

ASSESSMENTS AND IMPROVEMENT OF FILTER MEDIA CLEANLINESS IN RAPID GRAVITY SAND FILTERS

by

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Optimal Performance and Quality of the Filtrate*”**

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EXECUTIVE SUMMARY

Introduction

Rapid sand filtration is an essential unit process in the water purification process. It captures and removes coagulated and flocculated material and other suspended matter not removed during the preceding treatment processes. The pores in the filter bed gradually become clogged and the media progressively collects deposit through the continuous use and life of the filter. During normal operations cleaning is initiated by excessive head loss, deterioration in filtrate quality or when the predetermined time for a filter run has elapsed. Air scour, to remove deposit from filter media by vigorous agitation, and wash water, to remove this deposit from the filter bed, are applied. The combined action of air and water should quickly return the media to its original perfectly clean state for the cycle to continue. However, on inspection it is often found that filter sand on purification plants is unacceptably dirty and backwash systems are clearly incapable of cleaning the media to its initial state of cleanliness. It is at times possible to relate the dirty filter media to faulty designs or poor operating procedures, but often the reasons for the media deterioration remain elusive and the media becomes dirtier the longer it is in use.

As there was an almost complete lack of published or agreed upon procedures to measure the cleanliness of filter media, rudimentary methods for measuring filter media cleanliness and backwash efficiency were developed. Thereafter filter media from full-scale treatment plants was analyzed with these methods at regular intervals to establish some benchmarks for these determinants. These methods were also applied during the laboratory and pilot plant phases of the project.

Aims of the project

The broad aims of the project were:

- To establish a reliable procedure to measure the cleanliness of filter media in order to enable quantification of backwash efficiency.
- To determine the nature of the deposit on the media in a consistent way in order to identify the mechanisms that caused media deterioration.
- To isolate and chemically identify extra-cellular microbial compounds present in the deposit on the filter media, which rendered the media sticky and difficult to clean.
- To conduct a wide representative survey of South African water treatment plants to benchmark the general efficiency of backwash procedures and media cleanliness, to determine the leading causes of media deterioration and to suggest general ways in which South African treatment plants could improve their backwash efficiency.
- To quantify potential operational and capital savings that could be realised by implementing a multi-cycle sequential filter cleaning procedure.
- To quantify potential operational and capital savings that could be realised by implementing some *in situ* rehabilitation procedures.

During the course of the project, the methods that were designed and tested earlier to characterize and quantify specific deposit on filter media were used with notable success.

Overall cleanliness of the filter media

Analysis of the composition of specific deposit present on filter media before and after normal cleaning operations gives an indication of the amount of specific deposit that has accumulated in the filter media. These analyses show that only a relatively small fraction of the overall specific deposit present is removed by the normal filter cleaning process. This is illustrated by the fact that the removal efficiency by back washing on the plant or procedures that are similar to normal cleaning procedures are: back wash on plant $\pm 19\%$, controlled conditions in laboratory $\pm 29\%$, standardised inversion method $\pm 52\%$. The fraction that can only be removed by an acid wash is $\pm 80\%$ and was not included in the above as this would describe an extraordinary measure and in most cases was due to calcification of the filter media. These results support the qualitative observation that filter media at treatment plants in general, after a few years of operation, are unacceptably dirty and that this is a function of the local conditions.

Washout kinetics of specific deposit removal

Results confirmed that it is more beneficial to apply shorter consecutive applications of an air scour followed by a back wash than a single back wash only or a single air scour followed by a back wash. Most of the specific deposit is removed by the first two bed volumes of back wash that is applied. It is possible to remove 22 % more deposit by applying the consecutive air scour and back wash procedure and still use the same total volumes of air and wash water. Since the same amount of air and wash water is used there would be no saving on consumables and maintenance costs may increase slightly as equipment is activated twice as much. It was not possible to quantify the long-term benefits of improved filter media cleanliness on items such as increased filter run times, quality of filtrate and sustained quality of the filter media. However, all indications are that the removal of deposit will improve by applying the alternative washing regime, *i.e.* sequential cleaning cycles resulting in cleaner filter media, longer filter runs and improved filtrate quality.

The nature of the specific deposit

The specific deposit on the filter media analysed at the treatment plants was composed of a biological fraction, an inorganic acid-soluble fraction and inert inorganic material that was not soluble in acid. The presence of extracellular polymeric substances, which is a direct measure of biological activity, seems to be a key factor in the removal of specific deposit.

Seen as a whole, the specific deposit at the different treatment plants is a complex substance with very wide variations from treatment plant to treatment plant. It seems unlikely that a single in-situ rehabilitation strategy will be adequate for all filter media problems. The nature of the specific deposit will have to be determined first using one or more of the methods described in the report, which may then suggest the most appropriate rehabilitation strategy.

Combined effect of chemical treatment and back washing

An improvement of $\pm 12\%$ in the removal of specific deposit was observed following the application of chlorine in the form of calcium hypochlorite and applying a normal back wash procedure. This improvement can be attributed to the oxidation and degradation of the organic matter in the filter media.

Recommendations for future investigations

A number of issues as listed below could not be properly addressed during the investigation due to the fact that that it did not stretch over a long enough period and new potential areas of investigation were identified that warrant further investigation.

- Investigation into the long term effects of single *versus* double cleaning procedures, in combination with or excluding oxidation, on the quality of the filtrate and filter media as well as the associated operational costs.
- Investigate the difference in the performance of virgin media compared to used or encrusted media in terms of the removal efficiency of suspended matter in order to determine criteria to replace spent filter media.
- Investigate the effect of an *in situ* chemical method of filter rehabilitation on filtrate quality and subsequent filter run time.
- Investigate the composition and the fate of deposit remaining in or on filter media after soaking of the filter media with an oxidant.
- The effect of chlorination of water prior to filtration on the sand's affinity to trap suspended matter and the effect of such oxidation on factors that may influence the removal of suspended matter.
- Removal efficiency of algae and invertebrates by sand filters and the efficiency of different cleaning procedures to remove these organisms from the filter media.

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An Investigation into Alternative Methods to Clean Filter Media in Rapid Gravity Sand Filters to Ensure Optimal Performance and Quality of the Filtrate

The Steering Committee responsible for this project consisted of the following persons:

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LIST OF SYMBOLS/TERMINOLOGY

AASD	After acid specific deposit
ACSD	After column specific deposit
AISD	After inversion specific deposit
APSD	After plant specific deposit
BD	Bulk density
DF	Dilution factor
$d_{\text{percentile}}$	Percentile of diameter of media grains
EDS	Energy dispersive spectroscopy
EPS	Extracellular polymeric substances
FH1	Filter house 1. at Vereeniging Purification Plant
FH3	Filter house 3. at Vereeniging Purification Plant
ICP-OES	Inductively coupled plasma – optical emission spectroscopy
MC	Moisture content
MD	Material density
ME	Media
NS	Non-soluble
NTU	Turbidity (nephelometric turbidity units)
NV	Non-volatile
S	Soluble
SD	Specific Deposit
SUVA	Specific UV absorption
TSS	Total suspended solids
UC	Uniformity coefficient
V	Volatile
WW	Wash water
ε	Porosity

CHAPTER ONE – INTRODUCTION

1.1 Background

Filtration theory suggests that a sand filter starts its life with new, perfectly clean media. During each filtration cycle, its media pores become gradually clogged as the particles are trapped as *specific deposit*. When the specific deposit builds up to a point where either the head loss or the filtrate quality reaches their acceptable limits, the backwash cycle is initiated. The combined action of air and water quickly returns the media to its original perfectly clean state, and so the cycle continues.

The reality is different. It is common practice to return to a treatment plant a decade or more after its commissioning to find filter sand that is unacceptably dirty, with backwash systems that are clearly incapable of cleaning the media to its initial state of cleanliness. Frequently, it is easy to pinpoint the source of the problem – faulty design, substandard construction practices, gross negligence of operators, well-meant but disastrous attempts to “fix” earlier problems, *et cetera*. These problems have been systematically reviewed earlier (Lombard and Haarhoff, 1995). However, in a significant number of cases, the reasons for the media deterioration remain elusive. The design, construction and operation seem to be on par with the best international practice, yet the media steadily becomes dirtier and dirtier.

As a consequence, the Water Research Group at the University of Johannesburg started about five years ago with an investigation directed at this phenomenon. Following the adage of “to measure is to know”, it was immediately apparent that there was an almost complete lack of published or agreed procedures to measure the cleanliness of filter media. The first two years were therefore used to develop some rudimentary methods for measuring filter media cleanliness and backwash efficiency. Thereafter, the investigation progressed to the next step of visiting full-scale treatment plants at regular intervals to establish some benchmarks for these parameters. As a better picture emerged of the causes and nature of filter media deposit, a research proposal could be developed with clearly defined objectives and deliverables, which formed the basis for the project reported in the following pages. Besides the specific research objectives of this project, this report also provides an opportunity to consolidate and describe the numerous procedures developed for filter cleanliness assessment – a first draft of a “procedures manual”, if the reader so wishes.

It is of special relevance to note that the initiatives described above, unknown to the research team, were closely paralleled by similar ones in the USA. Earlier in 2005, a manual sponsored by the American Water Works Association entitled “Filter Troubleshooting and Design Handbook” became available. Although the scope and emphasis of that manual is different from what was done here, it underscores the increasing awareness that the *maintenance* and *rehabilitation* of filters deserve the same care and diligence as the proper *design* and *construction*, which were the main concerns in the past.

1.2 Aims and Deliverables

The research proposal stated the following broad aims for the project:

- To establish a reliable procedure to measure the cleanliness of filter media to enable the quantification of backwash efficiency

- To determine the nature of the deposit on the media in a consistent way in order to identify the mechanisms that caused the media deterioration.
- To isolate and chemically identify extra-cellular microbial compounds present in the deposit on the filter media, rendering the media sticky and difficult to clean.
- To conduct a wide representative survey of South African water treatment plants to benchmark the general efficiency of backwash procedures and media cleanliness, to determine the leading causes of media deterioration and to suggest general ways in which South African water treatment plants could improve their backwash efficiency.
- To quantify potential savings, operational and capital, that could be made by implementing the multi-cycle sequential filter cleaning procedure.
- To quantify potential savings, operational and capital, that could be made by implementing some *in situ* rehabilitation procedures.

The following deliverables were identified as specific objectives for this project:

- Investigate and describe chemical methods to analyse and identify residues from filter media for both inorganic and organic compounds.
- Define all determinations to be done and procedures to be followed to measure the effect of multi-cycle sequential washing operations compared to single cycle washing operations, with and without the addition of chemicals, on an experimental filter unit.

These above two deliverables deal with the development and standardisation of new analytical methods, which are fully reported on in Chapter Two of this report.

- Collect representative filter media samples from water treatment plants operating under different climatic conditions, using different water treatment techniques and abstracting water from different sources, during low-temperature winter conditions.
- Same, but under warm-water conditions in summer.

These visits were conducted as planned, with the results reported in Chapter Three.

- Chemically analyse and identify residues from Rand Water filter media.
- Chemically analyse and identify residues from filter media representative of South African treatment plants.

These deliverables formed the analytical work that emanated from the full-scale treatment plant surveys, reported on in Chapter Three.

- Perform multi-cycle sequential washing operations and single cycle washing operations, with and without the addition of chemicals, on used and virgin filter media as used by Rand Water according to the protocol developed.

This deliverable relates to the pilot work done at Rand Water and is reported on in Chapter Four.

- Perform multi-cycle sequential washing operations and single cycle washing operations, with and without the addition of chemicals, on used and virgin filter media representative of South African treatment plant according to the protocol developed.

This deliverable relates to a full-scale experiment to evaluate in situ chemical rehabilitation. It is reported on in Chapter Five.

- Treatment of water before filtration with oxidants.

The deliverable is reported on in Chapter Six.

- Quantify potential savings; operational and capital, that could be made by implementing the multi-cycle sequential filter cleaning procedure.

This is covered in Chapter Seven.

- Categorise filter media according to material type, chemical analyses of residues and response to various cleaning procedures.

This deliverable entails the electronic compilation of all data used in this project, which is submitted as a compact disc accompanying this report.

CHAPTER TWO – DEFINITIONS AND EXPERIMENTAL METHODS

2.1 A Proposed Conceptual Framework

2.1.1 Measures of the mass of filter media deposit

The specific deposit found on filter media is a complex matrix, which varies significantly in terms of physical properties and chemical composition. To achieve consistency for comparing the results amongst different treatment plants, four progressive “states of cleanliness” had to be adopted:

- APSD (After Plant Specific Deposit). This is a measure of how clean the filter media was *after the media had been backwashed by the backwash system at the treatment plant*. Where the same filter bed had been subjected to more than one consecutive wash, the state of cleanliness is designated by APSD [1] after the first wash, APSD [2] after the second wash, and so on.
- ACSD (After Column Specific Deposit). This is a measure of how clean the filter media was *after the media had been washed under standardised conditions in a laboratory column*. This backwash rate was selected to be close to the point where hydrodynamic shear was at its maximum (Amirtharajah *et al.*, 1991), and the wash was continued for five minutes.
- AISD (After Inversion Specific Deposit). This is a measure of how clean the filter media was *after it had been subjected to standardised agitation and cleaning in the laboratory*. The standardised agitation was achieved by placing the media in a measuring cylinder with water, and inverting the cylinder a fixed number of times, which is described later on in detail. Of six different methods that were comprehensively compared (Van Staden and Haarhoff, 2004), this method was the best compromise between reproducibility and simplicity.
- AASD (After Acid Specific Deposit). This is a measure of how clean the filter media was *after it had been immersed in a strong acid*. At this point, the filter media should be perfectly clean and in practically the same state as when it was new.

