filter assembly	Each filter column consists of a number of 0.5 m long flanged segments bolted together
Material of construction	Clear PVC
Filter diameter	0.15 m
Maximum number of segments per filter including underdrain and top of filter column	10
Segments	
Standard	2 manometer ports
Underdrain	Filtrate pipe Air and water backwash pipes
Base of sand bed	Flanged pipe for media removal 9 manometer ports
Top of sand bed	Filter influent channel
Top of filter	Backwash trough
Plant capacity	
Flowrates during filtration	90-530 l/h per filter
Air scour	650-1300 standard l/h
Backwash water rates	270-650 l/h
Filter rate control	Constant level tank and float valve on filtrate line
Media	
Effective sand sizes 0.8-2.0 mm	Uniformity coefficient < 1.5

4.3.3. Filtered water outlet pipes

Reducing the pipe diameter on the influent line reduced gas accumulation; however there was still evidence of accumulated gas in the filtered water. A clear flexible hose pipes was used to assist with visual detection of the air. Regular flushing of the trapped air improved the filter run length.

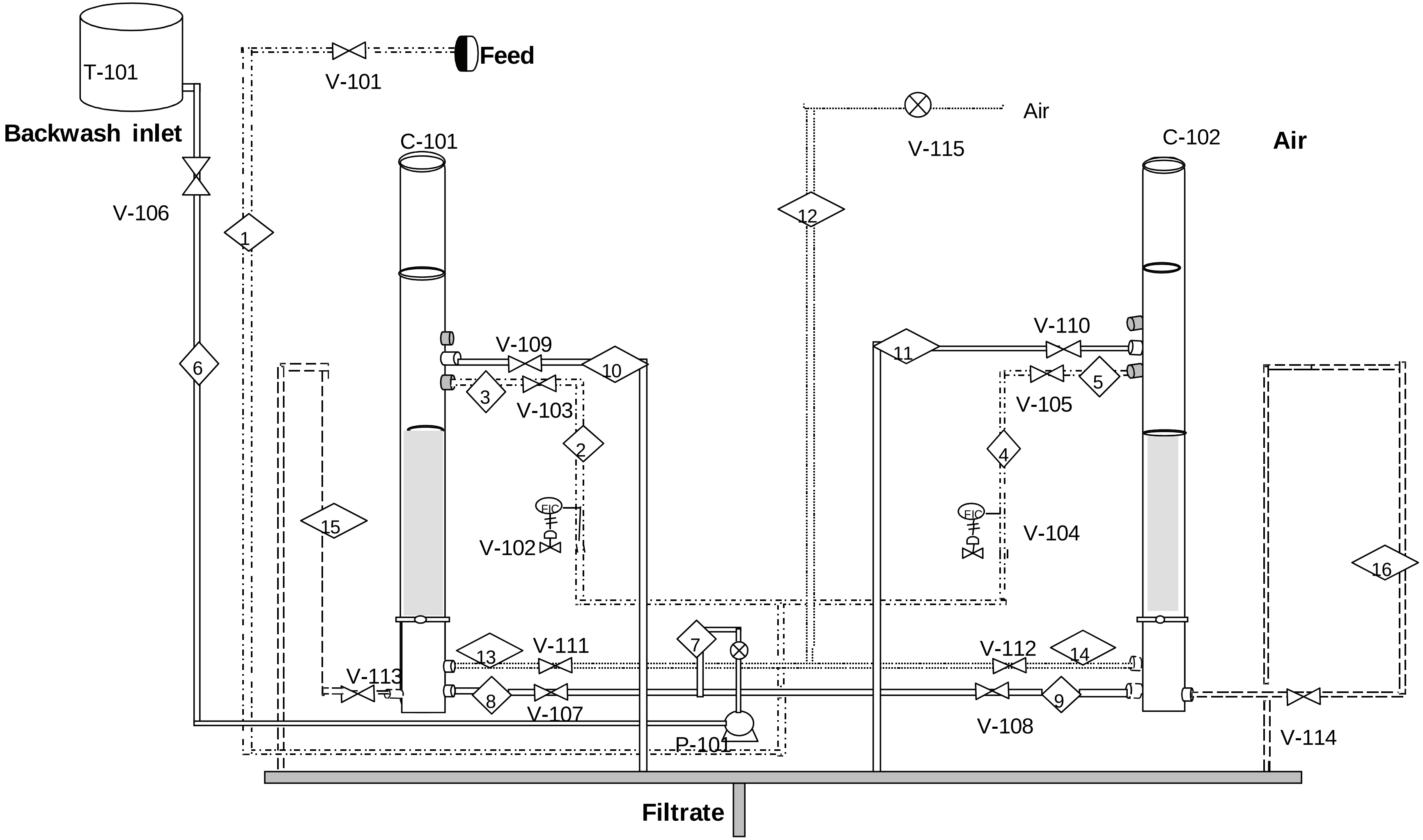


Figure 4: Schematic representation of the sand filter pilot plant.

5. Pilot plant study methodology

5.1. Objectives

- To determine the effect of filtration rate and media size on filtrate quality
- To determine the effect of filtration rate and media size on
- Rate of headloss development
- Determine evidence of air binding
- Turbidity breakthrough
- Determine maximum practical operating rate

5.2. Data analysis and modelling: headloss development

Models were developed to try and predict the volume of filtered water that could be achieved before terminal headloss for the various filter sand sizes and filter loading rates. Attempts were also made to extrapolate the results to terminal headloss or negative head development even if not actually reached. Extrapolation is easy for linear headloss development but was difficult for non-linear headloss development, especially when due to air binding.

Attempts were also made to determine the effect of filtration rate, media size, water level and influent conditions on volume filtered to terminal headloss.

A large data set was collected for the different media sizes and filter loading rates. The following results are a summary of some of the successful runs that were achieved. It should be noted that some runs were terminated due to operational problems and power failures.

5.3. Predicting headloss development for different bed depths

Figure shows the typical pressure drop that was achieved across the filters with increasing filter run time depicting an increase in head loss across the filter as the particles are removed from water and accumulate in the filter bed.

Figure 6 shows the relationship between the total head measured by the differential pressure probe and the piezometric headloss at various depths along the length of the filter bed (from point A at the top of the filter to point J at the bottom of the filter). It is clearly evident from the graph that as the total head loss across the bed increases, so too does the head loss at various points along the length of the filter bed. The general trends from the head loss profiles across the filter column indicate that the pressure loss increases incrementally with increasing depth along the length of the filter bed. This indicates that depth filtration rather than the phenomenon of surface filtration is occurring here.

Figure 7 illustrates the gauge pressure at different depths along the filter length during a filter run. The discussion that follows refers to the above summarised data sets.

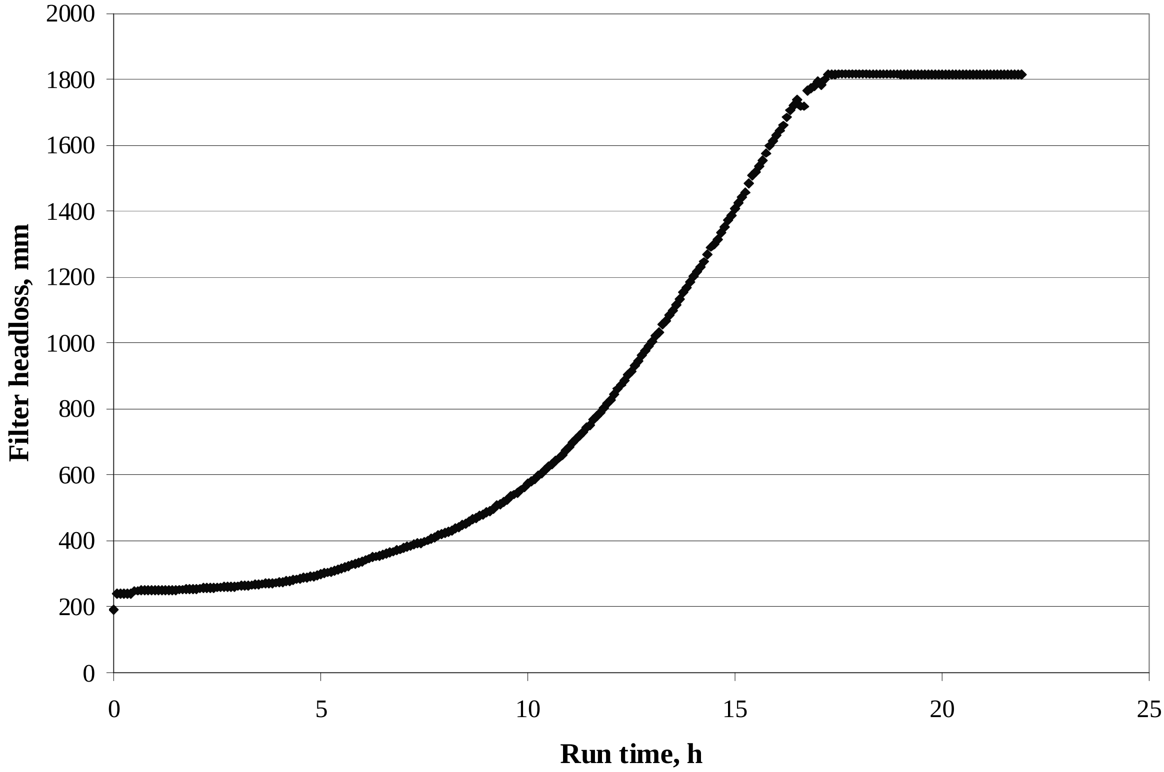


Figure 5: Pilot filter head loss versus time.

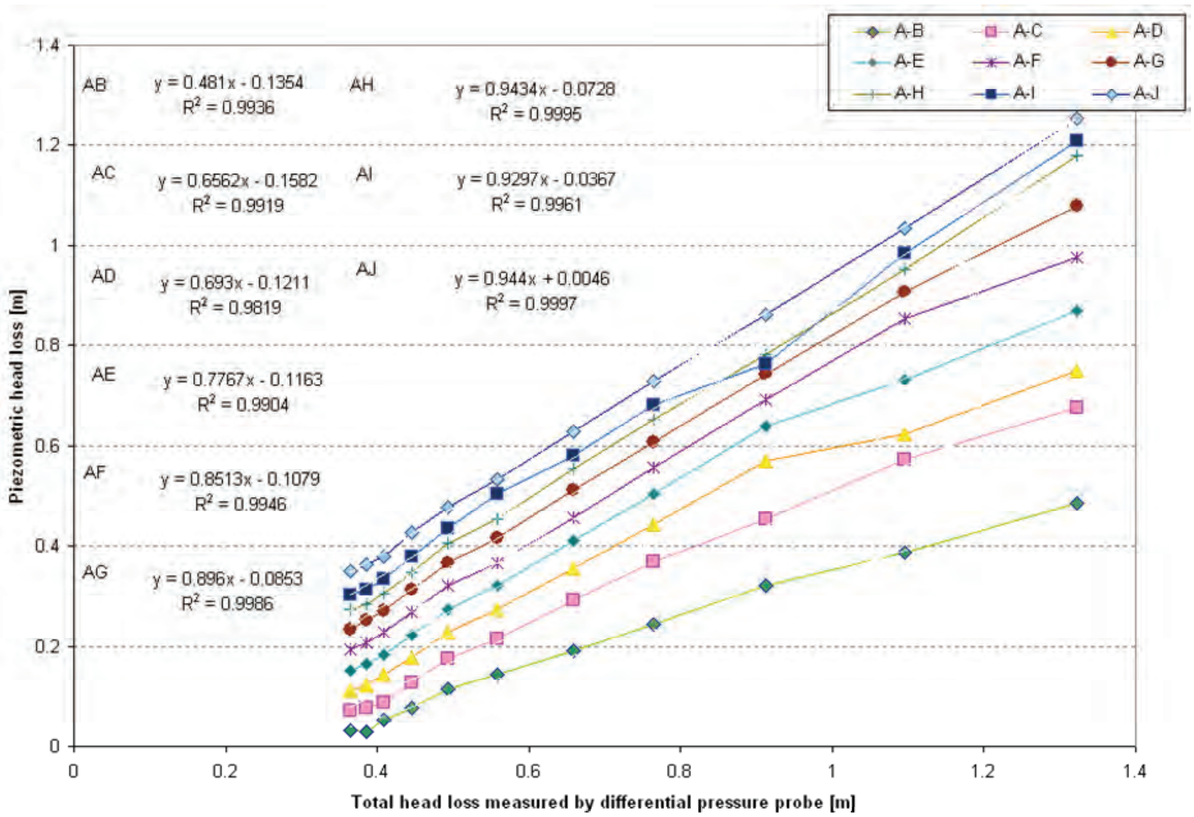


Figure 6: Head-loss across the filter at different depths.