Specific deposit could consist of “hard” calcium carbonate precipitates, (gradually formed on the media under certain chemical conditions) which are practically impossible to remove by normal physical means, as well as the “soft” matrix of particles temporarily detained in the filter bed before being washed out during the next backwash cycle. The border between “hard” and “soft” deposit is necessarily arbitrary - the more aggressive the stripping method, the more deposit will be removed. The AISD was adopted as the border between “hard” and “soft” deposit. As this project is about the efficiency of treatment plant backwash systems, only the “soft” deposit should be considered, as the “hard” deposit is commonly considered to have become part of the media. The benchmark for perfectly clean media that can be achieved by physical means only is therefore taken as the AISD state of cleanliness.

The four definitions above can now be mathematically juggled to obtain quantitative measures such as:

- (AISD – AASD) is a measure of the “hard” deposit only
- (ACSD – AISD) is a measure of that “soft” deposit, which cannot be removed by backwashing only. This fraction indicates a recalcitrant, sticky deposit, which will not be removed regardless of how well the plant backwash system works.

- (APSD[1] – ACSD) is a measure of how much specific deposit can be washed out in the laboratory, but not at the treatment plant. This is therefore a measure of “backwash inefficiency” of the treatment plant.
- (APSD[1] – ACSD[2]) is a measure of how much specific deposit could be washed out with a second consecutive wash at the treatment plant.

2.1.2 Measures of the nature of filter media deposit

The “soft” deposit can be further separated within a two-way classification, namely in terms of its *acid solubility* (NS = non-soluble *versus* S = soluble) and its *volatility* (NV = non-volatile *versus* V = volatile). This allows an operational interpretation:

- NS/NV is the inert, inorganic material such as silica and clay particles in the raw water.
- S/NV is the inorganic, soluble material such as ferric hydroxide or calcium carbonate, which originates within the treatment plant after chemical dosing.
- NS/V and S/V (the latter usually a negligibly small fraction) are lumped together and considered to be biological in origin.

A further, more detailed analysis is provided by *elemental analysis*, which provides the elemental composition of between 15 and 23 different elements.

2.2 Methods Relating To Filter Media Sampling

A tool referred to as a ‘core sampler’ was used if a representative sample through the entire bed was required. A core sampler is a steel tube with an internal diameter of 35 mm, with depth markings. A valve is welded at one end to close the tube after pushing it vertically into the media. When the core sampler is pulled out, this caused a negative pressure within the tube that prevented the media from ‘spilling’ during transfer to a suitable container. In the case of the core sampler being unable to lift the sample from the bed, undisturbed samples had to be obtained by digging by hand.

Due to the horizontal variance of filter deposit within a bed, it was necessary to sample at three or more locations in the bed and to combine the sample composites. The sample had to be homogenised without premature stripping of the filter deposit present on the media grains. For this purpose, a riffle splitter (as used in standard geotechnical laboratories) was used to split the sample five consecutive times. Thereafter, the sample was sealed in a plastic bucket or bag and refrigerated until analysis, which was done as soon as possible after sampling.

2.3 Methods Relating To Filter Media Characterisation

2.3.1 Moisture content

The moisture content (MC) of media samples differ with respect to draining duration and time elapsed before sampling. Therefore, the moisture content of each sample was determined to use for correction of values from wet mass to dry mass for further analysis of the results.

Approximately 40 to 60 ml of each media sample was, therefore, weighed and placed in an evaporating dish, dried at 105°C and weighed again to provide a measure of the moisture content of the particular media, using the equation below:

$$MC = \frac{\text{wet sample}(g) - \text{dry sample}(g)}{\text{wet sample}(g)} \dots\dots\dots[2.1.1]$$

This measure could then be used as follows to obtain a dry mass for the media sample:

$$\text{dry mass}(g) = \text{wet mass}(g) \times (1 - MC) \dots\dots\dots[2.1.2]$$

2.3.2 Sieve analysis

After washing in a portable column, the media sample was placed in an oven for 24 hours at 110°C.

The sample was weighed and transferred to the top sieve of an assembly of weighed US standard sieves (200 mm in diameter and 50 mm in height) of the following mesh sizes: bottom pan, 250µm, 300µm, 425µm, 500µm, 600µm, 710µm, 850µm, 1180µm, 1400µm, 1700µm, 2000µm, 2360µm, and 2800µm, as well as a top lid. The sample was sieved for 6 minutes using a sieve shaker with automatic timer and the new mass of each sieve determined to the nearest 0.01 g (Ceronio and Haarhoff, 1997). These masses were then used to calculate d_{10} , d_{60} and the uniformity coefficient (UC) of the media as follows:

$$\% \text{ retained on each sieve} = \frac{\text{mass of sieve fraction}(g) \times 100}{\sum \text{mass of sieve fractions}} \dots\dots\dots[2.2.1]$$

$$\text{cum. \% passed through each sieve} = 100 - \sum \text{cum. \% retained on each sieve} \dots\dots\dots[2.2.2]$$

$$d_{\text{percentile}} = \left(\frac{10 - \text{upper \%}}{\text{lower \%} - \text{upper \%}} \times (\text{lower size} - \text{upper sieve size}) \right) + \text{upper size} \dots\dots[2.2.3]$$

where: % are taken as cum. % passed through sieve size

$$UC = \frac{d_{60}}{d_{10}} \dots\dots\dots[2.2.4]$$

If the sum deviated more than 2.0 g from the initial test sample weight, the analysis was repeated.

2.3.3 Dry bulk density and material density

The method used was taken from Haarhoff (1982):

- The mass of a 500 ml measuring cylinder was determined and recorded as (a).
- Wet media was then transferred into the measuring cylinder to about the halfway mark and the mass recorded as (b).
- Water was then added to the cylinder containing the media to the 500 ml level and the mass recorded as (c).
- By placing a hand over the mouth of the cylinder, it was gently inverted to dislodge trapped air bubbles between the grains, taking care not to disturb the media excessively.

- The level of the media (*d*) and the water (*e*) were then recorded and the contents of the cylinder emptied.
- The cylinder was then filled up to level (*d*) and the mass recorded as (*f*), and then to level (*e*) and the mass recorded as (*g*).

In order to determine the dry bulk density (BD), the following calculations were made, bearing in mind that 1 g of water occupies a volume of 1 ml. NOTE: Masses are recorded in g, volumes in ml and densities in kg/m³:

$$\text{Mass of dry media} = (1 - MC) \times (b - a) \dots\dots\dots [2.3.1]$$

$$\text{Mass of water to level (d)} : h = f - a \dots\dots\dots [2.3.2]$$

$$BD = \frac{\text{mass of dry media}}{h} \times 1000 \dots\dots\dots [2.3.3]$$

The density of the material (MD) was also determined as follows:

$$\text{Mass of water between levels (d) and (e)} : i = (f - a) - (g - a) \dots\dots\dots [2.4.1]$$

$$\text{Mass of cylinder + media + water to level (d)} : j = c - i \dots\dots\dots [2.4.2]$$

$$\text{Mass of water in media at level (d)} : k = j - a - \text{mass of dry media} \dots\dots\dots [2.4.3]$$

$$MD = \frac{\text{mass of dry media}}{\text{volume of media}} \times 1000 \dots\dots\dots [2.4.4]$$

where : Volume of media = *d* - *k*

2.3.4 Porosity

Porosity (ϵ) can be determined from the same measurements described above, using the following equation:

$$\epsilon = \frac{k}{h} \dots\dots\dots [2.5]$$

2.4 Methods Relating To Filter Cleanliness

2.4.1 Contribution of “hard” deposit (AISD – AASD)

In all cases, samples for the acid solubility test were taken after the filter was backwashed once at the plant. The procedure for acid solubility testing of the media was taken from AWWA B100-89 (1989).

A glass beaker was weighed and its mass recorded. A minimum of 350 g of wet media was placed in the beaker and weighed. The sample was dried in an oven at 110°C ± 5°C. The beaker is allowed to cool and the mass of the beaker with dry media recorded. 20% HCl

solution was added slowly to the media (enough to immerse the sample completely) and the volume of acid solution added was recorded.

The mixture was stirred occasionally and allowed to stand until effervescence ceases. The “dirty” acid was drawn off for further analyses and the media sample washed several times in tap water and dried at $110^{\circ}\text{C} \pm 5^{\circ}\text{C}$. Once dry, the sample was allowed to cool and the mass of the acid-stripped media recorded.

Using the dry bulk density (in kg/m^3) previously determined for the media, the contribution of “hard” deposit (AISD – AASD) could be determined as follows:

$$(\text{AISD} - \text{AASD}) (\text{kg}/\text{m}^3) = \frac{(\text{mass before stripping}(g) - \text{mass after stripping}(g))}{1000 \times \text{volume}(\text{m}^3)} \dots\dots\dots [2.6.1]$$

$$\text{where : Volume}(\text{m}^3) = \frac{\left(\frac{\text{dry mass}(g)}{1000} \right)}{\text{dry bulk density}(\text{kg}/\text{m}^3)}$$

$$\% (\text{AISD} - \text{AASD}) = \frac{(\text{AISD} - \text{AASD})(\text{kg}/\text{m}^3)}{\text{dry bulk density}(\text{kg}/\text{m}^3)} \dots\dots\dots [2.6.2]$$

2.4.2 Contribution of “soft” deposit (ACSD – AISD)

Three samples of approximately 60 ml each were measured out and their exact dry mass determined, as outlined under *moisture content* earlier. Each sample was treated as follows:

The sample was placed in a 250 ml measuring cylinder, with 100 ml of clean tap water, sealed and inverted 20 times, with pauses between inversions to allow the media to settle at the bottom. The resultant suspension was drained into a clean, dry 500 ml Erlenmeyer flask. The procedure of adding 100 ml of water, inverting and decanting was repeated four times until the flask contained a 500 ml sample.

Two methods were used to determine how much deposit was stripped from the media. The first was that of a turbidity measurement (expressed as nephelometric turbidity units or NTU/100 g media), using a HACH ratio turbidimeter (Model 18900 with a range of 0-200 NTU). This was done by vigorously stirring the suspension, rapidly transferring the sample into the sample cell and taking consecutive readings at 5s intervals, starting at 5 s and ending at 30 s. The average of the six readings was taken as the representative turbidity of the sample.

Some samples did require dilution before they were within the measuring range of the instrument, therefore requiring the use of a dilution factor (DF) as shown below:

$$DF = \frac{\text{ml sample} + \text{ml clean water}}{\text{ml sample}} \dots\dots\dots [2.7.1]$$

$$NTU = \text{measured NTU} \times DF \dots\dots\dots [2.7.2]$$

The second method was based on the mass of solids in suspension, i.e. suspended solids.

Whilst vigorously stirring the resultant suspension, 20 ml to 100 ml was drawn off (depending on how “dirty” the sample was), and filtered through a weighed glass-fibre pre-filter, using filtration apparatus. *Standard Methods* procedure 209C was followed and the total suspended solids (TSS) of the sample determined as follows:

$$TSS(mg/\ell) = \frac{\text{dried residue}(mg) \times 1000}{\text{sample}(ml)} \dots\dots\dots [2.8.1]$$

In order to allow for a direct comparison of the specific deposit stripped from the media by the three methods, a common unit of measure needs to be used and it is suggested that a mass per volume measurement would best facilitate such a comparison. This was made possible by the bulk density, moisture content and media mass measurements previously determined for the media during testing. NOTE: In the absence of a moisture content value the median value of all other moisture contents was taken, i.e. 15.4%.

The following conversion was made to obtain the contribution of the “soft” deposit in terms of kg/m³ from suspended solids in mg/l:

$$(ACSD - AISD) (kg/m^3) = \frac{\left(\frac{TSS(mg/\ell) \times 0.5}{1000000} \right)}{\text{volume}(m^3)} \dots\dots\dots [2.8.2]$$

$$\text{where : Volume}(m^3) = \frac{\left(\frac{\text{dry mass}(g)}{1000} \right)}{\text{bulk density}(kg/m^3)}$$

NOTE: In most instances, the tests were performed in triplicate and, therefore, the median of the three values was taken to obtain a single value for “soft” deposit.

2.4.3 Measurement of “backwash inefficiency” (APSD[1] – ACSD)

A sample of ± 2 kg filter media was obtained after backwashing at each plant. This media was then transferred to a portable column, ensuring a media depth of between 150 mm and 250 mm. The column dimensions measured 100 mm in diameter (later adjusted to 70 mm) and 1000 mm in length. The column was fitted with rotameters and a manometer (see schematic) and was used to measure bed expansion, as well as backwash rate. The temperature of the water flowing through the column was also noted.

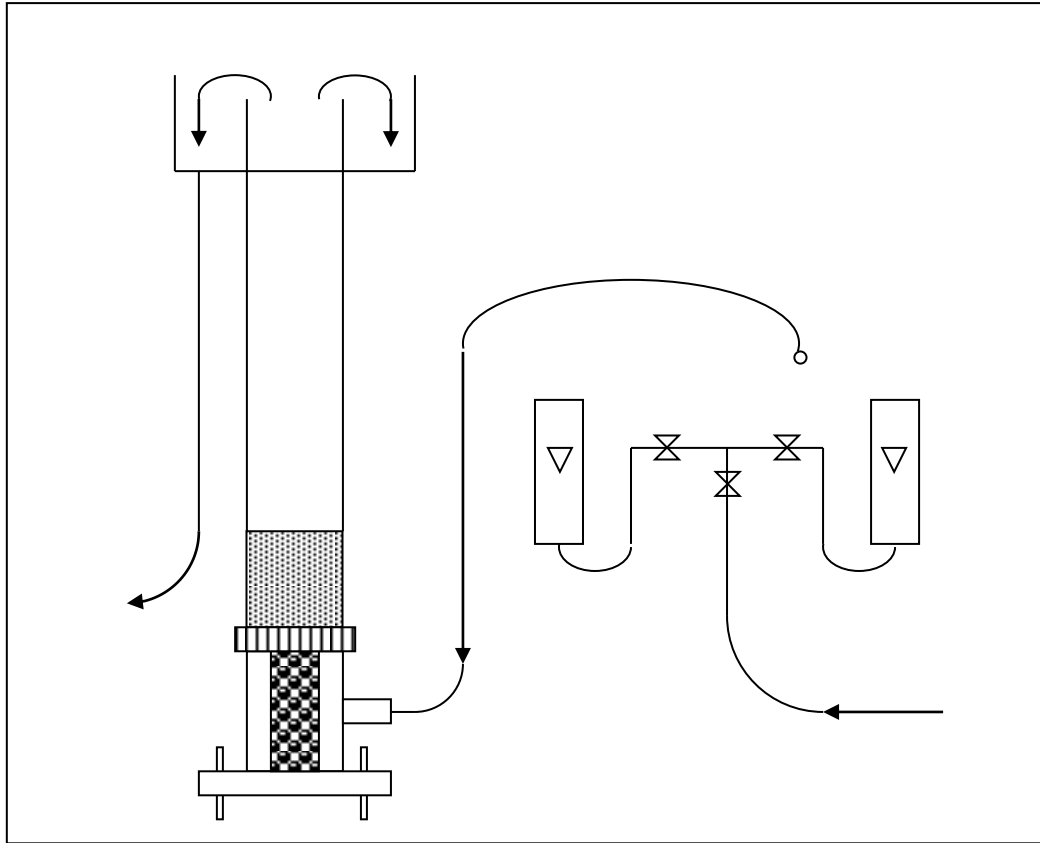


Figure 2.1: Schematic of portable column used for column washing of the media samples.

The depth of the media in the column was noted and the flow through the column set to 305 ℓ/h in the 100 mm diameter column (2003 sampling run), 150 ℓ/h (2004 sampling runs) and 225 ℓ/h (2005 sampling run) in the 70 mm diameter column, which are converted to backwash rates of 10.8 mm/s (both 305 ℓ/h and 150 ℓ/h) and 16.2 mm/s respectively.

The washwater samples were taken at specific intervals of time, e.g. every 30 s. Therefore, the start of the time step would be taken as the time between the previous sampling time and the sampling time in question, whilst the end of the time step as the time between the sampling time in question and the following time. E.g. in the case of a 30 second interval, the 0 second sample would represent time 0-15 seconds, i.e. a 15 s time step length; the 30 second sample = 15-45 seconds, i.e. length = 30 s; the 60 second sample = 45-75 seconds, i.e. length = 30 s and so on. In the case of the final sampling time, the length of the time step would be taken as the same as the previous sample time's length, with the start of the time step taken as the time between the previous sampling time and the sampling time in question as before.

The following conversion equation was used to obtain a value for the “backwash inefficiency” (APSD[1] – ACSD) in terms of kg/m^3 from suspended solids in mg/ℓ :

$$(\text{APSD}[1] - \text{ACSD}) (kg/m^3) = \frac{(\text{APSD}[1] - \text{ACSD}) (kg/m^2)}{\text{bed depth}(mm)} \times 1000$$

where $(\text{APSD}[1] - \text{ACSD}) (kg/m^2) = \frac{TS(mg/\ell) \times \text{volume}(m^2)}{1000000}$ [2.9]

and $\text{Volume}(m^2) = \text{time step length}(s) \times \text{backwash rate}(mm/s)$

NOTE: In order to get a single value to represent “backwash inefficiency” per backwash, a cumulative total was taken of the (APSD[1] – ACSD) values.

In the case of plant backwashing, the backwash rate was measured by noting the time taken (in s) for the water to rise a certain height (in mm) within the filter, thereby giving us the backwash rate directly in mm/s.

2.5 Methods Relating To The Nature Of Filter Media Deposit

The value determined for total suspended solids (TSS) was quantitatively separated on the grounds of acid solubility as well as volatility at 550°C.

2.5.1 Acid soluble and non-soluble fractions

“Non-soluble solids” is the term applied to the residue of total, suspended, or dissolved solids that remain after treatment with an acid solution.

10 ml of a 0.185M (20%) HCl solution was mixed with 100 ml of the suspension and *Standard Methods* procedure 209C followed again to determine the total non-soluble solids (NS) of the sample, as follows:

$$NS(mg/\ell) = \frac{\text{non - soluble residue}(mg) \times 1000}{\text{sample}(ml)} \dots\dots\dots[2.10]$$

2.5.2 Volatile and non-volatile fractions

“Non-volatile solids” is the term applied to the residue of total, suspended, or dissolved solids remaining after ignition for a specified time at a specified temperature. The mass loss on ignition is called "volatile solids". However, the determinations of non-volatile and volatile solids do not distinguish between organic and inorganic matter, as the loss on ignition cannot be confined to organic matter, but also includes losses due to decomposition or volatilisation of some mineral salts.

Using *Standard Methods* procedure 209D and the filtrates obtained for TSS and NS, the total non-volatile solids (NV) and the total non-soluble non-volatile solids (NS/NV) of the sample were determined:

$$NV(mg/\ell) = \frac{\text{non - volatile residue}(mg) \times 1000}{\text{sample}(ml)} \dots\dots\dots[2.11.1]$$

$$NS / NV(mg/\ell) = \frac{\text{non - soluble non - volatile residue}(mg) \times 1000}{\text{sample}(ml)} \dots\dots\dots[2.11.2]$$

The above values were then used to determine the unknown values in the table below, thereby, characterising the filter media residue in terms of four values:

Table 2.1: Suspended solids composition matrix

	Soluble	Non-soluble	Total
Volatiles	SV (A - B - C + D)	NSV (B - D)	(A - C)
Non-volatiles	SNV (C - D)	NSNV D	NV C
Total	(A - B)	NS B	TSS A

By using the percentages of the fractions obtained for each sample, the amount of solids of each fraction of the matrix in kg/m^3 could be determined through simple multiplication. Once this was done for each sample, the median values were determined to provide insight into the composition of the physical strippable specific deposit.

As in the case of the “soft” deposit, the percentages of the fractions obtained for each backwash water sample could be used to determine the composition of the deposit in kg/m^3 . Once this was done for each sample, the cumulative values could be calculated through simple addition to provide insight as to the composition of the deposit attributable to “backwash inefficiency”.

2.5.3 Elemental analysis of specific deposit

Analyses of elements were done through either inductively coupled plasma optical emission spectroscopy (ICP-OES) or energy dispersive spectroscopy (EDS).

In order to prepare each sample for these analyses, 10 ml of 20% HCl was added to 90 ml of “soft” deposit or deposit attributable to “backwash inefficiency” and mixed thoroughly for a minimum of two minutes. In the case of the “hard” deposit, 10 ml of the “dirty” acid retained during the acid-stripping step is added to 90 ml of distilled water and mixed thoroughly for a minimum of two minutes.

Each of these resultant 2% acid solutions was then filtered through a pre-weighed glass pre-fibre filter and total suspended solids determined as outlined above. The same procedure was followed for the dilution waters to allow for the correction for the elemental content of the dilution water.

The filtrate was then used for ICP-OES analysis, which was used to analyse for between 16 and 18 elements, as listed in the table below (along with the quantitative detection limits of each element), with the output expressed in mg/l .

Table 2.2: Elements and limits for the ICP-OES analysis of this study.

Element	Limit (mg/l)	Element	Limit (mg/l)	Element	Limit (mg/l)
Lead (<i>Pb</i>)	0.10	Calcium (<i>Ca</i>)	0.05	Magnesium (<i>Mg</i>)	0.05
Barium (<i>Ba</i>)	0.05	Strontium (<i>Sr</i>)	0.05	Sodium (<i>Na</i>)	0.10
Manganese (<i>Mn</i>)	0.02	Copper (<i>Cu</i>)	0.02	Nickel (<i>Ni</i>)	0.05
Aluminium (<i>Al</i>)	0.10	Cadmium (<i>Cd</i>)	0.05	Cobalt (<i>Co</i>)	0.10
Iron (<i>Fe</i>)	0.05	Chromium (<i>Cr</i>)	0.05	Boron (<i>B</i>)	0.05
Zinc (<i>Zn</i>)	0.05	Lithium (<i>Li</i>)	0.10	Bismuth (<i>Bi</i>)	1.00

The dried residue was used for the EDS analysis. Each sample was coated with carbon and analysed for the presence of between 15 and 23 elements (see table below) using a JEOL scanning electron microscope. The results were reported as relative fractions of the total elements tested for.

Table 2.3: Elements for the EDS analysis of this study.

Lead (<i>Pb</i>)	Calcium (<i>Ca</i>)	Magnesium (<i>Mg</i>)
Barium (<i>Ba</i>)	Strontium (<i>Sr</i>)	Sodium (<i>Na</i>)
Manganese (<i>Mn</i>)	Copper (<i>Cu</i>)	Nickel (<i>Ni</i>)
Aluminium (<i>Al</i>)	Cadmium (<i>Cd</i>)	Cobalt (<i>Co</i>)
Iron (<i>Fe</i>)	Chromium (<i>Cr</i>)	Boron (<i>B</i>)
Zinc (<i>Zn</i>)	Lithium (<i>Li</i>)	Silicon (<i>Si</i>)
Phosphorus (<i>P</i>)	Sulphur (<i>S</i>)	Chlorine (<i>Cl</i>)
Potassium (<i>K</i>)	Titanium (<i>Ti</i>)	

2.5.4 Measurement of extracellular polymeric substances (EPS)

EPS extraction was performed using a centrifugation method on the “soft” deposit. The sample was homogenised by stirring thoroughly using a magnetic stirrer. While all the particles were still in suspension, 10 ml of the sample was added to the centrifuge tube and centrifuged for 5 minutes at 3500 rpm at room temperature. The supernatant was removed and stored in another container for further use.

The pellet was re-suspended in 10 ml of double distilled water and then homogenised for 30 s using a Cole–Parmer homogeniser with the output of 50%. The previously removed supernatant was then added to the homogenised supernatant. The mixture was centrifuged at 12 000 rpm at 4°C for 30 min. using a Sorvall RC-5B refrigerated centrifuge. The supernatant containing the EPS was collected using a 20 ml syringe without disturbing the pellet. The collected supernatant was filtered through a 0.22 µm Millipore filter. The filtrate was frozen using liquid nitrogen and freeze-dried for 24 h. The mass of the EPS (in mg/ml) was determined.

CHAPTER THREE – ANALYSIS OF FULL-SCALE TREATMENT PLANTS

3.1 The Full-Scale Treatment Plant Database

The broader problem of approaching filter media cleanliness in a quantitative way had been a challenge to the Water Research Group at the University of Johannesburg for a number of years, with much data being collected from full-scale treatment plants. The entire database of the Group was screened for data that could be relevant to the problem addressed in this investigation. These previous data sets have been added to the field data collected under this contract. The resulting database includes the following:

- Eight plants are included at seven different locations
- The plants were intermittently visited from May 2002 until January 2005
- A total of 31 plant visits were made, of which 10 were made under this WRC contract.

Not all the plant visits were conducted in exactly the same way. The investigations in the earlier visits were more exploratory and new questions were posed as the understanding improved. To enable the utilisation of the full data sets, some homogenisation of the data was necessary.

3.1.1 *Converting turbidity (NTU) to mass concentration (TSS)*

The entire database, including all measurements for all plant visits and laboratory tests, yielded 942 data pairs where both TSS and NTU were measured. The data was screened with the following rejection criteria:

- Where less than 5 mg of solids were captured on the filter paper, the values were rejected, following the recommendations of Standard Methods (1992). This eliminated 161 data pairs.
- For each data pair, the NTU/TSS ratio was calculated. The range of values indicated that it would be very unlikely that the ratio would be below 0.15 or above 2.0. The values that were outside this range, reflected gross measurement or transcription errors and were thus rejected. This eliminated 2 (<0.15) and 8 (>2.0) data pairs.
- Where there were less than 3 data pairs for each visit, no meaningful correlation could be made and this eliminated 4 more pairs.

The remaining 767 pairs represented 44 different sets, a set being the pairs collected during a specific date at a specific plant, measured for either the backwash water or the specific deposit tests on the media. The 44 resulting correlations were compared with a chi-square statistical test and could not be readily collapsed into larger sets, each one being significantly different ($\alpha = 0.05$). (The rejected hypothesis was that the correlations between say media and backwash samples at the same plant may have been statistically similar, or that the correlations for the same plant at different dates may have been the same, etc.)