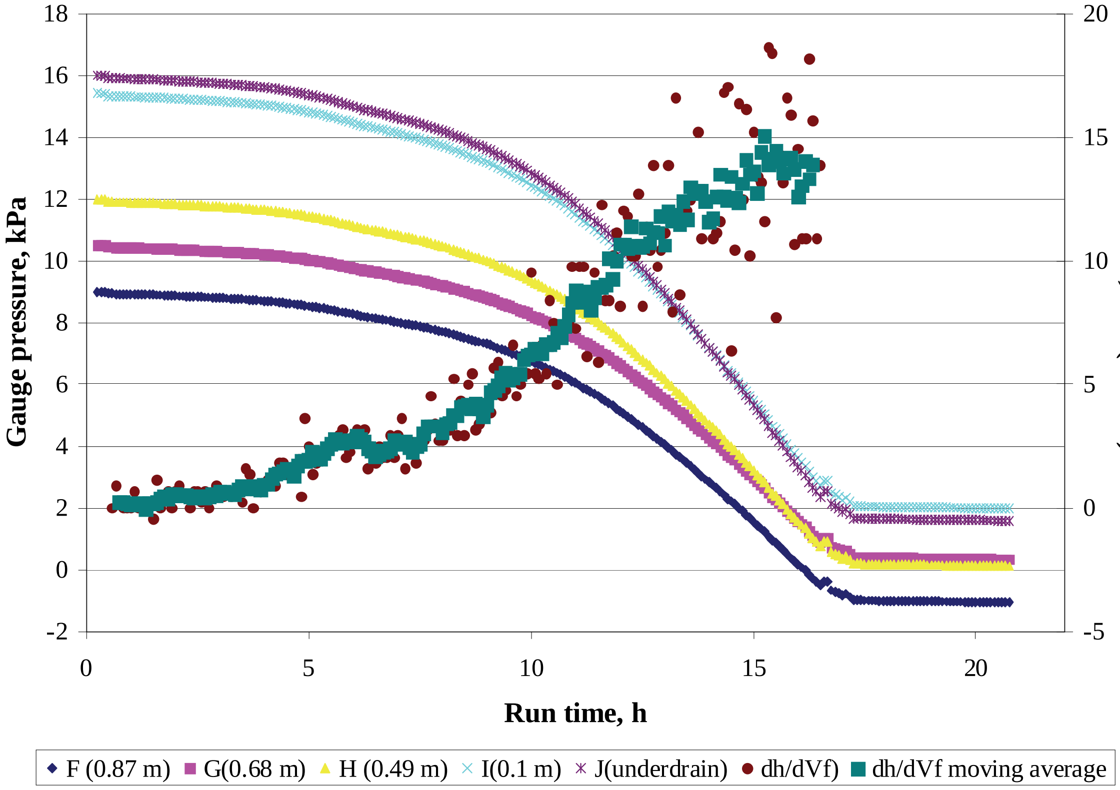


Figure 7: Relationship between gauge pressure, run time and headloss at different media depths.

5.3.1. Air binding

Figure shows the headloss measured by the DP cell over the course of the filter run. Figure shows the development of headloss between A, the top measurement port and each of the other ports as a function of run time. No data for ports H-J was collected after 11 hours run time. Headloss measurements for ports G and F stopped at 13 and 14 hours respectively. (This was because the water level dropped below the measurement scale or because air was sucked into the ports?). The DP headloss is also shown.

The reason for the dip in the probe signal (in Figure 9) between 8 and 10.5 hours is not clear. Measurements of the headloss profile during this period indicated that there was no disruption in headloss development, and whatever the problem was, only the DP cell measurements were affected, possibly due to a bad connection in the data logger. However, the drop in signal after 11.2 hours was most likely due to the accumulation of gas in the underdrain. From Figure 10, it can be seen that gas accumulated rapidly in the underdrain from some time before 12.6 hours into the run. Figure 11 illustrates the headloss developing in relation to pressure.

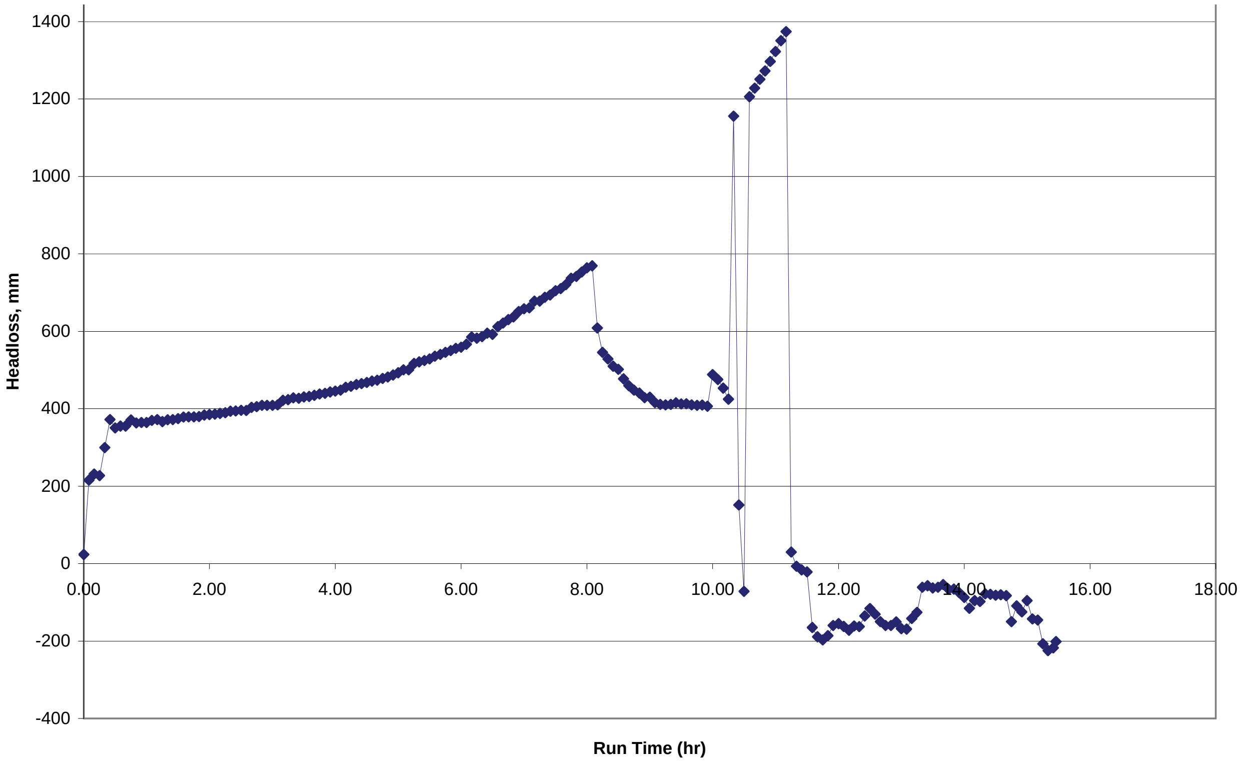


Figure 8: Headloss measured by the DP cell over the course of the run.

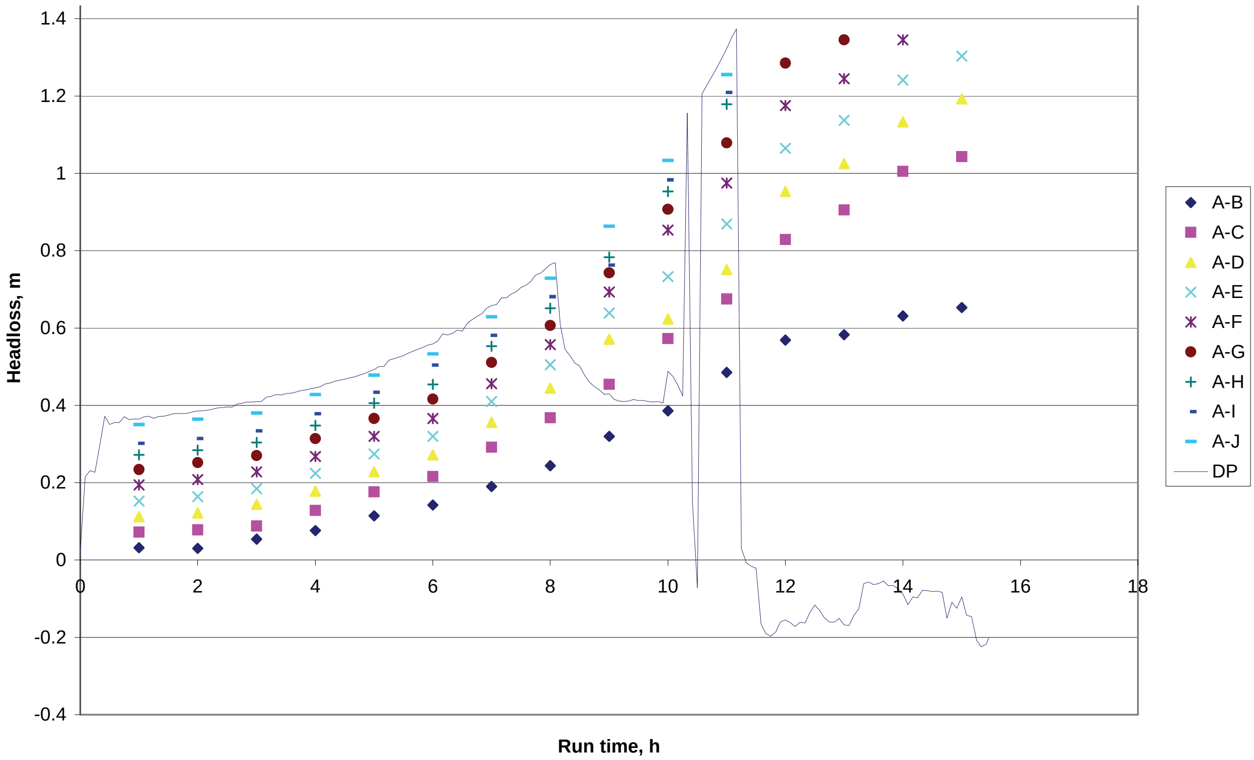


Figure 9: Headloss between A, the top measurement port and each of the other ports.

(a) Run time 0 h. Underdrain, no air layer.