Table 3.1: Summary of NTU/TSS ratios determined at full-scale treatment plants. (WW indicates ratios measured on washwater; ME indicates ratios measured on “soft” deposit.)

Plant	WW/ME	Date	N	Ave	Cov	
A	WW	09/2003	25	0.724	24%	
	ME	09/2003	13	1.468	15%	
	ME	02/2004	24	1.113	7%	
	WW	07/2004	3	0.989	3%	
	ME	07/2004	12	0.909	7%	
	WW	01/2005	11	0.862	36%	
B	ME	01/2005	11	0.808	14%	
	WW	09/2002	3	0.736	4%	
C	ME	09/2002	8	0.817	8%	
	ME	05/2002	53	0.451	16%	
D	ME	02/2004	112	0.337	22%	
	WW	08/2003	16	0.773	23%	
	ME	08/2003	21	1.086	6%	
	ME	02/2004	23	1.032	35%	
	WW	08/2004	6	1.034	15%	
	ME	08/2004	12	1.227	21%	
	WW	01/2005	11	0.605	41%	
	ME	01/2005	10	0.635	6%	
	E	WW	09/2002	4	0.527	2%
		ME	09/2002	12	0.491	11%
F	ME	05/2002	6	0.580	7%	
	WW	08/2003	18	0.397	9%	
	ME	08/2003	21	0.518	10%	
	ME	02/2004	15	0.508	16%	
	WW	07/2004	12	0.524	33%	
	ME	07/2004	24	0.622	21%	
	WW	01/2005	11	0.794	47%	
	ME	01/2005	10	0.855	8%	
G	ME	09/2002	8	0.969	48%	
	WW	09/2003	43	0.530	12%	
	ME	09/2003	27	0.677	12%	
	ME	02/2004	21	0.841	33%	
	ME	07/2004	6	0.585	8%	
	WW	01/2005	9	0.584	24%	
H	ME	01/2005	10	0.641	12%	
	WW	10/2002	6	0.464	28%	
	ME	10/2002	12	0.499	20%	
	WW	09/2003	52	0.536	19%	
	ME	09/2003	12	0.806	11%	
	ME	02/2004	12	0.693	43%	
	WW	07/2004	6	0.745	21%	
	ME	07/2004	9	0.810	22%	
	WW	01/2005	11	0.636	77%	
	ME	01/2005	11	0.931	15%	

Having these correlations, it became possible to express the backwash water turbidity results in terms of TSS. Where TSS values were measured and met the screening criteria, they were directly used. Where no direct TSS measurements were made and the screening criteria were not met (mostly during the latter part of the washes when the washwater became fairly clean and not enough solids were captured on the filter paper), the turbidity values were used and converted to TSS values using the correlations developed above.

A total of 55 washout tests were conducted (made up of 45 full-scale tests and 10 column tests conducted in the laboratory) representing 720 individual samples. Some 198 TSS values could be used directly, while 522 values had to be substituted. This data set formed the basis for the washout analysis reported later on.

3.1.2 *Converting specific deposit from mass/mass to mass/volume*

Before this project, the specific deposit on the filter media was expressed on a mass/mass basis, as mg/g. For the purpose of this report, and for future work, it is suggested that the specific deposit should be expressed on a mass/volume basis that is as kg/m³. This allows direct comparison between the specific deposit measured on media of different densities, for example silica sand, anthracite and granular activated carbon. To convert the values from a mass/mass basis to a mass/volume basis, the dry bulk density of the media is required. For example, the conversion 5.0 mg/g to a mass/volume basis is done as follows:

$$5.0 \text{ mg/g} = 5.0 \text{ g/kg}$$

But knowing that the dry bulk density is say 1300 kg/m³:

$$1 \text{ kg} = 1/1300 \text{ m}^3$$

Thus:

$$5.0 \text{ g/kg} = 5.0 * 1300 \text{ g/m}^3 = 5.0 * 1.3 \text{ kg/m}^3 = 6.5 \text{ kg/m}^3.$$

Up to January 2005, the specific deposit was measured for 194 different samples, of which 60 were from activated carbon, 28 from sand/anthracite mixtures and 106 from silica sand alone. The dry bulk density was measured on typical samples of each media type. The dry bulk density values used for converting all the previous are presented in the following table.

Table 3.2: Density and porosity of the filter beds surveyed.

Plant	Date	Material density	Dry bulk density	Porosity	Media type
A	All dates	2479	1297	0.52	Silica sand
B	All dates	2601	1334	0.51	Silica sand
C	All dates	1535	514	0.34	GAC
D	All dates	2651	1412	0.53	Silica sand
E	All dates	2601	1334	0.51	Silica sand
F	Up to 02/2004	1957	1035	0.53	Sand/Anthracite
F	After 02/2004	2288	1118	0.49	Sand/Anthracite
G	All dates	2597	1258	0.48	Silica sand
H	All dates	2678	1369	0.51	Silica sand

3.1.3 *Filter media properties of the treatment plants*

The most important physical properties of the filter beds sampled during the full-scale treatment plant survey are listed below.

Table 3.3: Other physical properties of filter beds surveyed.

Plant	d10	d60 / d10	Depth	backwash rate
A (sand)	722 μm	1.39	525 mm	2.70 mm/s
B (sand)	879 μm	1.48	600 mm	4.34 mm/s
C (GAC 1)	761 μm	1.87	1400 mm	5.60 mm/s
C (GAC 2)	1204 μm	1.49	1400 mm	5.60 mm/s
D (sand)	912 μm	1.64	755 mm	5.00 mm/s
E (sand)	902 μm	1.41	920 mm	2.67 mm/s
F (sand)	674 μm	1.51	173 mm	7.90 mm/s
F (anthracite)	1368 μm	1.57	162 mm	7.90 mm/s
G (sand)	719 μm	1.66	462 mm	6.93 mm/s
H (sand)	669 μm	1.51	720 mm	7.85 mm/s

3.2 The Kinetics Of Specific Deposit Washout

This section deals with “how quickly” specific deposit was washed out from a filter. The later sections will deal with “how much” and “which type” of specific deposit was removed.

3.2.1 How can the washout be measured?

Two options were considered during this investigation:

- The specific deposit removed can be determined from the *media* by subtracting the AISD of the after backwash sample from the AISD of the before backwash sample – the *media* method.
- The specific deposit removed can be determined from the *backwash water* that is carried away – the *washout* method. The mass of solids washed out is determined by simple calculation from the backwash rate and the TSS concentration in the backwash water. By dividing the total mass of solids washed out by the total media bed volume, the solids washout can be expressed in terms of the specific deposit.

In theory, these two methods should give the same results, but there are practical obstacles in the paths of both. If the media is dirty and the backwash is inefficient, the media method faces the danger of placing too much faith in a small difference derived from two much larger numbers. The washout method, in turn, suffers from the time lag between media contact and sampling and the difficulty of taking representative samples from a large flow of backwash water, which is not necessarily homogenous in terms of its TSS concentration.

The database yielded a total of 55 backwash cycles where both media and washout methods were used. Taking a global average of all these backwash cycles, the washout method indicated an average reduction in specific deposit of 0.85 kg/m³ during a backwash cycle, while the media method indicated that 1.50 kg/m³ had been removed. Closer inspection of the data shows that the media method was very erratic and yielded negative numbers in 10 of the 55 cases – an obvious impossibility. The washout method is therefore the method of choice for determining the reduction in specific deposit during backwash.

3.2.2 The kinetics of specific deposit washout

Backwash theory suggests that media cleaning requires more than just hydrodynamic shear. It also requires abrasion of the media surface by adjacent media grains rubbing onto each other. This is the express purpose of the air scour step, where the rising air bubbles cause

continuous media movement. The primary purpose of the water washing is to remove the deposit from the bed. To account for different bed depths and backwash rates, the concept of “empty bed volumes” is used in this report as a measure of the volume of backwash water passed through the bed. In other words, one bed volume of washwater is equal to the total volume occupied by the media bed.

Three different sets of backwash data will be presented in this section:

- The first set comprises those “first” backwashes that were conducted after the filters had been taken out of service at the time of the visit. Some of these filters had been in service for many hours; some only for a short period. The backwash water was sampled from the backwash channel.
- The second set comprises “second” backwashes immediately following the first described above. After the “first” backwash, the air scour cycle was repeated, and the filters washed and sampled as before.
- The third set comprises backwashes that were conducted in the laboratory column. After the “first” plant backwash, a media sample was transferred from the filter to the column and given a “column” backwash.

Figures 3.1, 3.2 and 3.3 show the rates at which specific deposit was washed out for the three different sets. The data shows the amount of specific deposit washed out by each consecutive bed volume of washwater. It must be borne in mind that there is inevitably some water above when the cycle starts, leading to some time lag. In the case of the laboratory column, the lag could be kept fairly small. Also, the lateral movement of water in large full-scale filters will tend to “blur” the curve that would be theoretically expected.

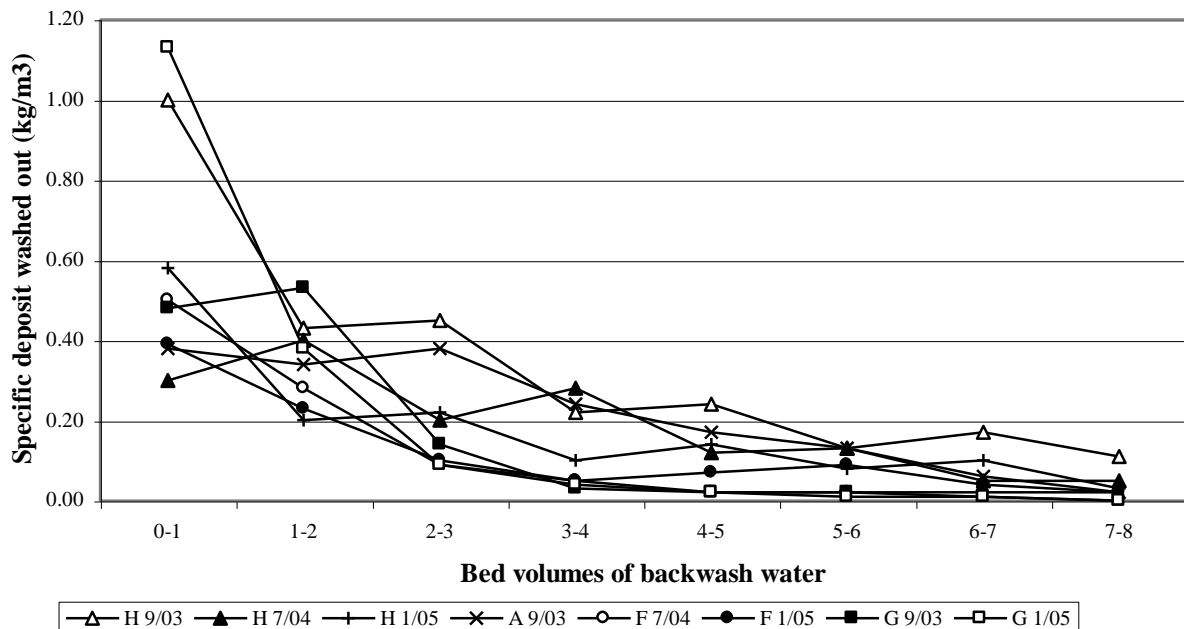


Figure 3.1: Rate of specific deposit washout for “first” backwash data set.

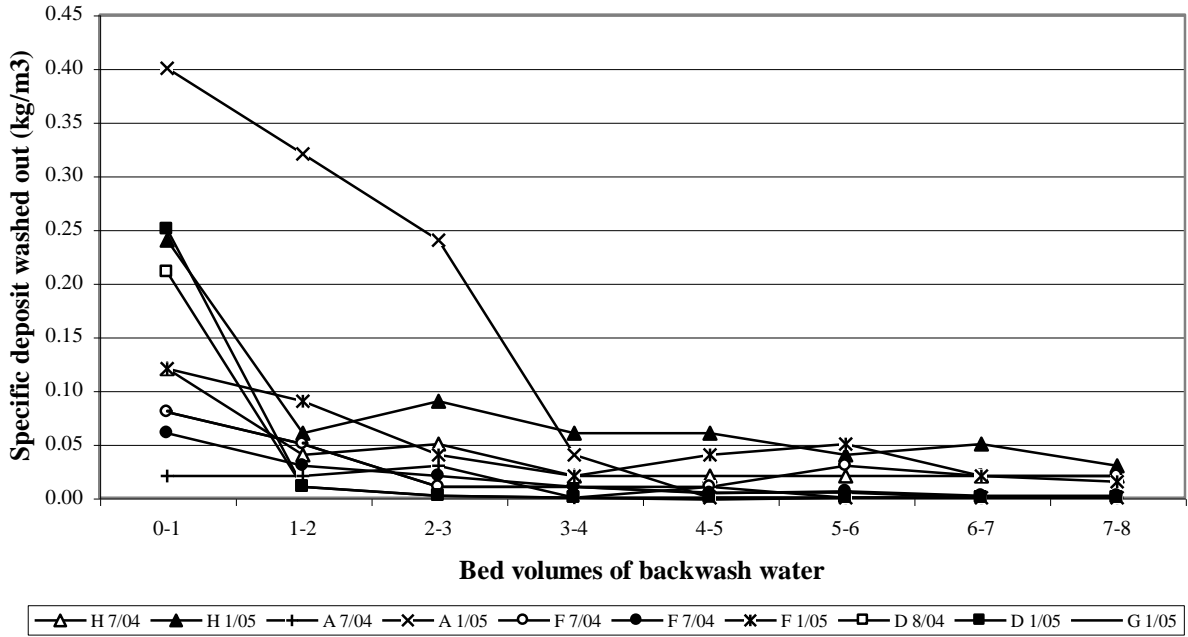


Figure 3.2: Rate of specific deposit washout for "second" backwash data set.