(b) Run time 12 h. Air layer developing.

(c) Run time = 13 h. J port exposed by now.

(d) Run time = 17 h.

(e) Run time 25 h

(f) Run time 36 h

Figure 10: Gas accumulation in the underdrain.

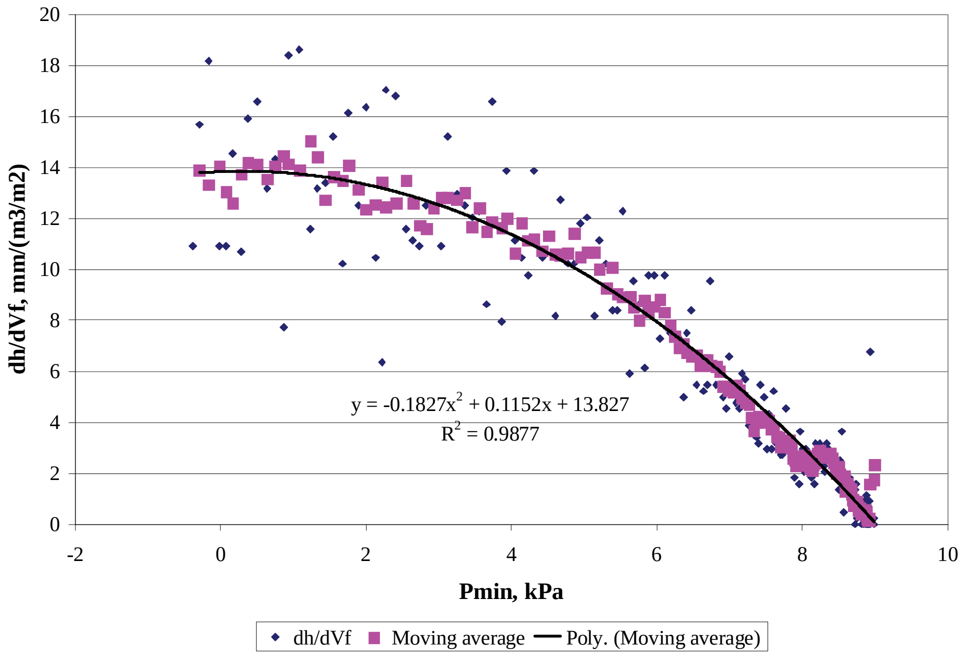


Figure 11: Rate of headloss development *vs*. pressure.

5.3.2. Turbidity removal and breakthrough

Since filtrate turbidity varies throughout any given filter run regardless of the filter operating conditions, carefully defined quantities are required to compare performance for different filter runs. Figure 12 shows a typical filter run with distinct ripening, steady state and breakthrough phases. Note that previous authors (Amburgey and Brouckaert, 2005) have shown distinct turbidity peaks during the filter ripening phase and have related them to the passage of particles from both backwashing and the early stages of filtration through the filter. In the current study, a more exponential decline in measured filtrate quality was observed, possibly as a result of mixing in the underdrains and filtrate rate control tanks of the pilot filters.

This study aimed to quantify the following:

- Volume filtered to achieve NTU < × during ripening
- Volume to terminal breakthrough
- Maximum influent turbidity for which filtrate turbidity × NTU can be achieved at rate *y* m/h

Figure shows the results for influent turbidity at 25 m/h between filter ripening and filter break through. It can be seen that at a flowrate of 25 m/h, even though there is some scatter, the general trend is that the filtrate turbidity appears to increase with increasing influent turbidity. Based on the line that has been defined, all points lie either on the line or below the line. Therefore one can for instance conclude that at 25 m/h, in order to achieve a filtrate turbidity of less than 0.4 NTU for this filter, the influent turbidity would need to be less than 1 NTU.

It must be noted that at 10 m/h, this relationship between the filtrate turbidity and influent turbidity was not evident. At the lower flowrate of 10 m/h, the filtrate turbidity appeared to be independent of the influent turbidity, with filtrate turbidities below ~ 0.17 NTU being achieved (influent turbidities up to ~ 2.5NTU were used in the investigation). It is therefore expected that the filtrate turbidity becomes more sensitive to the influent turbidity between 10 m/h and 25 m/h. Further investigations would need to be conducted in order to establish this, due to there not being any reliable data available for this filter between these flowrates.

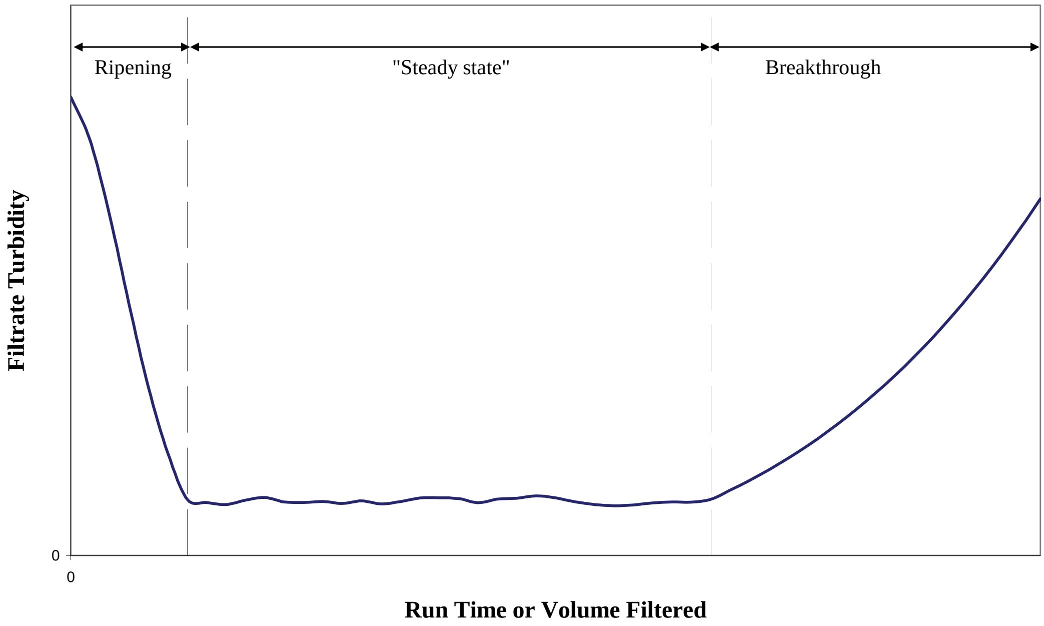


Figure 12: Typical variation in filtrate turbidity as a function of run time.

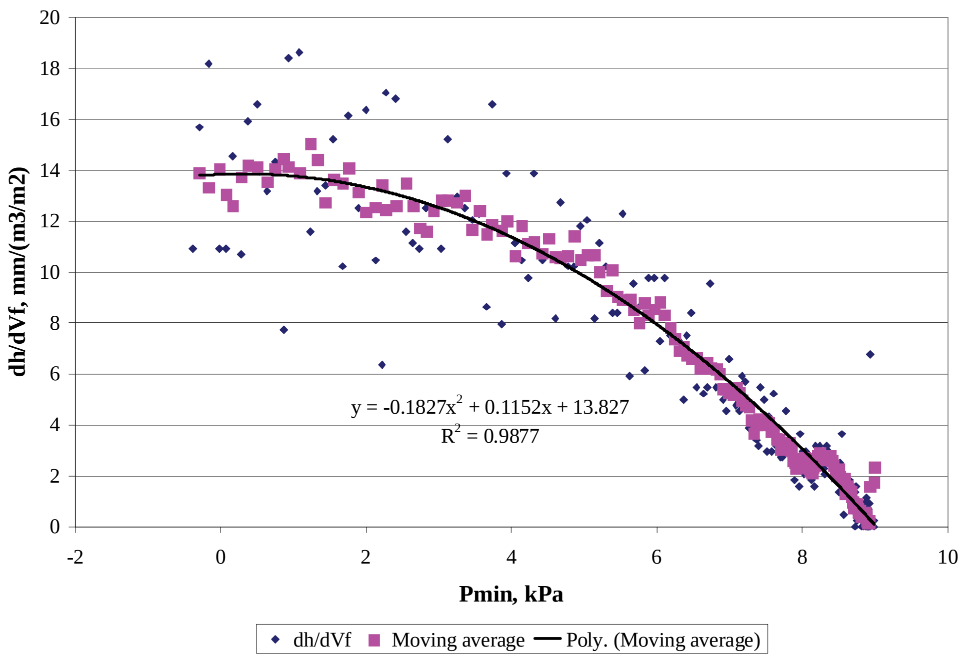


Figure 13: Apparent sensitivity to influent turbidity, 25 m/h.

At 4 m/h, no relationship between the influent turbidity and the filtrate turbidity is apparent, as was evident at 25 m/h (Figure 14).

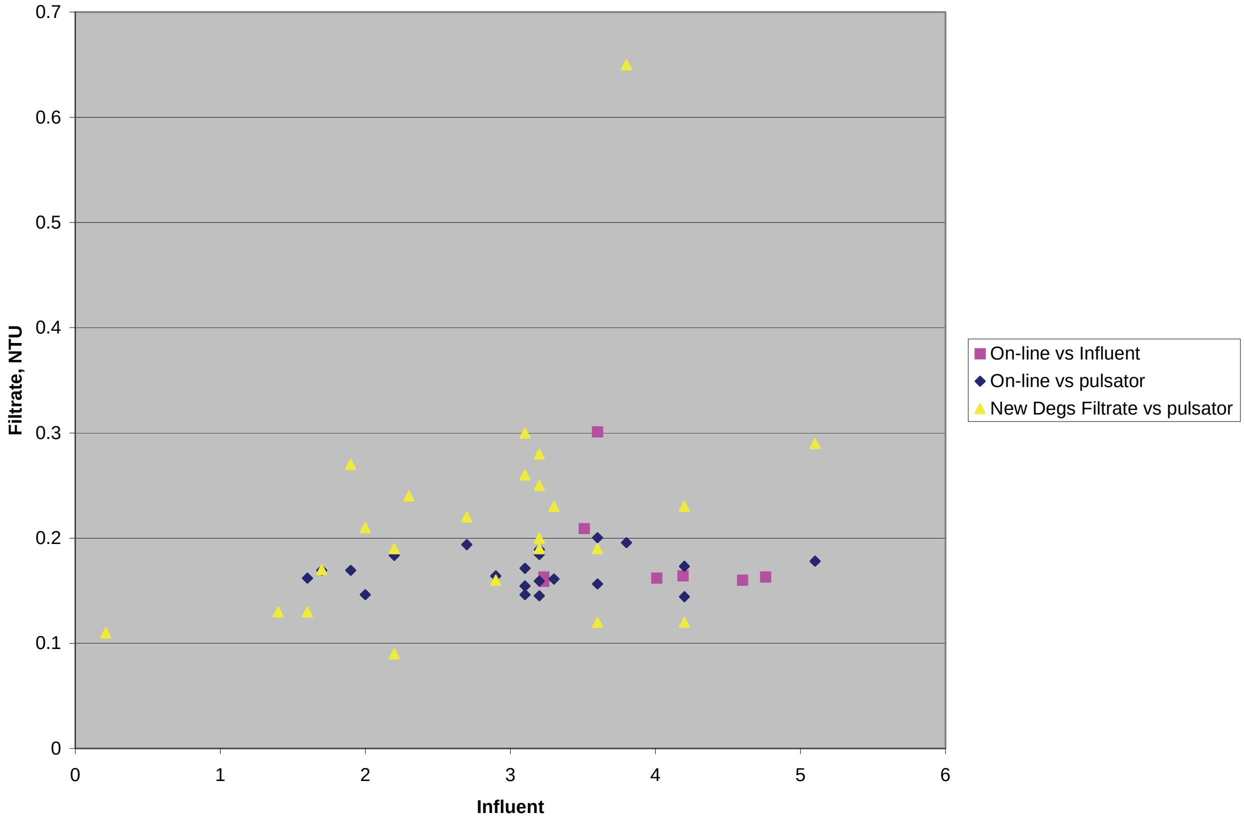


Figure 14: Apparent lack of sensitivity to influent turbidity at loading rate of 4 m/h.

5.3.3 Factors expected to influence filtrate turbidity

- Volume filtered since start of run
- Influent turbidity
- Relative efficiency of coagulation (e.g. jar/cascade test results)
- Media size
- Filtration rate
- Temperature
- Headloss/headloss profile? (as indicator of clogging)
- Air binding?

6. Pilot plant results

6.1. Durban Heights

6.1.1. Summary of experiments conducted

A total of 25 successful runs were conducted and analysed for the 0.95 mm sand. Fifteen runs were completed for the 1.7 mm sand. For each sand size the filtration rate and water level were varied respectively. Attempts were also made to evaluate the effects of the influent turbidity on the filtered water quality at the different filtration rates and sand size. The results of the experiments are included in the appendix.

6.1.2. Headloss development and filter run time

6.1.2.1 Headloss development and air binding

- Air binding occurs at higher pressures than expected
- If there is a critical pressure, it is different for different runs
- Not yet clear what factors influence rate of headloss development as a function of pressure

6.1.2.2. Relationship between rate of headloss development and gauge pressure

Headloss decreased as gauge pressure increased, as shown in Figure 15.

6.1.2.3 Turbidity removal

- There were very few cases where terminal breakthrough could be confirmed.
- Higher rates tended to produce higher turbidities but clearly other factors were involved.
- Filtrate turbidity was sensitive to influent turbidity in some cases.

Figures 16 and 17 illustrate the relationship between volume filtered and filtrate turbidity for the two sizes of sand. They indicate variability on the repeated runs with each media size; cascade test data/dosing problems may explain some of the variations between runs. Figure 18 indicates the volume required to be filtered in order to achieve filter ripening at various filtration rates.

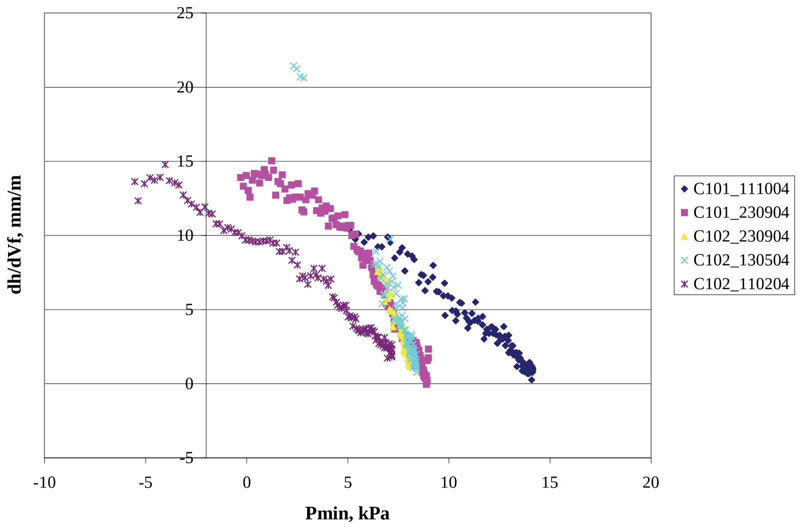


Figure 15: Rate of headloss development *vs*. gauge pressure.

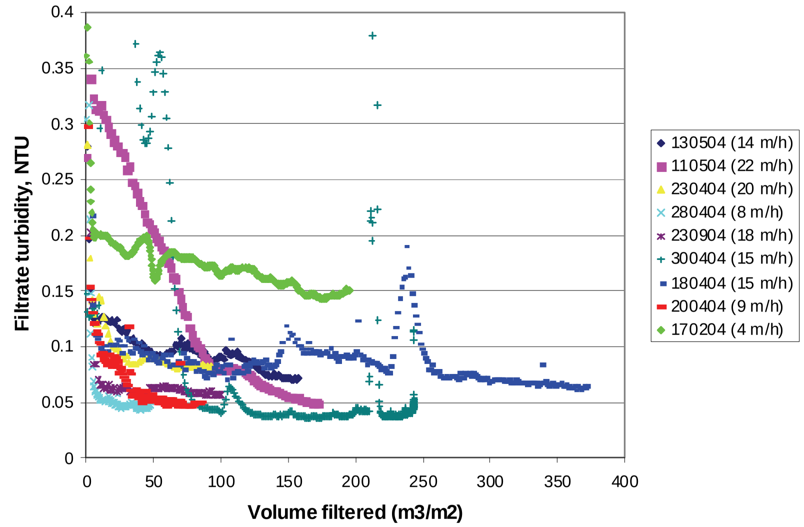


Figure 16: Volume filtered *vs*. filtrate turbidity for 0.95 mm sand.

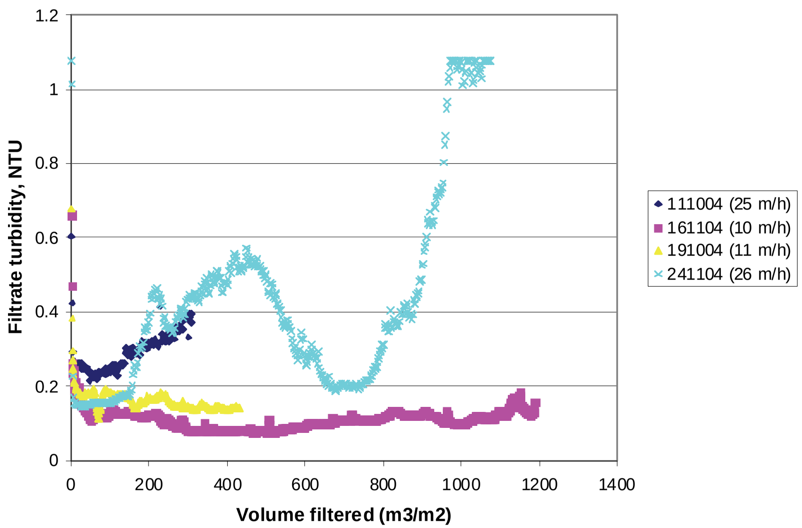


Figure 17: Volume filtered *vs*. filtrate turbidity for 1.7 mm sand.

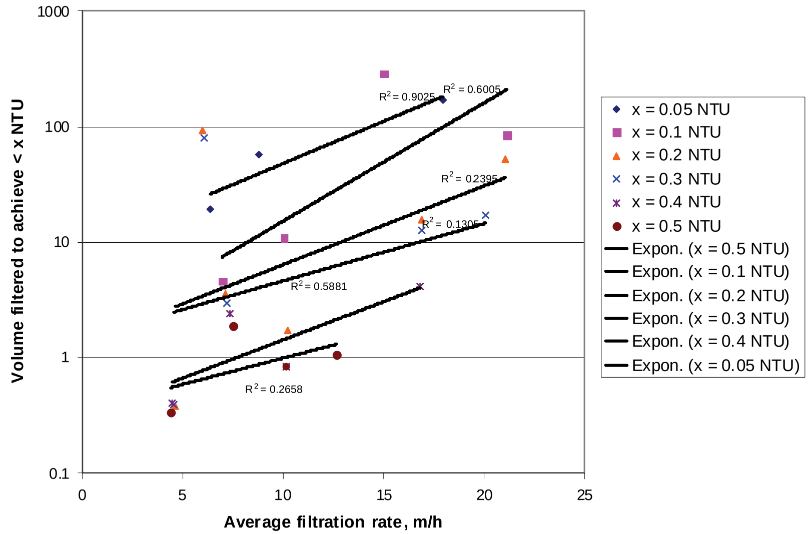


Figure 18: Volume filtered to achieve filter ripening at various filtration rates.

6.1.3. Conclusions and Recommendations

- Air binding can occur at high filtration rates and is confirmed by physical observation in the both the pilot filters and main water works filters and is related to a possible shortcoming in the design of the main plant filters.
- The use of a larger media size will reduce the onset of air binding
- The only proven method of reducing air binding is to ensure that the outlet water level is above the media/inlet water level interface thus ensuring that there is always a positive hydrostatic head on the sand media.

6.2. Craigieburn

6.2.1. Summary of experiments conducted

A total of nine runs each were conducted in the 0.95 mm and 1.4 mm sand filters. This included five runs where the two filters were operated in parallel. For the first three runs in the 0.95 mm sand bed the bed height was 1 m. Thereafter the bed height was reduced to 0.9 m because the highest piezometric port for headloss measurement was 0.925 m.

Table 7 lists the experiments conducted and experimental conditions in order of increasing filtration rate. The filter influent turbidities recorded at both the pilot plant (sampled at the influent rate control tank) by the pilot plant operator and the main plant (sampled in the filter influent channels) by the main plant operators are both reported. These values tended to be similar but the main plant turbidities also covered the periods when the pilot plant operator was not on site.

The main plant filtrate turbidities provide an indication of coagulation efficiency and the general stability of the main plant operation and are also reported for comparison purposes.

For the low filtration rate runs in particular, the operator struggled to set the flow accurately at the beginning of each run and consequently the filtration rate went through one or more step changes before the desired rate was achieved. These step changes are also reported in Table 7 for the filter, runs for which online flow and turbidity measurements were available.

Table 7: Experimental conditions for Craigieburn pilot plant trials.

Experiment	**3-4 October 2006**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		6.6 m/h	16 m/h (3-12 m^3/m^2) 9.0 m/h (14-18 m^3/m^2) 5.6 m/h (> 18 m^3/m^2)
Online measurements			Turbidity, headloss, flow
Filter influent	4.1-4.8 (pp); 2.4-5.2 (mp)		
pH	7.4-7.7		
Temperature	20 -21ºC		
Main plant filtrate	0.21-0.32 NTU, average = 0.26 NTU		
Notes:	Disruptions in data logger signal during last 4 hours of run means it was unclear whether breakthrough could have occurred.		
Experiment	**7-8 September 2006**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		7 m/h	11 m/h (0-20 m^3/m^2) 6.0 m/h (> 20 m^3/m^2)
Online measurements			Turbidity, headloss, flow
Filter influent	2.7-3.4 (pp); 2.3-4.1 (mp)		
pH	8.1-8.2		
Temperature	20-22		
Main plant filtrate	0.26-0.32 NTU, average = 0.29 NTU		
Notes:	Plant shut down overnight while operator was away		
Experiment	**12 April 06**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate			10 m/h
Online measurements			Turbidity, headloss, flow
Poly dose	~ 2.8-4.6 ppm		
Filter influent	6.2-7.4 (pp)		
pH	8.4-8.7		
Temperature	25		
Notes:	Run terminated early due to data logger problems.		
Experiment	**14-16 November 2005**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate			12 m/h
Online measurements			Turbidity, headloss, flow
Filter influent	4.2-6.4 (pp); 2.5-5.9 (mp)		
pH	7.7-8.3		
Temperature	25-26		
Main plant filtrate	0.21-0.60		
Notes:	1 m filter bed. Power failures caused disruptions and instrument failures at main plant. Temporary deterioration of turbidity between 15 and 25 hrs run time. Increase in influent turbidity and rate of headloss development around 21 hr run time.		