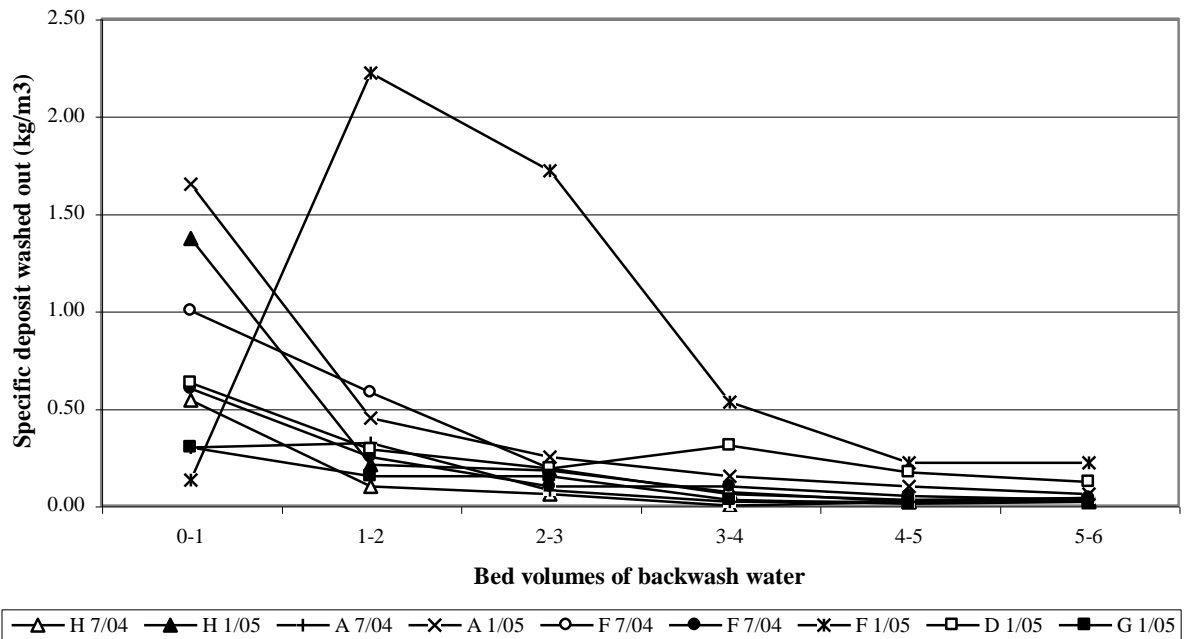


Figure 3.3: Rate of specific deposit washout for "column" backwash data set.

The three figures show a remarkably consistent pattern, given all the experimental concerns. It is clear that there was little benefit by using more than four or five bed volumes of washwater per wash. In the case of the "first" wash as well as the "column" wash, less than 0.20 kg/m³ of specific deposit was removed per bed volume if the wash was extended beyond five bed volumes. In the case of the "second" wash, it was less than 0.05 kg/m³.

3.2.3 The benefit of multiple backwash cycles

It is well known that a “second” and a “third” backwash will continue to remove specific deposit from the bed, albeit in smaller consecutive amounts. This is ascribed to a further abrasion of the media grains by air scour, after the media had been refluidised by the previous water backwash. The concept of multiple washes is not new and had been, to the knowledge of the project team, been introduced at least three treatment plants over the past decade and more. In fact, it is a stated objective of this project to bring this perceived benefit into better quantitative focus.

A series of multiple wash tests were therefore conducted at the treatment plants visited. The amount of specific deposit removed by the first wash was erratic and cannot be used as a benchmark, as the filters were in different stages of their filtration cycles when the tests were conducted. However, the “second” wash provided a better benchmark as it always starts with a filter that had just been washed once.

Table 3.4 shows the amount of specific deposit washed out by consecutive washes, taking five bed volumes as the consistent endpoint for each wash. The specific deposit is expressed as a percentage of the amount washed out by the “second” benchmark wash.

Table 3.4: Specific deposit washed out by consecutive washes, expressed as a percentage of the “second” wash. The endpoint of each wash is taken as five bed volumes of backwash water.

Plant	Date	Wash 1	Wash 2	Wash 3	Wash 4	Wash 5
A	09/2003	368%	100%	76%	-	-
A	07/2004	150%	100%	-	-	-
A	01/2005	434%	100%	-	-	-
D	08/2003	179%	100%	93%	50%	50%
D	08/2004	114%	100%	-	-	-
D	01/2005	99%	100%	-	-	-
F	08/2003	423%	100%	123%	108%	77%
F	07/2004	588%	100%	-	-	-
F	07/2004	266%	100%	-	-	-
F	01/2005	271%	100%	-	-	-
G	09/2003	1100%	100%	73%	45%	45%
G	01/2005	1071%	100%	-	-	-
H	09/2003	384%	100%	-	-	-
H	07/2004	520%	100%	-	-	-
H	01/2005	243%	100%	-	-	-

3.3 The Cleanliness Of Filter Media

3.3.1 Specific deposit removed by the treatment plant backwash systems

During the treatment plant visits, the first step was to remove the designated filters from service and backwash them once. This does not mean that these filters were then loaded necessarily to the point where they would have been backwashed under normal conditions – most of them were therefore only partly as dirty as they normally would have been. The mass of specific deposit that was washed out, nevertheless provides a first indication of how much was typically removed during a backwash cycle. The masses of specific deposit washed out by the first backwash during the site visits are summarised in Table 3.5.

Table 3.5: Mass of specific deposit washed out during the first backwash at full-scale treatment plants after five empty bed volumes of washwater had passed the bed.

Treatment Plant	Date of Test	Specific Deposit
A	09/2003	1.51 kg/m ³
	07/2004	0.12 kg/m ³
	01/2005	4.34 kg/m ³
D	08/2003	0.25 kg/m ³
	08/2004	0.25 kg/m ³
	01/2005	0.26 kg/m ³
F	08/2003	0.55 kg/m ³
	07/2004	0.94 kg/m ³
	07/2004	0.33 kg/m ³
	01/2005	0.84 kg/m ³
G	09/2003	1.21 kg/m ³
	01/2005	1.66 kg/m ³
H	09/2003	2.34 kg/m ³
	07/2004	1.30 kg/m ³
	01/2005	1.24 kg/m ³

The low values in Table 3.5 obviously correspond to those filters, which were only in service for a short time before the site visit. The values suggest that a maximum of about 5 kg/m³ was washed out by the first wash.

3.3.2 Backwash efficiency of the treatment plant backwash systems (APSD[1] – ACSD)

According to the conceptual framework presented in Chapter Two, the backwash efficiency can be expressed as the amount of specific deposit washed out by the laboratory column (the “maximum washable” amount) minus the specific deposit washed out by the treatment plant. The laboratory column was always loaded with media that had already been washed once by the treatment plant, and the “second” wash of the treatment plant must therefore be compared. Once again, the endpoint of all washes was taken as five bed volumes of backwash water. The results are shown in Table 3.6.

Table 3.6: Backwash efficiency of the treatment plants visited, expressed as APSD[2] - ACSD.

Plant	Date	APSD[1] – ACSD	APSD[1] - APSD[2]	APSD[2] – ACSD
A	07/2004	0.76 kg/m ³	0.08 kg/m ³	0.68 kg/m ³
A	01/2005	2.60 kg/m ³	1.00 kg/m ³	1.60 kg/m ³
D	08/2004	1.75 kg/m ³	0.22 kg/m ³	1.53 kg/m ³
D	01/2005	1.59 kg/m ³	0.26 kg/m ³	1.33 kg/m ³
F	07/2004	1.86 kg/m ³	0.16 kg/m ³	1.70 kg/m ³
F	07/2004	1.10 kg/m ³	0.12 kg/m ³	0.98 kg/m ³
F	01/2005	5.04 kg/m ³	0.31 kg/m ³	4.73 kg/m ³
G	01/2005	0.64 kg/m ³	0.16 kg/m ³	0.49 kg/m ³
H	07/2004	0.72 kg/m ³	0.25 kg/m ³	0.47 kg/m ³
H	01/2005	1.85 kg/m ³	0.51 kg/m ³	1.34 kg/m ³

Table 3.6 shows that the backwash systems at all the treatment plants were fairly effective, with the laboratory column capable of only washing out less than 2 kg/m³ after the filters had been backwashed at full-scale. The one high value for Plant F seems to be an outlier, as the same test at a neighbouring filter on the same day showed a much lower value.

3.3.3 Washability of the filter media

How washable is the media? In other words, how much of the specific deposit is so recalcitrant that it cannot be washed off the media grains, even in a well-controlled laboratory column? For this measure, the difference between the after inversion deposit (AISD) and the after column deposit (ACSD) is considered, as explained earlier. The deposit removed by the laboratory column (the maximum that can be expected from hydrodynamic shear only) is subtracted from the AISD (which is removed by the much more aggressive cylinder inversion method). The results are shown in Table 3.7.

Table 3.7: Filter media washability at the treatment plants visited, expressed as ACSD - AISD.

Plant	Date	APSD[1] – AISD	APSD[1] – ACSD	ACSD – AISD
A	07/2004	2.85 kg/m ³	0.76 kg/m ³	2.09 kg/m ³
A	01/2005	7.46 kg/m ³	2.60 kg/m ³	4.86 kg/m ³
D	08/2004	3.87 kg/m ³	1.75 kg/m ³	2.12 kg/m ³
D	01/2005	7.33 kg/m ³	1.59 kg/m ³	5.74 kg/m ³
F	07/2004	4.55 kg/m ³	1.86 kg/m ³	2.69 kg/m ³
F	07/2004	5.49 kg/m ³	1.10 kg/m ³	4.39 kg/m ³
F	01/2005	12.45 kg/m ³	5.04 kg/m ³	7.41 kg/m ³
G	01/2005	1.39 kg/m ³	0.64 kg/m ³	0.75 kg/m ³
H	07/2004	1.44 kg/m ³	0.72 kg/m ³	0.72 kg/m ³
H	01/2005	3.67 kg/m ³	1.85 kg/m ³	1.82 kg/m ³

Table 3.7 shows a wide scatter of values, with most of the values fairly high. This supports the hypothesis of this project, namely that the phenomenon of dirty filter media in practice cannot only be ascribed to imperfect backwashing and maintenance.

3.3.4 The “hard” component of the specific deposit

Finally, the “hard” deposit, which is normally considered to be part of the media grains and difficult to remove, was determined and the results are presented in Table 3.8.

Table 3.8: The “hard” component of the specific deposit, in terms of mass/volume of the media bed, as well as a fraction of the total media mass.

Plant	Date	AISD – AASD	AISD – AASD
A	02/2004	12.0 kg/m ³	0.9%
A	07/2004	21.7 kg/m ³	1.7%
A	01/2005	9.5 kg/m ³	0.7%
D	02/2004	176.0 kg/m ³	12.5%
D	02/2004	181.1 kg/m ³	12.8%
D	08/2004	245.7 kg/m ³	17.4%
D	01/2005	83.8 kg/m ³	5.9%
F	02/2004	4.4 kg/m ³	0.4%
F	07/2004	9.1 kg/m ³	0.8%
F	07/2004	123.6 kg/m ³	11.1%
F	01/2005	6.2 kg/m ³	0.6%
G	02/2004	55.3 kg/m ³	4.4%
G	07/2004	53.0 kg/m ³	4.2%
G	01/2005	47.8 kg/m ³	3.8%
H	02/2004	79.2 kg/m ³	5.8%
H	07/2004	77.7 kg/m ³	5.7%
H	01/2005	88.8 kg/m ³	6.5%

These values show a very large scatter, which is closely tied to the chemical stabilisation practices at the different treatment plants. These values, high as some of them seem to be, are very typical – values as high as 30% of the filter media mass have been encountered by the project team in previous studies.

3.3.5 Putting it all together

The conceptual framework used in this report allows for three components of specific deposit after the media had been backwashed *in situ* at the treatment plant:

- The specific deposit that can be additionally removed by a laboratory column after the plant backwash
- The specific deposit that can be additionally removed by cylinder inversion after the laboratory column backwash
- The specific deposit that can be additionally removed by acid after cylinder inversion

Figure 3.4 shows these three fractions in the form of a cumulative bar chart for the 10 site visits conducted during this project.