Table 7: Experimental Conditions for Craigieburn Pilot Plant Trials, continued.			
Experiment	**4-6 July 2006**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		14 m/h	16 m/h
Online measurements		NTU, headloss, flow	
Poly dose	2.3-3.8 ppm		
Filter influent	0.86-4.9 NTU		
pH	7.3-7.8		
Temperature	15-18		
Notes:	Data logger batteries failed in middle of run. Recharged and continued logging. Significant change in rate of headloss development around 400 m3/m2. Requires further data and analysis		
Experiment	**17-18 Jul 06**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		15 m/h	18 m/h
Online measurements			NTU, headloss, flow
Poly dose	2-2.7 ppm		
Filter influent	3.5-4.5 (pp)		
pH	7.6-8.1		
Temperature	18		
Notes:	Runs terminated early due to flow control failure		
Experiment	**4-5 April 06**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate			19 m/h
Online measurements			Turbidity, headloss, flow
Poly dose	2.5-2.9 ppm		
Filter influent	5-7.6 NTU (pp); 3-4.6 (mp)		
pH	8.4-8.9		
Temperature	27-28		
Main plant filtrate	0.2-0.29 NTU		
Notes:	Apparent breakthrough. To be confirmed		
Experiment	**27 to 28 Jun 06**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		20 m/h	19 m/h
Online measurements		Turbidity, headloss, flow	
Filter influent	2.9-7.3 (pp); 3-4.1 (mp)		
pH	8.1-8.9		
Temperature	13-15		
Main plant filtrate	0.22-0.35 NTU		
Experiment	**5-6 April 06**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate			22 m/h
Online measurements			Turbidity, headloss, flow
Filter influent	5.6-7.3 (pp); 2.5-5 (mp)		
pH	8.3-8.8		
Temperature	27-28		
Main plant filtrate	0.27-0.38 NTU		

Table 7: Experimental Conditions for Craigieburn Pilot Plant Trials, continued.			
Experiment	**2-3 Nov 05**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		30 m/h	
Online measurements		Turbidity, headloss, flow	
Filter influent	3.6-6 NTU		
pH	8-8.5		
Temperature	28-29		
Notes:	1 m filter bed		
Experiment	**17-18 Oct 05**	**0.95 mm sand**	**1.4 mm sand**
Filtration rate		28 m/h	
Online measurements		Turbidity, headloss, flow	
Poly dose	2.2-2.3 ppm		
Filter influent	2-4.3 (mp)		
Main plant filtrate	0.24-0.4		
Notes:	1 m filter bed		

6.2.2. Headloss development and filter run time

Preliminary results indicate that rate of headloss development is an order of magnitude lower in the 1.4 mm sand filter compared to the 0.95 mm sand filter(0.1-0.4 mm headloss/ m^3 filtered/ m^2 filter area as opposed to 0.3 to 6 mm/m^3/m^2).

Air binding did not appear to be an issue at this site and headloss development tended to be fairly linear. However, in at least two experiments (14-16 Nov 05 and 4-6 Jul 06) there was a significant change in rate of headloss development in the middle of the run, which may have been due to changes in coagulation conditions or other disruptions in the main plant operation.

Figure illustrates the relationship between volume filtered and headloss development for the 0.95 mm media.

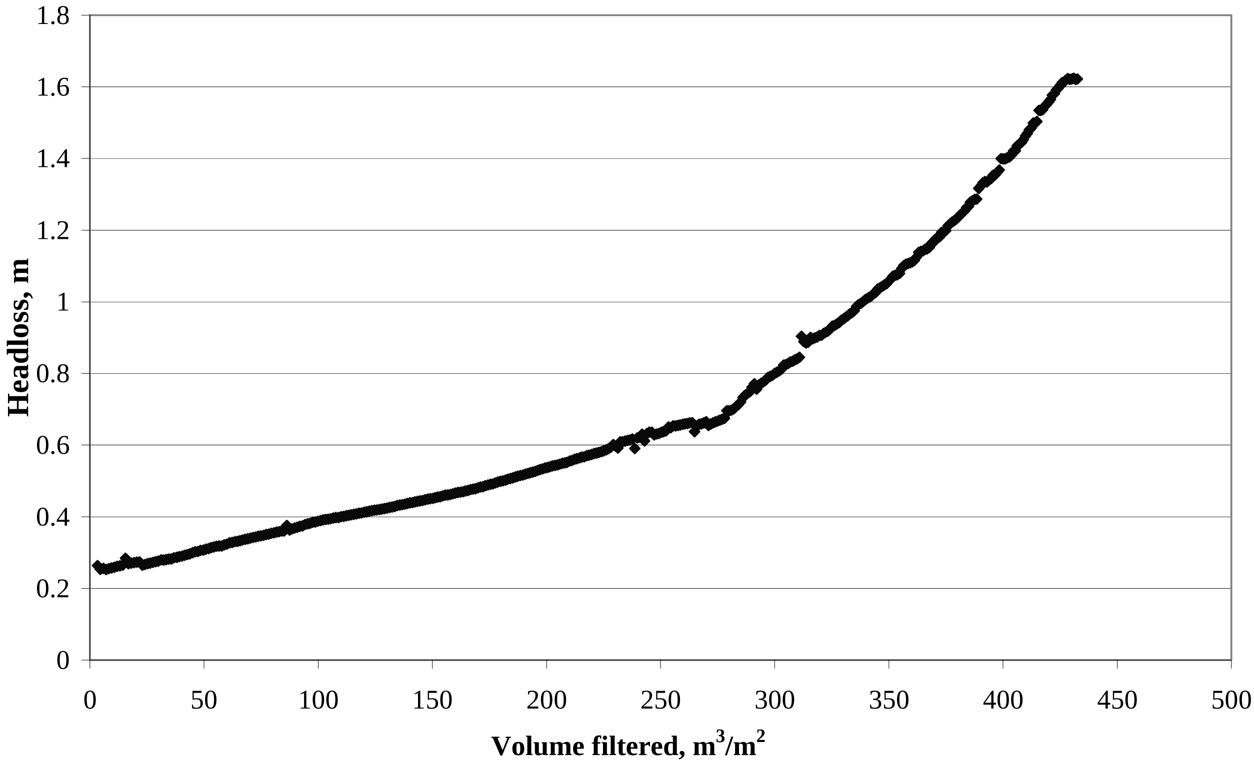


Figure 19: Headloss development in the 0.95 mm sand filter for 14th-16th November 2005.

6.2.3. Turbidity removal

Turbidity removal in the pilot filters appeared to depend on a number of factors. These included filtration rate, influent turbidity (in some cases), effectiveness of coagulation as indicated by the main plant filtrate turbidity, the filter media size and the stage of the filter run (filter ripening, steady state, etc.). Of these factors, stage of the filter run state had the greatest impact on filtrate quality with high initial filtrate turbidities being observed in all filter runs and breakthrough occurring towards the end of a few of the runs. During the steady state phase of the filter operation, the other factors listed above appeared to have effects of similar magnitude to each other.

Figure and 21 show the online turbidity measurements plotted as functions of volume filtered per m^2 filter area for the 0.95 mm and 1.4 mm sand filters.
For both the 0.95 mm and 1.4 mm sand filters, there was an overall increasing trend in steady state filtrate turbidity with filtration rate. For the 0.95 mm sand, steady state filtrate turbidities of less than 0.2 NTU (measured using the Hach 1720 C online turbidimeter) were achieved for filtration rates of up to 20 m/h and were even achieved briefly at 28-29 m/h. Steady state turbidities of less than 0.3 NTU were achieved for up to 35 m/h, although the volume filtered before breakthrough was relatively small at this highest rate (~ 250 m^3/m^2).

The volume of poor initial filtrate quality (filter ripening) tended to greater at higher rates (~ 120 m^3/m^2at 35 m/h as opposed to ~ 20 m^3/m^2 at 14 m/h) although there were exceptions (nearly 100 m^3/m^2 at 12 m/h). The relatively poor turbidity removal at 12 m/h (14-16 November 2005) both during ripening and subsequently appeared to be related to disruptions at the main plant caused by power failures. Main plant filtrate turbidities of up to 0.6 NTU were observed during the same period.

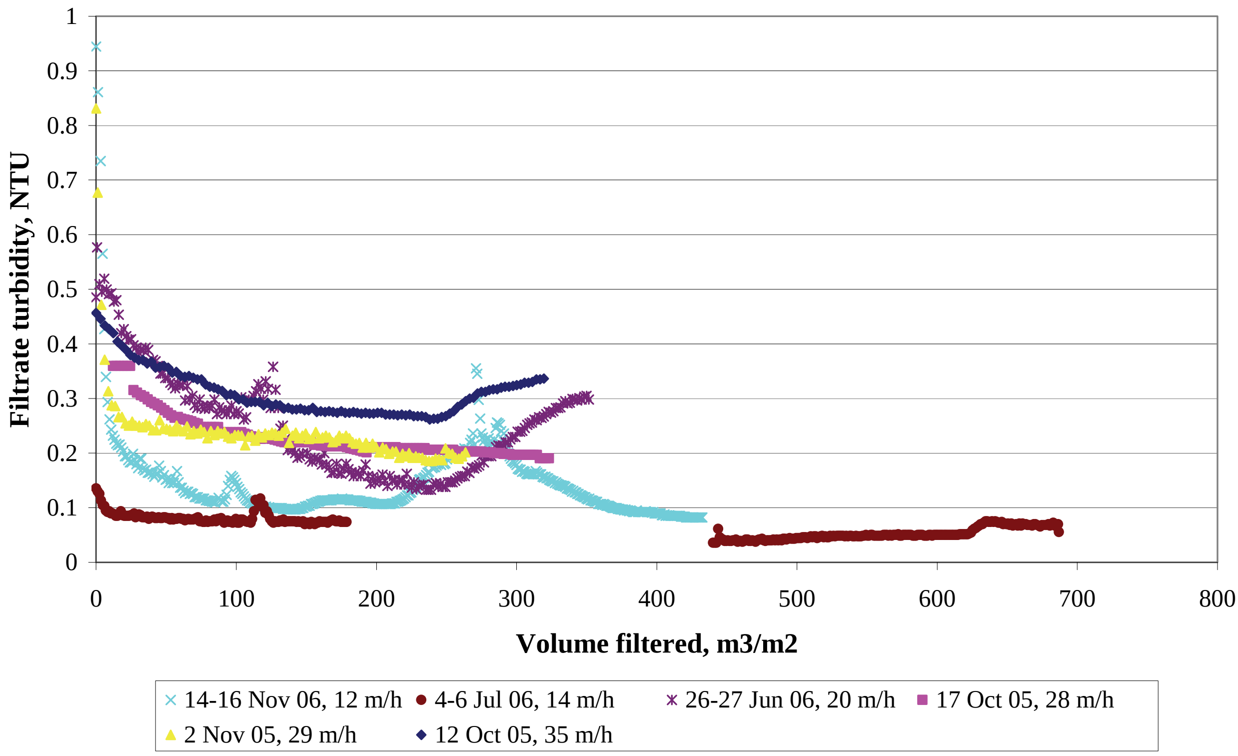


Figure 20: Online turbidity as function of volume filtered for the 0.95 mm sand filter.

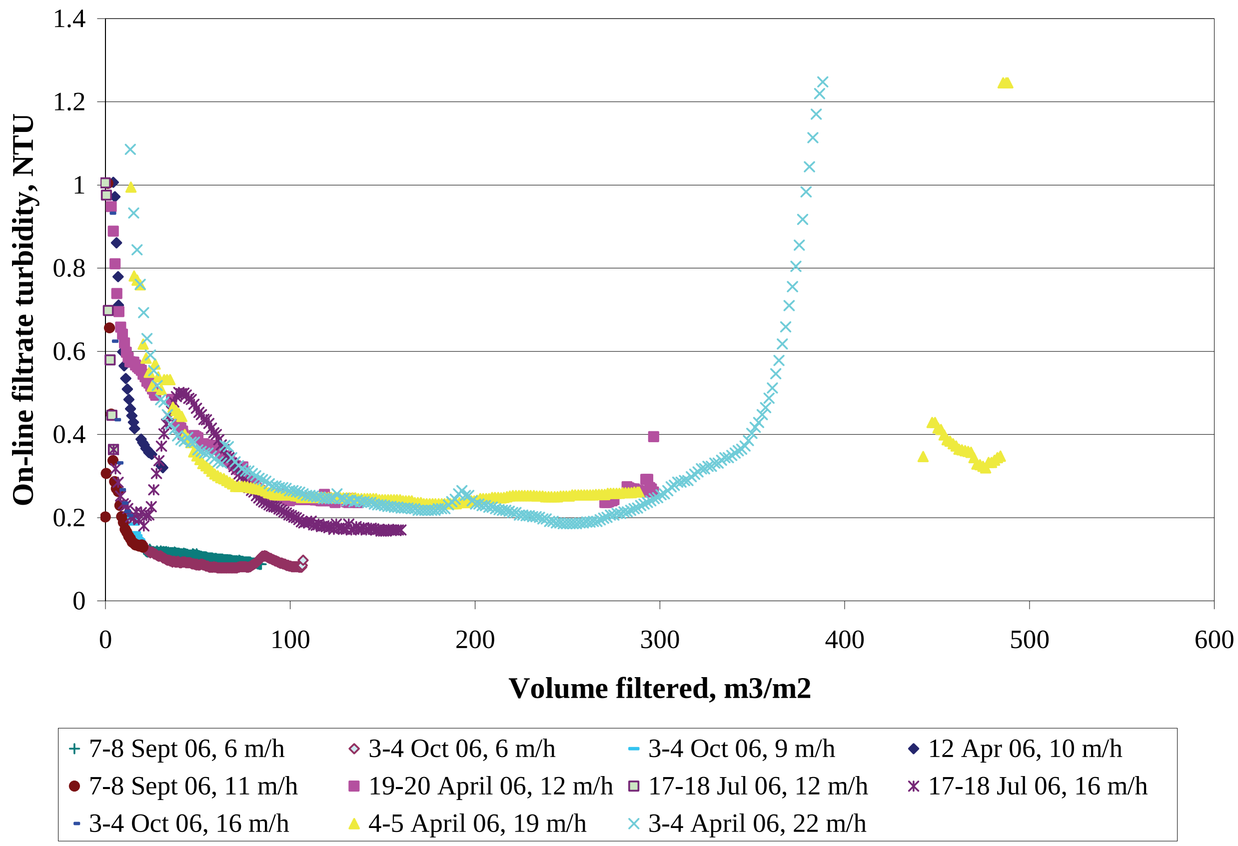


Figure 21: Online turbidity as function of volume filtered for the 1.4 mm sand filter.

The 1.4 mm sand filter produced steady state filtrate turbidities of less than 0.2 NTU for up to 16 m/h and turbidities less than 0.3 NTU for up to 22 m/h. The relatively poor filtrate turbidity at 12 m/h on 19-20 April 2006 and the secondary peak in 17-18 Jul7 2006 run were likely due to disruptions or dosing problems at the main plant. The main plant operating records will be obtained in order to confirm this.

The volume of poor initial filtrate quality was significantly larger at higher rates (80-100 m^3/m^2 for rates of 19-22 m/h) compared to 20-40 m^3/m^2 at 6 m/h. The initial filtrate quality tended to be significantly worse for longer in the 1.4 mm sand filter compared to the 0.95 mm sand filter. This is illustrated by Figure and Figure which show just the first 200 m^3/m^2 from Figure and Figure .

For the purposes of this study, breakthrough was defined as a significant increase in filtrate turbidity in the absence of a flow disruption or increase in influent turbidity. For the 0.95 mm sand filter, no breakthrough was observed for up to 12 m/h and 433 m^3/m^2 at this filtration rate. The minimum filtration rate and volume at which breakthrough was observed was 14 m/h and 470 m^3/m^2. For 1.4 mm sand, probable breakthrough was observed at a rate of 16 m/h and occurred after 515 m^3/m^2. There was insufficient data (runs ended too early) to determine if breakthrough occurred at lower rates.

6.2.4. Effects of influent quality and variability

An important consideration in assessing the potential for upgrading filters to high rate is determining the required influent quality to ensure that the filter is able to produce acceptable quality of filtrate at higher rates. This in turn determines the influent pre-treatment requirements. Figure 5.5.5 shows steady state filtrate turbidities (excluding filter ripening and turbidity breakthrough) plotted against pilot plant influent turbidity for both 0.95 mm and 1.4 mm sand. All the turbidity measurement in this Figure were made with the Hach 2100P portable turbidimeter. Measurements made with this meter tended to be up to twice as high as measurements made with the Hach 1720 C online meter. Runs in which both filter columns were run simultaneously are labelled with the starting date of the experiment.

Figure indicates the following:

- Steady state filtrate turbidities < 0.3 NTU (as measured by the Hach 2100P) could be achieved for influent turbidities < 3 NTU and filtration rates < 16 m/h for both the 0.95 mm and 1.4 mm sand.
- For influent turbidities > 3 NTU for the 1.4 mm sand and > 4 NTU for the 0.95 mm sand, steady state filtrate turbidity tended to increase with increasing influent turbidity. This sensitivity to influent quality was greater for the 1.4 mm sand the 0.95 mm sand and tended to increase with increasing filtration rate.
- According to measurements made with the Hach 2100P, there is little difference between filtrate turbidities for the two filters when they are run in parallel for filtration rates < 15 m/h. For higher filtration rates, the 0.95 mm sand filter produces lower turbidities. Significant differences in turbidity removal in the two filters were observed only during the 27 June 2006 (19-20 m/h) and 17 July (15-18 m/h) runs.
- For lower filtration rates, the time period during which the experiments were carried out appeared to be more important than either flow or influent turbidity in determining the filtrate quality, i.e. it appears that the efficiency of coagulation and the floc characteristics were probably the dominant factor involved.

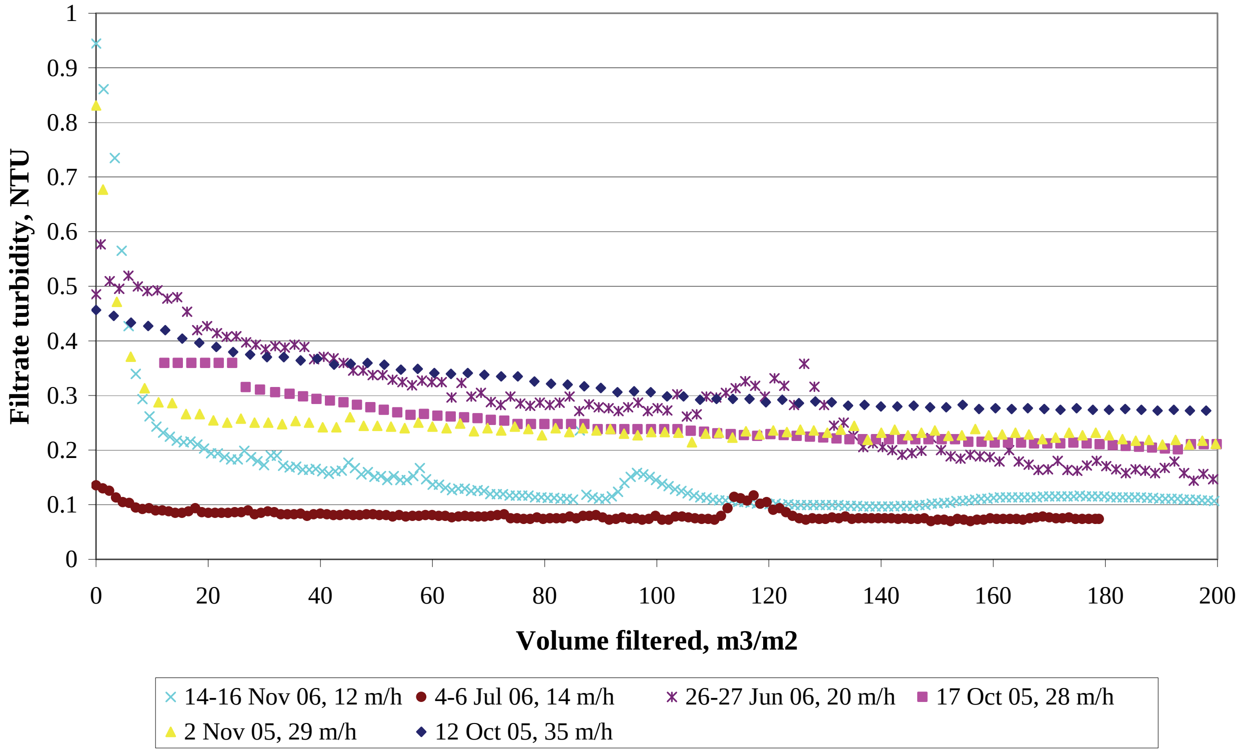


Figure 22: Filter ripening in the 0.95 mm sand.

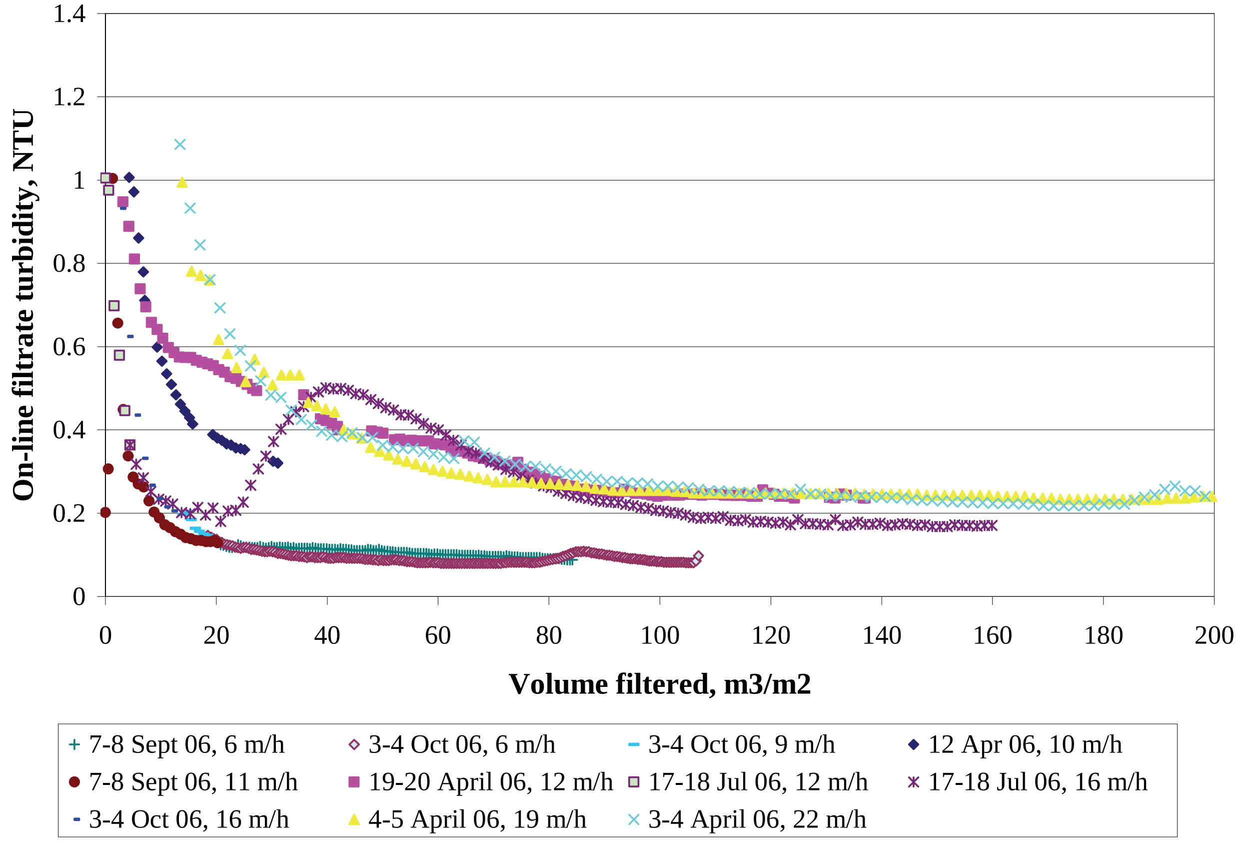


Figure 23: Filter ripening in the 1.4 mm sand.