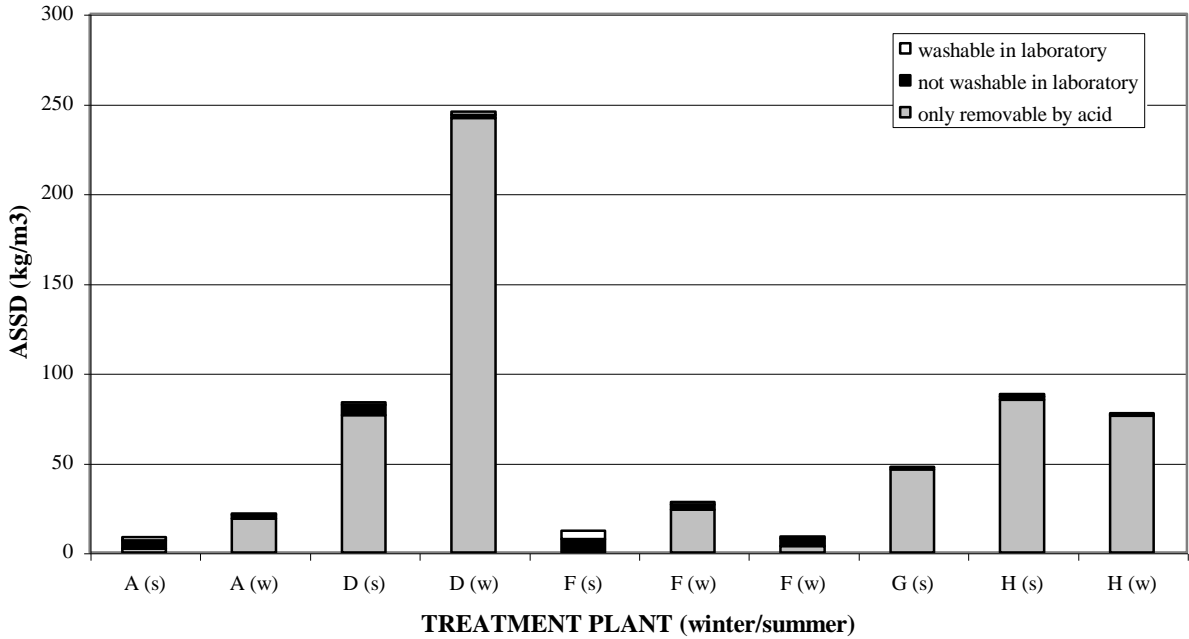


Figure 3.4: Cumulative specific deposit fractions removed by three methods (column, cylinder inversion and acid strip) during plant visits.

It is immediately obvious that the “hard” deposit, which can only be removed by acid, dominate the specific deposit in most cases. However, this deposit is considered by most to be a part of the media once they are formed. The focus of this report is rather on the parts of the specific deposit that could be operationally removed after they are formed. Figure 3.5 therefore shows the same values as in Figure 3.4, but without the “hard” deposit.

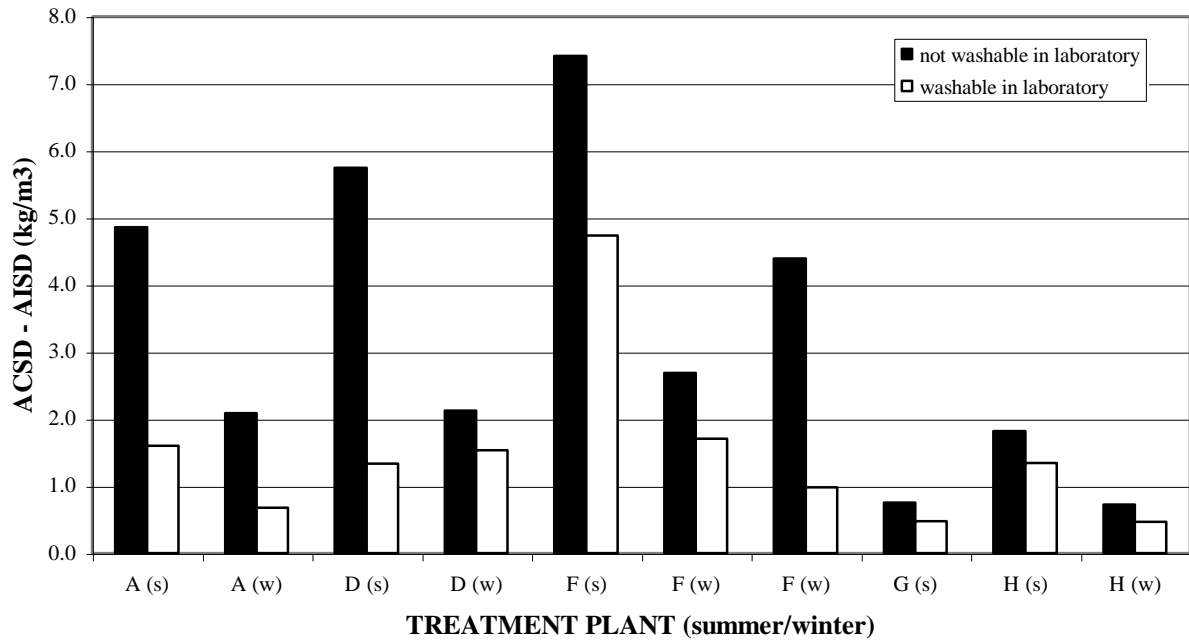


Figure 3.5: Cumulative specific deposit fractions removed by two methods (column, and cylinder inversion) during plant visits.

Figure 3.5 allows three observations. Firstly, the summer values are consistently between two and three times higher than the winter values when the same treatment plants are compared. (The values for Plant G could unfortunately not be measured during the winter visit due to practical difficulties.) Secondly, the values for the backwash efficiency is reasonably constant (excepting the outlier discussed before), while the washability of the media is much more variable. Thirdly, the washability of the media is significantly larger than the backwash efficiency.

3.4 The Nature Of The Specific Deposit

3.4.1 Classification by acid solubility and volatility

Previous work (Clements and Haarhoff, 2004) as well as the increased deposit in the summer months, suggest that biofilm formation may be the key to the problem of insufficiently cleaned filter media. The volatile fraction of the deposit (assumed to be biological in origin) was thus determined during each site visit. The relationship between the volatile fraction and the specific deposit is shown in Figure 3.6.

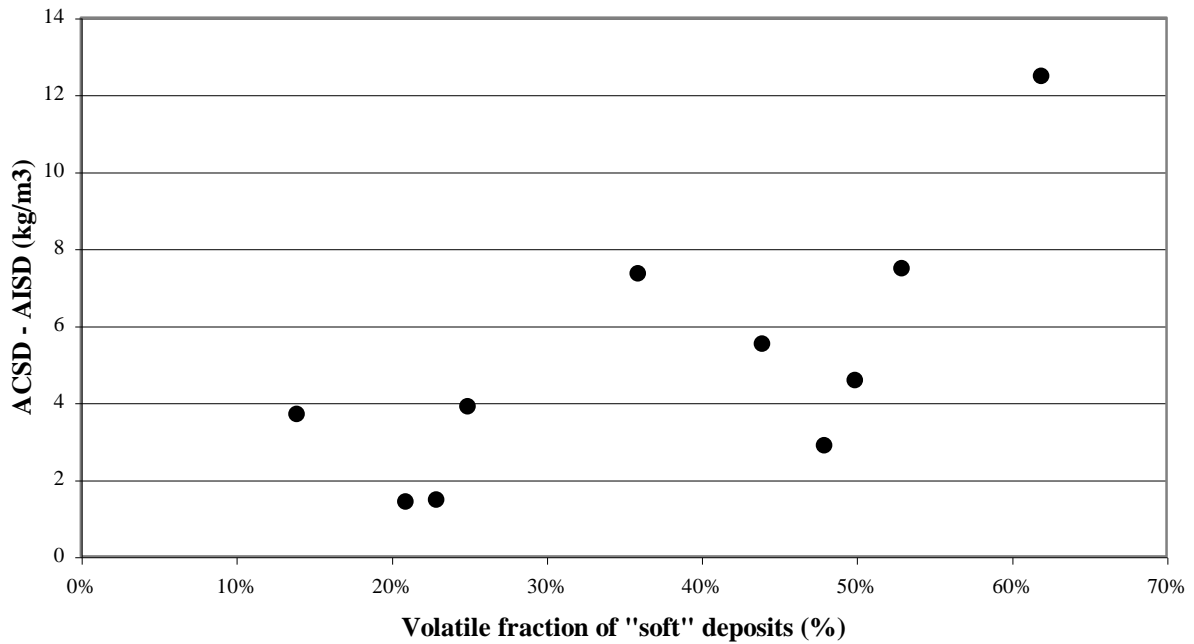


Figure 3.6: Relationship between volatile fraction and specific deposit.

Figure 3.6 supports an underlying dependency between the amount of non-washable specific deposit and the volatile fraction (i.e. the biological component) of the specific deposit.

3.4.2 Extracellular polymeric substances (EPS)

In order to verify the assumption that the volatile fraction of the specific deposit is indeed biological, the EPS was directly measured during the two field trips conducted during this project. The results are shown, plotted against the volatile part of the specific deposit.

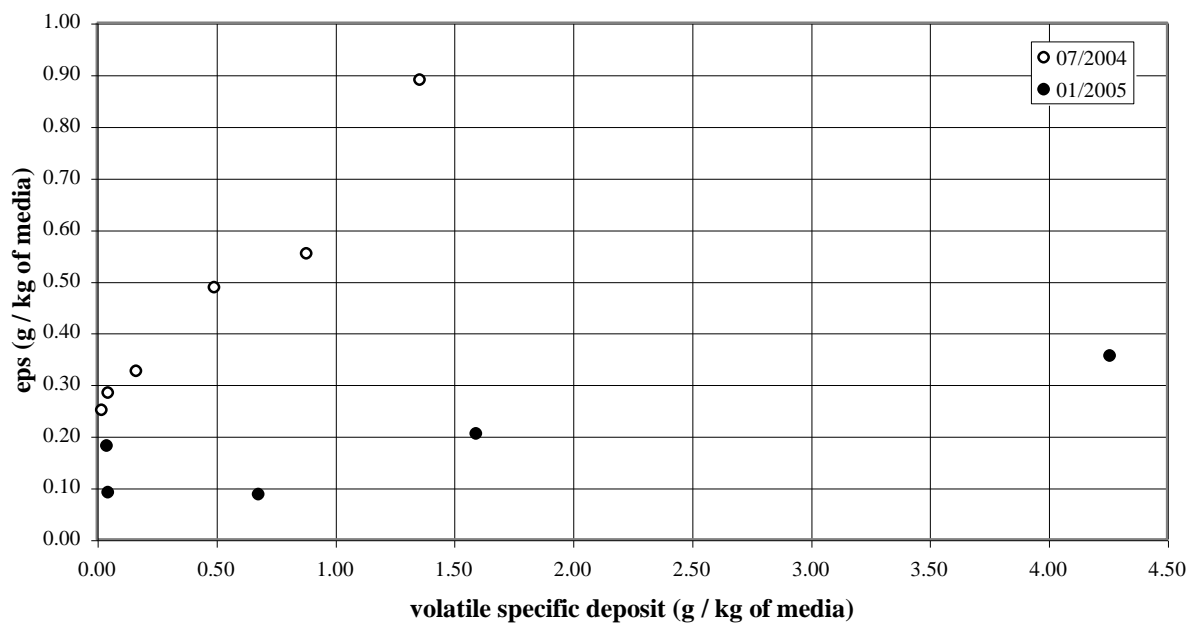


Figure 3.7: Contribution of extracellular polymeric substances to the volatile fraction of the total specific deposit.

During the winter survey, the EPS made up about 60% of the volatile material, but in summer this dropped to about 15%.

According to Marshall (1996), biofilms appear to form part of the survival strategy of microorganisms. The EPS matrix itself is able to take nutrients out of the bulk water phase (Decho, 1990), which is particularly important when nutrient supply is limited (oligotrophic environment) as in the case of the winter season. In addition, Evans et al. (1994) found that sessile cells produce significantly more EPS during slow growth rates, as would occur during winter months when nutrients are limited, than suspended cells, whilst in summer there is no difference. These references provide a logical rationale for the finding that a higher EPS fraction was found in winter than in summer.

3.4.3 Elemental analysis

The elemental composition of the specific deposit was determined by the methods described earlier. A total of 23 elements were measured. The following criteria were used for “significant presence”:

- The concentration had to be above the analytical detection limit
- The average contribution to the total mass (taken over all the site visits) had to be 3% or above
- The maximum contribution to the total mass (calculated for individual site visits) had to be 5% or above

The following 17 elements were found not to have a significant presence; boron, barium, cadmium, cobalt, chromium, copper, potassium, lithium, magnesium, sodium, nickel, phosphorus, lead, sulphur, strontium, titanium and zinc. This left 6 elements which made up a significant portion of the specific deposit; aluminium, calcium, chloride, iron, manganese and silicon. Their contribution to the total specific deposit is shown in Figure 3.8.