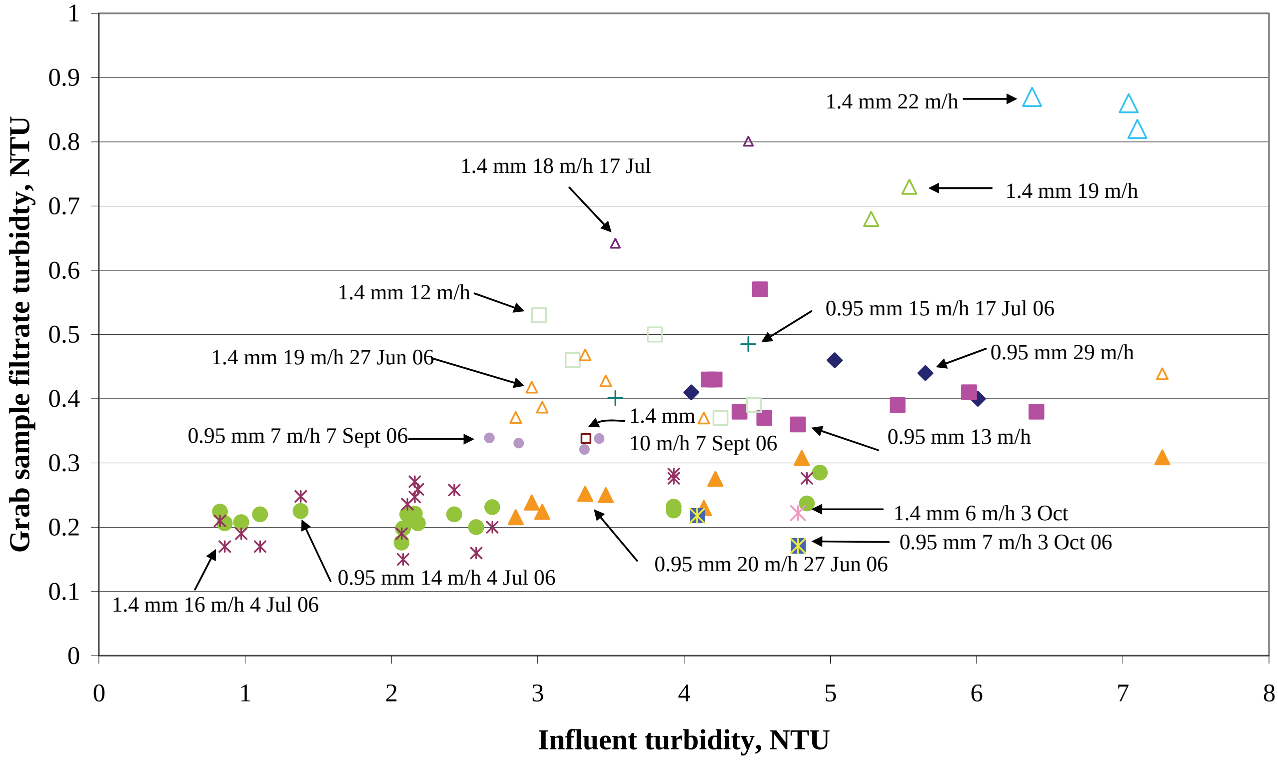


Figure 24: Relationship between influent and filtrate turbidity.

It should be noted that the pilot plant operator had no control over the coagulation conditions in these experiments while for full scale operation; the operator could potentially adjust the chemical doses to compensate for higher filtration rates. This would require tighter control and more rigorous optimisation because of more challenging operating conditions and shorter response times to changes in raw water quality.

6.2.5. Effects of media size

Increasing the filter media size from 0.95 mm to 1.4 mm without increasing the bed depth tends to result in less efficient turbidity removal, especially during the filter ripening period.

6.2.6. Conclusions and Recommendations

The following conclusions have been reached:

- The sensitivity of filtrate turbidity to influent turbidity tends to increase with increasing rate and filter media size. The influent turbidity should be maintained at less than 3 NTU for 0.95 mm sand and 4 NTU for 1.4 mm sand.
- Filters can produce good quality filtrate at significantly higher rates than are currently being used at this site provided optimal coagulation conditions are maintained. The causes of disruptions should be identified in order to minimise their occurrence.
- Strategies for minimizing the initial period of poor filtrate quality need to be investigated for uprating the filters to be a feasible option.

7. Conclusions and recommendations

It is recommended that design engineers seriously consider the possibility of uprating existing filtration plants before adding additional filters. As indicated in the literature review, the use of high rate filters can result in major savings in terms of capital costs for either new filtration plants or the uprating of existing plants. It is recommended that the following factors be considered when undertaking this process.

7.1. Assessing the suitability of plants for high rate filtration

These guidelines pertain only to water treatment plants which are already able to consistently achieve filtered turbidities of less than 0.5 NTU and would like to increase their capacity. There are many very small treatment plants (< 2 ML/d) in the country which are operated so poorly that they are unable to produce adequate filtrate turbidities at any rate. Increasing the plant filtration rate will make their problems worse and therefore must be strongly discouraged. In order to be considered for uprating plants must meet the following criteria:

- They must be manned 24 hours a day or have on-line control systems which can initiate automatic adjustments to dose rates when the raw water quality or flow changes.
- Operators must be adequately trained. A minimum qualification of M+2 is recommended for the operation of high rate filters.
- Operators must be able to measure at least flow, turbidity, disinfectant residual and pH on an hourly basis if necessary, i.e. the plant must be equipped with all the necessary instrumentation in good working order.
- Maintenance issues and faulty equipment must be dealt with promptly and effectively. Plants must have documented procedures for dealing with equipment failures and routine maintenance to prevent disruptions in finished water quality.

In addition, the effects of increasing the flow through the filters cannot be considered in isolation from the operation of the rest of the plant. Increasing the flowrate affects the efficiency of hydraulic mixing (weirs, hydraulic jumps and baffled flocculation channels), negatively impacts sedimentation efficiency and decreases chlorine contact times. Existing pipes and channels may also not be able to accommodate the increase in flow. If the filters are to be uprated, then other parts of the plant also have to be upgraded unless sufficient excess capacity already exists.

In considering the design of new treatment plants, high rate filters can only be considered if there are sufficient resources in the area to support their effective operation, i.e. the local water services provider must be willing and able to invest in and sustain adequately trained operators, instrumentation and maintenances procedures. Designers and municipalities should not be tempted to try to reduce capital costs by installing high rate filters in areas without sufficient skilled personnel (both maintenance and operational) that would generally struggle to achieve turbidity goals even at conventional rates. For these sites, designers should actually consider using slow sand filters (filters which operate at rates less than <0.3 m/h and are scraped rather than backwashed) with or without pre-treatment (e.g. coagulation, flocculation and sedimentation

Regardless of whether a given filtration plant is deemed suitable for uprating, these guidelines can also be used to improve the operation of existing plants at lower rates.

7.2. Design of New High Rate Filters

7.2.1. Filter Media and Bed Depth

The literature review provides an excellent summary of the relationship between filter media size and bed depth. An important consideration is to take into account the relative changes in backwash velocity requirements as media size changes or when using dual media filters. In general, high rate filters favour the use of coarser media or dual media.

7.2.2. Filter Rate Control

Filter rate control is an often neglected component of the filtration unit process, yet it is the most critical factor that ultimately determines the overall performance of the plant. Four control mechanisms can be utilised and are summarized as follows:

Figure 25 depicts a constant rate filter with flow splitting and a constant water level above the sand. In this control mode, the flow is equally split between all the filters off a common inlet channel. As the filter clogs, a sensor measures the water level above the sand and transmits a signal to the outlet modulating valve to open or close as required. Figure 26 is very similar to the mode in Figure 25, however the water level varies, i.e. rises with increasing head loss.

Figure 27 illustrates a filter that has traditionally been used in Eastern Europe and America, but is now being well marketed in South Africa, especially for rural areas where there are fewer trained process controllers. This filter operation mode is known as the Self-backwashing filter. This filter will automatically initiate a backwash when the head-loss reaches the design limit.

Two water works in South Africa were found to be using declining rate filtration, namely, the Faure Water Works in Cape Town and the Cullinan Water Works in the diamond mining town of Cullinan in the Gauteng Province. The filtration rate control mechanism is depicted in Figure 28.

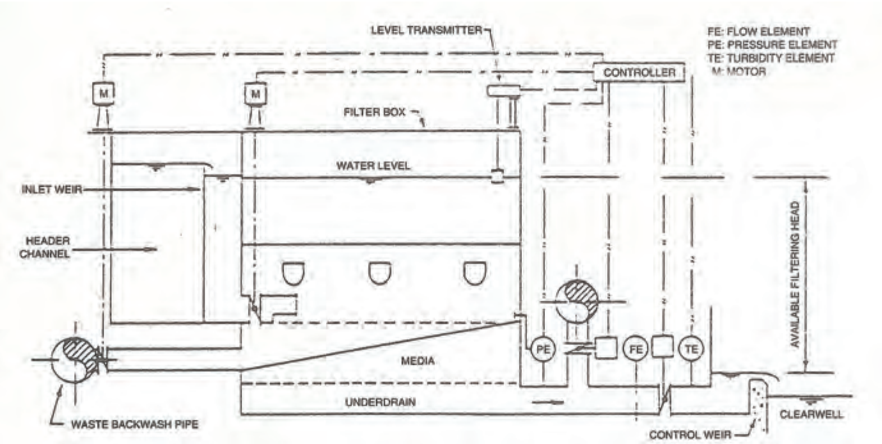


Figure 25: Constant Rate Filter Control with inlet flow splitting and constant water level (Monk 1987).

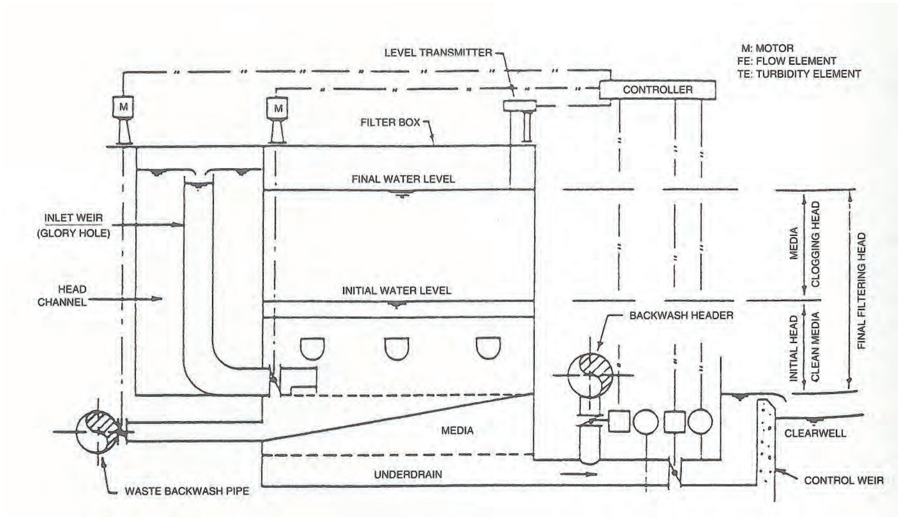


Figure 26: Constant rate filtration with flow splitting and varying water level.

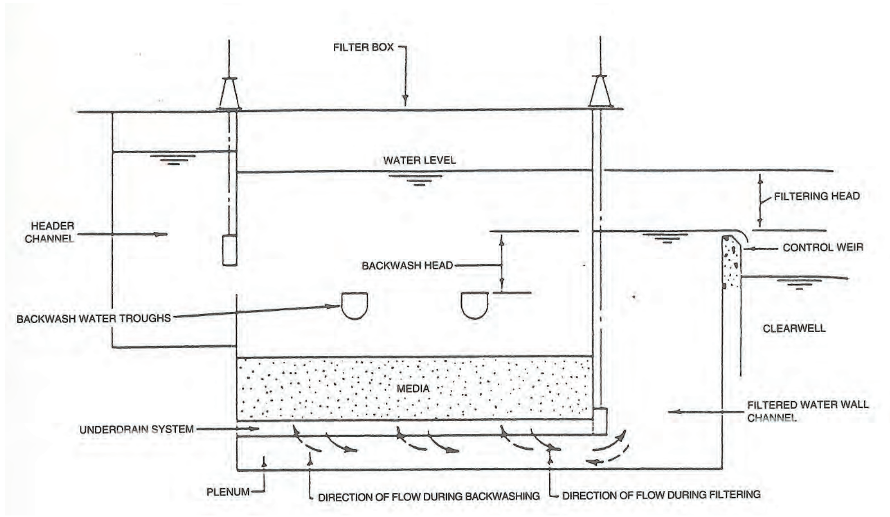


Figure 27: Automatic backwash filtration rate control (Monk 1987).

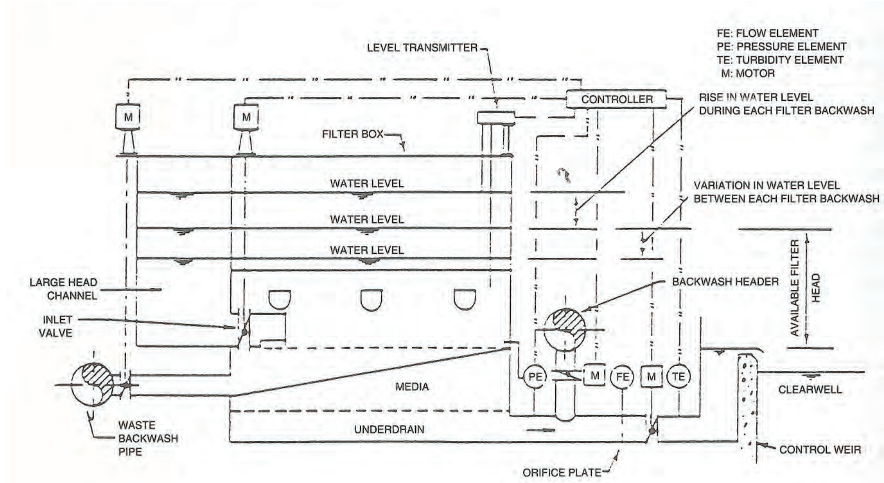


Figure 28: Declining rate filter control (Monk 1987).

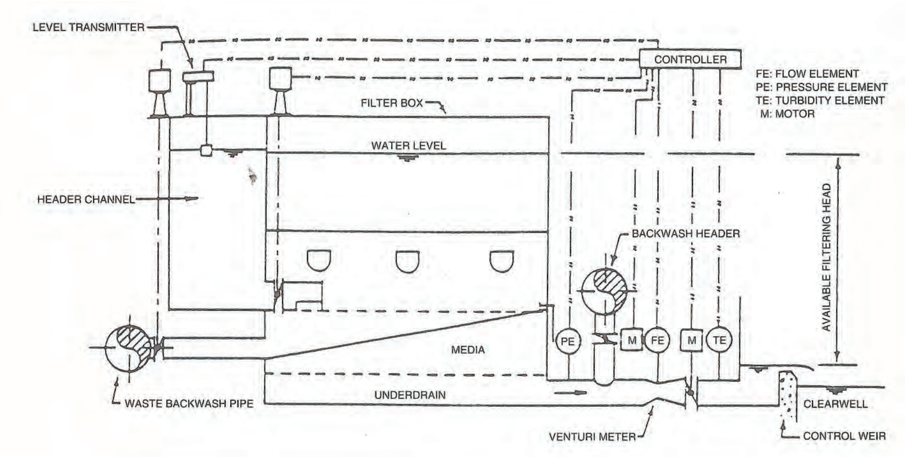


Figure 29: Constant rate with rate of flow controller (Monk, 1987).

The fifth method of filtration rate control is the Constant Rate filter with rate-of-flow controller as depicted in Figure 29. In this mode of control, water levels in all the filters and the inlet channel is kept at a constant level. The plant flow is split proportionally between all the filters. As the filters clog or a filter is taken off-line, a level sensor in the common inlet channel detects the increase and sends a signal to the filters to increase/decrease the flow rate as required.

7.2.3. Filter Backwash Requirements

Backwash rates are a function of media particle size and the mode of backwashing envisaged. Combined air and water backwashing is recommended for deep coarse bed filters usually used for high rate filtration. An important consideration when selecting the backwash mode is the design of the under-drain system.

Higher rates may result in greater passage of particles through the filter at the beginning of the run. The management of filter ripening needs to be addressed at the design stage. Options are to filter-to-waste, to operate with a slow start or to add polymers in the backwash water.

7.2.4. Pre-treatment

Pre-treatment for high rate filtration is the same in principle as pre-treatment for conventional rapid filtration and will depend on the quality of the raw water. However, since high rate filters are more sensitive to poor pre-treatment than conventional filters, it is most important that pre-treatment be closely controlled and optimised.

Optimal coagulation is especially important. For filtration rates greater than 10 m/h, polymeric coagulants are required to achieve acceptable filtrate turbidities (Sindt et al., 1990). This can be achieved by the use of cationic polymeric filter aids in addition to inorganic coagulants such as alum (aluminium sulphate) or ferric chloride, or the use of polymeric blends as primary coagulants. When upgrading their filters to higher rates, plants may have to reassess their coagulation regimes and switch to coagulants which produce a stronger floc. Since high rate filters require the use of polymers, they should always be designed with auxiliary backwash systems in order to prevent the rapid development of mudballing problems.

Filter influent water turbidities (following sedimentation, flotation, up-flow or roughing filtration) of 3 to 5 NTU are recommended to achieve filtrate turbidities of <0.5 NTU. However, high rate filters can also be operated in direct filtration mode (the sedimentation step is eliminated) provided that the raw water is of a consistently good quality (will include a guideline turbidity range based on results) and that optimal coagulation can be maintained at all times. This generally requires a sophisticated control system which can respond instantaneously to changes in raw water quality as the lag time between coagulant addition and filtration is reduced to a matter of minutes.

7.2.5. Monitoring and Process Control

Operating filters at high filtration rates leaves very little room for error and it is recommended that each filter be fitted with on-line turbidity meters. Monitoring of the upstream processes is critical and it is recommended that the coagulation and flocculation unit processes be monitored every two hours. Optimization jar tests should be done on a weekly basis or when the raw water turbidity changes by more than 20% if a streaming current monitor is being used to optimize coagulation.

7.3. Uprating Existing Filters

In some cases where coarse bed or multimedia filters are being operated at conservative rates, it may be possible to increase filtration rates with minimal design and process changes. A change in coagulation regime and tighter process control including the installation of on-line instrumentation may be necessary. Impact on filter ripening need also be considered. Rates should be stepped up gradually and pilot plant trials are recommended where possible.

Where an existing filter bed design is not suitable for high rate filtration (e.g. the filter media is too fine and the bed is too shallow) options are limited. Coarser media requires deeper beds and the depth of the bed is limited by the depth of the existing filter compartment (water level above filter media during both filtration and backwashing needs to be considered). Modifications to backwash system and rates might also be required if the filter media is changed, as might modifications to influent arrangements to prevent scouring of the bed during filtration. Managing filter ripening at higher rates may also require some design modifications.

If the design modifications required to uprate the filter are feasible, then similar specifications as in new filter designs apply regarding pre-treatment, process monitoring and control, operator training.

7.4. Design of New Filters

Before any filtration plant is upgraded a detailed engineering study of the existing plant must be undertaken. The evaluation must not be limited to the filtration unit process, but must include the following areas as well:

- Chemical dosing systems
- Hydraulics of the existing plant to determine whether pipes/channels can handle the increased flow rate
- Weir loading rates
- Detention times
- Flocculation and Mixing Energy
- Pilot plant filtration studies including pilot and control filters

A pilot study must be undertaken to determine the design criteria as these will differ for each water source and climatic operating conditions, especially with regard to temperature for coagulation and backwashing.

7.5. Uprating Existing Filters

In order to determine the eligibility of a plant for uprating, the following parameters should be taken into consideration:

- Does the plant receive water from a river or dam? Preference should be given to plants that receive water form an impounded dam as this would provide a consistent raw water quality in terms of turbidity, algae, TOC and alkalinity.
- Efficient pre-filtration treatment
- Good compliance history
- 24-hour operation
- Existing settling water turbidity below 3 NTU for 95% of the time
- Combined filtered water turbidity 0.2 NTU or less 95% of the time

7.6. Detailed Process Engineering Assessment

A detailed process engineering assessment must be undertaken by a professional engineer or suitably qualified person. The study should include the following:

- Detailed pilot plant study with sufficient results that can be translated to full scale operation.
- Detailed water quality assessment including a report on the raw water, clarified water and filtered water, reporting statistical (minimum, maximum, average, 95th percentiles) data for a minimum of a one year study period.
- Graphical representation of settled and filtered water turbidity.
- Head loss profiles over a 24 hour period for pilot and control filters.
- Filter run lengths and backwash periods must be documented.
- A suitably qualified process controller should be present at all times while the plant is in operation.

Designing filters that can operate at high filtration rates will result in the least number of filter units at a reduced capital cost without compromising on filtered water quality. South African engineers need to note the recommendations in this report and implement them where feasible. It is, however, accepted that many new installations and upgrades of existing plants are poorly planned and engineers will thus take the conservative route when designing the one of the final barriers to the treatment process. The use of high rate filters in South Africa will only be feasible when process and civil engineers are given a 3-5 year planning period which will allow them to undertake the detailed pilot plant testing that is required to minimise the risks associated with the application of this technology.

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