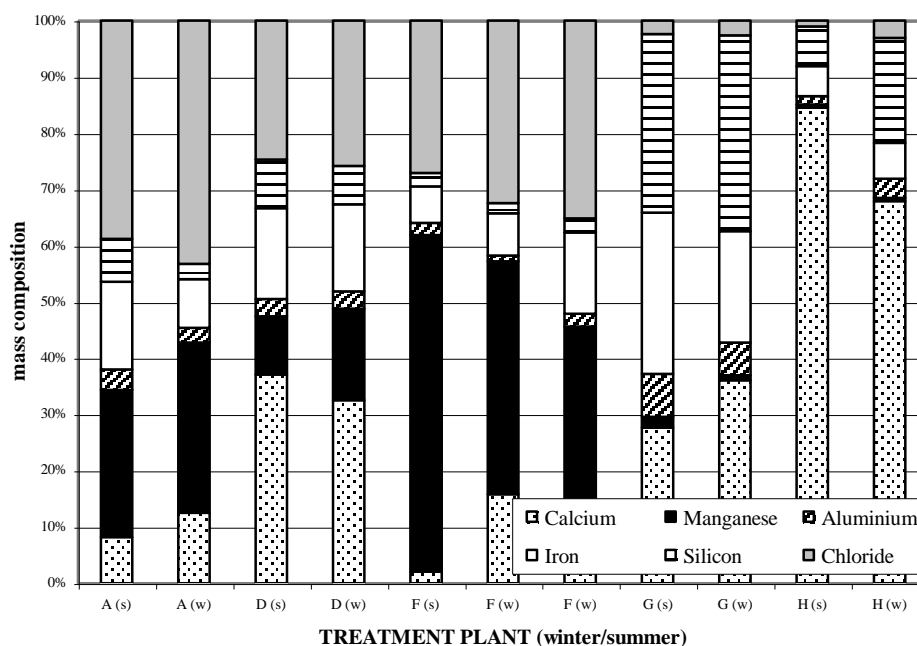


Figure 3.8: Contribution of six significant elements (Al, Ca, Cl, Fe, Mn, and Si) to the total specific deposit.

The elemental composition correlates closely with the water quality history, as well as the chemical coagulants used at the different treatment plants.

3.5 Interpretation of the Full-Scale Treatment Plant Survey Data

The conceptual framework adopted for this report, coupled with the results of the treatment plant surveys, brings a hitherto obscured understanding of filter cleanliness into much better focus. The winter survey (July 2004) and the summer survey (January 2005) yielded 10 data points, and their median values are used to demonstrate the new insights.

The first set of observations deal with the overall cleanliness of the filter media:

- A normal, reasonably effective backwash at a treatment plant removed 0.89 kg/m^3 (varying between 0.12 kg/m^3 and 4.34 kg/m^3) of specific deposit. This variation depended on how dirty the filters were and the operational practice at the treatment plant.
- This does not mean that the filter media was perfectly clean. By washing the media in a laboratory column, a further 1.34 kg/m^3 (varying between 0.47 kg/m^3 and 4.73 kg/m^3) was washed from the media.
- When this media was subjected to even more agitation, namely a standardised cylinder inversion procedure, yet more specific deposit was released from the media. During the surveys, the median value was 2.41 kg/m^3 (varying between 0.72 kg/m^3 and 7.41 kg/m^3).
- Finally, the remaining specific deposit was stripped by immersion in a strong acid. This removed a median of 35.2 kg/m^3 of specific deposit (showing an extreme variation between zero and 241.8 kg/m^3).
- The specific deposit removed by the treatment plants was therefore a relatively small fraction of the overall specific deposit, supporting the qualitative observation at numerous other treatment plants that filter media, after a few years of operation, were unacceptably dirty.
- The chemical precipitates, which are impossible to remove unless strong acid is used, are best considered to be “hard” deposit and part and parcel of the filter media. The focus should be on the nature and removal of the remaining part of the specific deposit.

The second set of observations deal with the washout kinetics of specific deposit removal:

- The concept of bed volumes of washwater is useful for comparing backwash data when backwash rates and media bed depths are different.
- When using washwater alone, the vast bulk of the specific deposit is washed out during the first two bed volumes. There is little point in continuing the backwash cycle beyond five bed volumes per wash.
- If a wash is repeated (using both the consecutive air and water again), more specific deposit can be removed. At the treatment plants surveyed, a third wash, for example, removed between 50% and 100% of what was removed during the second wash.
- This suggests that it may be a good strategy to use say three consecutive wash cycles – the first two using say 2 bed volumes, and the third with 4 bed volumes. In this way, much more specific deposit can be removed, but still only using 8 bed volumes, which

is what is typically used when a single wash is continued until the washwater appears perfectly clean.

The third set of observations deal with the nature of the specific deposit:

- The specific deposit of all the treatment plants was composed of three components; biological, inorganic but acid-soluble, and inert inorganic material, which was not soluble in acid.
- The biological component seems to be the key to the difficulty in removing the specific deposit. The higher the biological fraction of the specific deposit, the more specific deposit remained in the bed after the plant backwash.
- This was confirmed by presence of the extracellular polymeric substances, which is a direct measure of biofilm.
- The elemental composition showed that 6 elements made up the dominant part of the specific deposit. The relative abundance of different elements could be related to the raw water quality as well as the chemical coagulants used at the different plants.
- Seen as a whole, the specific deposit at the different treatment plants is a complex substance with very wide variations from one treatment plant to the other. It seems unlikely that a single in-situ rehabilitation strategy will be adequate for all filter media problems. The nature of the specific deposit will have to be determined first with one or more of the methods described here, which may then suggest the most appropriate rehabilitation strategy.

CHAPTER 4 – PILOT SCALE EXPERIMENTS

4.1 Purpose

The objective of the investigation on a pilot plant scale was to examine the cleaning of filter media by applying alternative backwash procedures. In these experiments the single filter cleaning procedure comprising of 5 minutes air scour and 7 minutes backwash was compared to a double cycle filter cleaning procedure. The double cycle procedure comprised two consecutive cycles, each 2.5 minutes air scour followed by 3.5 minutes backwash.

4.2 Introduction

The purpose of backwash is to remove all the foreign material from the filter bed collected in the bed during the preceding filter run. Many of the problems that occur in the filtration facilities of water treatment plants are associated with ineffective cleaning of filter media at the end of a filter run. Failure to adequately clean filters during backwash result in deterioration of the condition of the filter bed, which can impair the performance of the filter. Filters with inefficient backwash tend to accumulate aggregates of dirt, media and coagulant known as mud balls (Brouckaert *et al.*, 2006). The formation of mud balls is a direct consequence of the failure to fluidize the entire filter bed during backwash (Qureshi, 1982). Backwash efficiency was found to decrease as the floc deposit remained in the filter bed for longer periods, and it was concluded that the deposit, which remained after one backwash, would unlikely be removed in the subsequent backwashes (Brouckaert *et al.*, 2006).

These small mud balls can grow into inactive sub-surface masses of clogged material which increase local velocities in the filter with a potentially negative impact on filtrate turbidity and filter run time (AWWA, 1991).

In most South African water treatment plants, filter cleaning procedures normally comprise: (1) draining of the water in the filter basin to the top of the filter medium, (2) air scour at a predetermined rate for a specific time, (3) upward water scour at a predetermined rate for a specific time to achieve a minimum required bed expansion and (4) possibly a horizontal flush across the surface of the filter medium. Unfortunately, this cleaning method does not guarantee clean media. Often the failure to clean filters properly can be related to specific reasons, such as incorrect air or water scour rates, blocked or broken filter nozzles, etc. In many cases, however, the reasons for dirty filters are not apparent.

Proper backwash rate and percent filter bed expansion should be determined for the type of filter media, grain size and its uniformity co-efficient. These are the important factors that must be determined when establishing proper backwash procedures (Amirtharajah, 1984). Utilities should consider the following when evaluating filter backwash practices (Fitzpatrick, 1998).

- **Whether the backwash rate is appropriate for the specific filter media.** Filters can either be underwashed or overwashed. Appropriate backwash rates need to be determined to prevent mud ball formation but the backwash rate should not upset the filter media to the extent that the supporting media are disturbed, the under drain is damaged or filter media is lost.

- **Set backwash initiation criteria.** Systems should establish criteria such as filter run time, head loss, and filtrate turbidity for initiating filter cleaning.
- **Filter start-up strategy.** Media should be allowed to settle after backwashing before bringing filters back in operation. Filters should be brought back on line employing a slow start mechanism. To prevent a reduction in total throughput in the filter plant, several filters should not be brought on line at the same time.
- **Filter shock prevention.** During cleaning, the flow through the remaining filters that could be affected may need to be kept steady to ensure the filters in operation are not overloaded or subjected to a hydraulic surge, causing particle breakthrough.
- **Filter to waste may also be considered.** The amount of filtrate produced directly after putting the filter back into service after cleaning is not put into supply but recycled until the filter media has settled and the filtrate is of the desired quality.

4.3 Experimental Work

4.3.1 Experimental setup

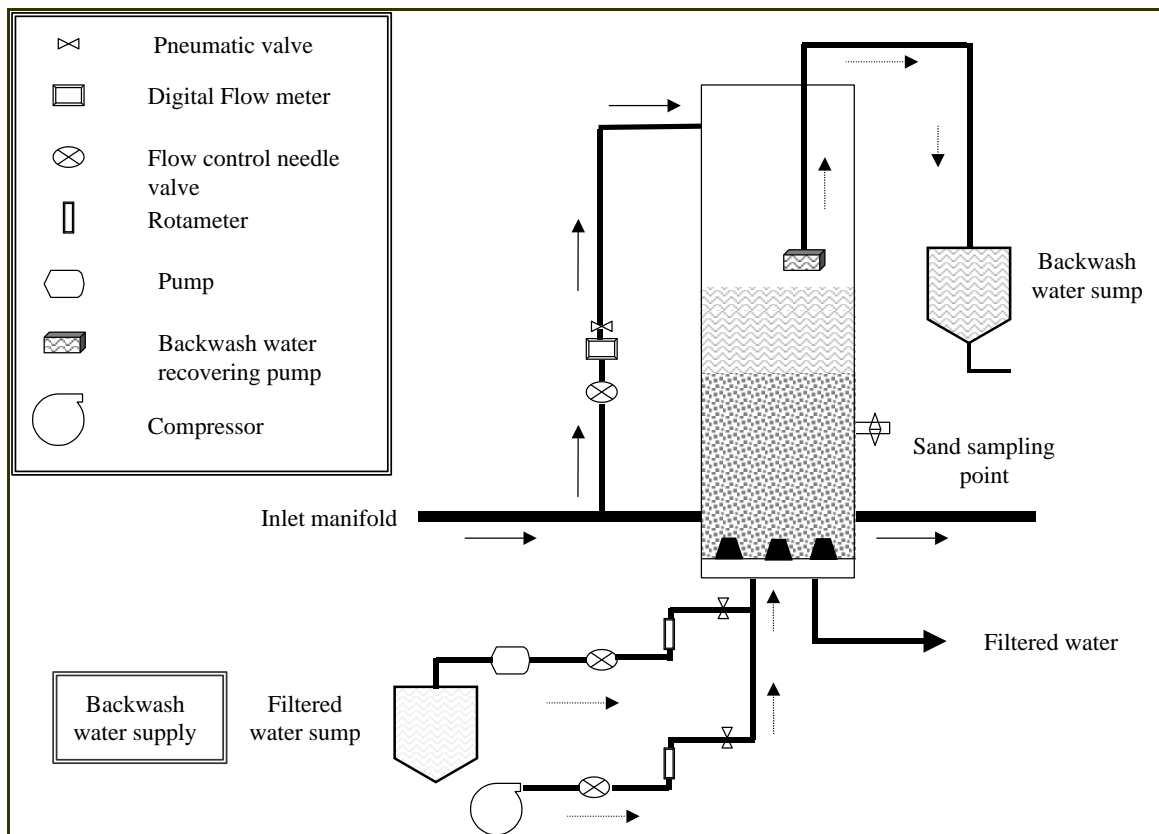


Figure 4.1: Schematic of experimental filter plant used for conducting experiments.
 : Indicates flow direction of settled water during filtration process.
 : Indicated flow direction of air and water during backwashing process.

The experimental filters were situated in an operational filter plant to simulate as closely as possible, prevailing conditions on the full-scale purification plant and operating conditions were kept as far as possible, consistent to the full scale filters.

The pilot plant comprised six experimental filter columns, each 3 meters tall, 20 centimeters internal diameter and filled to a depth of 800mm with filter media.

Representative filter media from the full scale plant used in the experimental filters were obtained from Filter House 1 (FH1) and Filter House 3 (FH3) at the Vereeniging Purification Plant. See Table 4.1 for the respective media properties. Virgin media complying with the media specification as used in the full scale plant was used for comparison. Two pilot filters were each filled with respectively virgin media, two with media from Filter House 3 (FH3) and the remaining two with media from Filter House 1 (FH1). Clarified water from a full-scale plant at the Vereeniging Purification Station, System 5, was used as the supply to the experimental filters. The pilot filters were run for 48 hours prior to cleaning. Filter media from all six columns was sampled before and after backwash. The amount of specific deposit present in the filter media was determined using the cylinder inversion test. The backwash water was profiled for turbidity and total suspended solids (TSS). The clarified water and filtrate quality was monitored using online turbidimeters.

All the filter media used were characterized in terms of grain size, actual density, and porosity and acid solubility. Results are depicted in Table 4.1.

Table 4.1: Characteristics of the filter media used for conducting pilot experiments.

Parameters	Virgin silica sand	Filter media From FH1	Filter media From FH3
Effective grain size (ES), (d_{10}) (mm)	0.66	0.66	0.66
d_{60} (mm)	0.91	1.56	0.91
*Uniformity coefficient, (UC)	1.4	2.4	1.4
Grain density, g/cm^3	2.64	2.48	2.62
Porosity (dimensionless)	0.54	0.60	0.54
Acid solubility. %	2.5	60.1	8.2

*Uniformity coefficient, (UC) = d_{60}/d_{10}

4.3.2 Media cleanliness

The cylinder inversion test gives an indication of how well the filter media was cleaned by backwashing. Specific deposit (SD) and fractions of specific deposit (i.e. Non-soluble Non-volatile suspended solids (NSNV), Soluble Non-volatile suspended solids (SNV) and Volatile suspended solids (V) were determined after stripping the filter media using this standardized inversion method. Specific deposit is defined as solid organic and inorganic particles that are in suspension after stripping the filter media with water. Specific deposit is retained on a 0.45 μ m-pore size glass-fibre filter paper and dried at 105°C for 60 minutes. Non-soluble Non-volatile solids (NSNV) represent that fraction of the specific deposit that is not soluble in acid and does not ignite and burn when heated at 550°C. Soluble Non-volatile suspended solids (SNV) is that fraction of the specific deposit that is soluble in acid but does not ignite and burn when heated at 550°C. Volatile suspended solids (V) is that fraction of the specific deposit that ignites and burns when heated at 550° in an oxygen-containing atmosphere.

Van Staden *et al*, 2004, suggested the following rehabilitation strategies after stripping the specific deposit from the media grains:

- If the stripped deposit is mostly biological (Volatile solids, [V]), the media could be treated *in situ* with an oxidant such as chlorine (Cl₂).
- If the stripped deposit is mostly chemical precipitates (Soluble Non-volatile solids, [SNV]), the media could be treated *in situ* with an acid such as hydrochloric acid (HCl).
- If the stripped deposit is mostly natural silts (Non-soluble Non-volatile solids, [NSNV]), mechanical cleaning methods should be employed to clean the media.

Table 4.2: Suggested guidelines for filter media cleanliness in South Africa as determined with the cylinder inversion test (van Staten *et al.*, 2004)

Class	Filter media cleanliness	*SA Guidelines (kg/m ³)
I	Clean filter and ripened bed	< 4
II	Slightly dirty, less than ideal bed, but not yet a concern	4 - 7
III	Dirty bed with need for evaluating the filter washing system And backwashing procedure	7 - 15
IV	Could indicate a mud ball problem	> 15

*Specific deposit (SD) on filter media expressed as kg specific deposit /m³ of filter media

4.4 The Effect of Different Cleaning Procedures on the Removal of Specific Deposit from Filter Media

4.4.1 Media analysis

Rand water uses filter media with an effective size of 0,7 mm and a uniformity coefficient of 1,4 or less, while as appropriate media with a uniformity coefficient of 1.3 to 1.8 and effective grain size of 0.35mm to 0.7mm may be used in other water purification plants (AWWA, 1998) has been advocated for use as sand filter media. The larger grain size and high acid solubility of filter media from FH1 was attributed to the deposition of calcium carbonate as a result of using hydrated lime as coagulant.

The distribution of specific deposit on media from FH1 and FH3 and virgin media through which clarified water from the same clarifier was filtered and then cleaned by the single and double cycle cleaning methods is shown in Table 4.3.

Table 4.3: The distribution of the different fractions of specific deposit on the filter media after applying single and double cleaning procedures (average of 10 experiments based on the cylinder inversion test).

		Filter Media Sample	TSS	Composition per fraction characterisation					
				NSNV		SNV		V	
			kg/m ³	kg/m ³	% content	kg/m ³	% content	kg/m ³	% content
Virgin Medium	Single Cleaning Control	Virgin B/BW	2.2	0.90	33.83	0.74	30.33	0.62	36.00
		Virgin A/BW	0.72	0.25	33.17	0.12	15.83	0.34	51.00
	Double Cleaning Experiment	Virgin B/BW	3.4	1.3	36.50	1.3	33.00	0.87	30.50
		Virgin A/BW1	0.81	0.34	34.50	0.20	23.00	0.27	42.67
		Virgin B/BW2	0.39	0.12	30.17	0.05	8.17	0.22	61.50
Used Medium from FH3	Single Cleaning Control	FH3 B/BW	2.8	0.94	31.00	1.4	50.00	0.51	18.83
		FH3 A/BW	0.57	0.16	25.67	0.30	40.17	0.16	34.17
	Double Cleaning Experiment	FH3 B/BW	2.9	0.94	33.67	1.3	42.50	0.66	23.50
		FH3 A/BW1	0.81	0.18	22.67	0.33	40.50	0.30	37.00
		FH3 A/BW2	0.53	0.12	24.00	0.21	34.83	0.21	41.17
Used Medium from FH1	Single Cleaning Control	FH1 B/BW	3.5	0.70	19.00	2.0	57.00	0.80	24.00
		FH1 A/BW	1.6	0.25	16.50	0.82	49.33	0.52	34.00
	Double Cleaning Experiment	FH1 B/BW	3.8	1.1	26.17	2.0	52.67	0.77	21.00
		FH1 A/BW1	1.8	0.35	19.00	0.96	52.17	0.48	29.00
		FH1 A/BW2	1.6	0.23	14.50	0.86	54.00	0.49	31.67

B / BW: Filter media sample taken before the pilot filter was backwashed

A / BW: Filter media sample taken after the pilot filter was backwashed

Control: Single backwash procedure

Experiment: Double cycle backwash procedure

The results obtained from experiments as shown in Table 4.3 are summarized in Table 4.4

Table 4.4: Comparison of the removal efficiency of specific deposit from different filter media with the single (control) and double cycle (experiment) cleaning procedure based on the cylinder inversion test.

		Filter media sample	TSS, kg/m ³	% Removal	Total % Removal
Virgin Medium	Control	Virgin, B / BW	2.2	67	67
		Virgin, A / BW	0.72		
	Experiment	Virgin, B / BW	3.4	76	89
		Virgin, A / BW1	0.81		
		Virgin, A / BW2	0.39	58	
Used Medium FH3	Control	FH3 B / BW	2.8	80	80
		FH3 A / BW	0.57		
	Experiment	FH3 B / BW	2.9	72	82
		FH3 A / BW1	0.81		
		FH3 A / BW2	0.53	35	
Used Medium FH1	Control	FH1 B / BW	3.5	54	54
		FH1 A / BW	1.6		
	Experiment	FH1 B / BW	3.8	53	59
		FH1 A / BW1	1.8		
		FH1 A / BW2	1.6	11	

B / BW: Filter media sample taken before the pilot filter was backwashed

A / BW: Filter media sample taken after the pilot filter was backwashed

Control: Single cleaning procedure

Experiment: Double cycle cleaning procedure

For the virgin media, the single cleaning procedure proved to be less effective than double cycle cleaning procedure. However for the used media from FH1 and FH3, the difference between the single cleaning procedure and double cycle cleaning procedure was negligible.

4.4.2 Relationship between backwash water turbidity and total suspended solids analysis

In order not to have to determine the TSS on every occasion when the backwash water quality was measured, the relationship between TSS and turbidity (NTU) of the backwash water was determined. Table 4.5 shows the turbidity: TSS ratios obtained.

Table 4.5: Turbidity: TSS ratio established from the composite sample of backwash water samples taken every 30 seconds during backwash

	Turbidity: TSS
Min	0.52
Max	0.56
Average	0.54
Median	0.54

The results are comparable to some of the results reported on in paragraph 3.1.1 and Table 3.1.

The efficiency of the single cleaning and double cycle cleaning procedure was compared based on the amount of specific deposit removed by the two methods.

The results of the single cleaning procedure compared to the double cleaning procedure on the removal of specific deposit collected in the backwash water, are summarized in Table 4.6.

Table 4.6: Efficiency of single backwash versus double cycle backwash procedure by measuring specific deposit (as TSS) in backwash water.

Backwash water	TSS, mg/l	Volume of backwash water (l)	*TSS (g)	Total TSS (g)	% Difference
Virgin Exp BW1	467.4	58.6	27.4	31	12
Virgin Exp BW2	61.4	58.6	3.6		
Virgin Ctrl	235.4	117.3	27.6	27.6	
FH3 Exp BW1	511.1	58.6	30	33.6	1
FH3 Exp BW2	61.6	58.6	3.6		
FH3 Ctrl	289.8	117.3	34	34	
FH1 Exp BW1	405.4	58.6	24	28	3.6
FH1 Exp BW2	71.2	58.6	4		
FH1 Ctrl	232.2	117.3	27	27	

Control: single cleaning procedure
Experiment: double cycle cleaning procedure
***TSS (g) =** $\frac{\text{TSS (mg/l)} \times \text{Volume (l)}}{1000}$

From Table 4.6 it can be seen that based on the amount of suspended matter in the backwash water, it seems as though the double cleaning procedure removes substantially more captured matter from the virgin media compared to the single cleaning procedure. For the used media from FH1 and FH3 there was little difference between the amounts of captured matter removed by the single cleaning compared to double cycle cleaning procedures. This correlates with the amount of specific deposit removed by two cleaning procedures applied on different filter media, as it is summarized in Table 4.4.

4.3.2 Filtrate quality

It is assumed that cleaner filter media would result in an improved quality of filtrate. Filtrate quality was monitored to establish the effect of single cleaning versus double cleaning procedure on filtrate quality by measuring turbidity. During the experiments filtrate quality was measured with an on-line turbidimeter. The average filtrate turbidity for each filter medium for two experimental runs is shown in Table 4.7 below.

Table 4.7: Average filtrate turbidity measured online in two experiments conducted using virgin sand and media from FH1 and FH3 (average of 48 hours).

Date	Media Type	Filtrate quality measured as turbidity (NTU)	
		Single Cleaning Procedure	Double Cleaning Procedure
14 August 2005	Virgin	0.28	0.26
	FH3	0.30	0.30
	FH1	0.32	0.34
29 August 2005	Virgin	0.44	0.42
	FH3	0.47	0.48
	FH1	0.48	0.51

From Table 4.7 it can be seen that the turbidity of the filtrate for media which was cleaned with either the single or double cycle, was consistently below or close to 0.5 NTU which is the Rand Water production standard. The results collected are too few to make any valid conclusions, but it seems as though the turbidity of the filtrate from the virgin media was slightly lower than the turbidity of filtrate from used media.

4.5 Summary and Conclusions

- The double cycle cleaning procedure improved the removal efficiency of the specific deposit from the virgin media by twenty two percent compared to a single cleaning procedure. There was very little difference in the amount of specific deposit removed from used media from FH1 and FH3 by the single cleaning procedure, compared to the double cycle cleaning procedure. The specific deposit that remained on the filter media as determined by the cylinder inversion test after applying both single and double cycle cleaning procedures, were within class I of the suggested guidelines for cleanliness of filter media.
- The double cleaning procedure removed substantially more captured matter from the virgin media compared to the single cleaning procedure. There was little difference between the amount of captured matter removed by the single cleaning procedure compared to the double cycle cleaning procedure in used media from FH1 and FH3.
- The turbidity of the filtrate for media which was cleaned with either the single or double cycle cleaning procedure was consistently below or close to 0.5 NTU which is the Rand Water production standard.

CHAPTER 5 – *IN SITU* CHEMICAL METHOD OF FILTER REHABILITATION

5.1 Purpose

The objective of this investigation was to examine the chemical cleaning of filter media with chlorine to rehabilitate dirty filter media *in situ*. This filter rehabilitation method has been done before, however the efficacy of soaking filter media in chlorine solution has never been quantified. The experiment was conducted by soaking the filter medium after cleaning, in a 50mg/l chlorine solution (i.e. 85g Ca(OCl)₂ / m²) for 2 hours.

5.2 Introduction

The effective pre-treatment of source water and adequate and regular cleaning of filter media should maintain filter media in a satisfactory and clean condition. Proper cleaning would remove suspended matter that has been retained on the filter medium from the clarified water. It is often found that deposit, that is difficult to remove, accumulates in the filter bed. This deposit may consist of residues of the coagulants, inorganic compounds or biological residues. Water treatment plants may also experience an increase in the grain size of the filter media. This may be due to inorganic chemical precipitates, most often calcium carbonate.

Once the problem of dirty filter media has been recognized there are several ways of dealing with it. The easiest and most cost effective method involves *in situ* chemical cleaning of filter media (Underwood, 1993).

Hydrolysed metals that precipitate as hydroxides are often used as coagulants in conventional drinking water treatment. These processes require addition of chemicals such as hydrated lime to the water to attain the optimum pH for the minimum solubility of the target contaminants and optimal formation of floc particles. The hydroxide compounds formed are generally sticky, gelatinous particles that are easily trapped on the filter media and once there, may not always be easily removed by normal cleaning procedures (Underwood, 1993).

Another important factor, is the abundance of calcium in almost all waters. Calcium readily reacts with available alkalinity to form calcium carbonate. At elevated pH, common to many of these reactions, calcium carbonate is readily formed and, because of its low solubility in water, it tends to precipitate and crystallize onto any available surface area, specifically filter media that offers a large reactive surface area.

Filter media provide a site for the accumulation of the precipitated particles, which is the start of the crystal growing cycle. Although each layer may be microscopic, over a period of time, just like a pearl develops, the grains of the filter media gradually increase in size (Underwood, 1993).

Cleaning the filter can be effective in reversing this growth by providing an abrasive action of one particle against another; however, for a variety of reasons, not all of the accumulated materials may be removed. Progressively the filter media grow over a period of time, usually too gradually to be noticed immediately, until some of the particles may be several times their original size. This often goes unnoticed because as the bed size gradually increases, small

amounts of the filter media may be lost through the backwash so that the freeboard in the filter appears to remain the same.

As the size of the particles increases so does the size of the space between the particles. This allows larger particulate matter to flow into and through the filter with potentially serious consequences. This may allow suspended matter and pathogenic organisms to pass through the filter and into the distribution system.

By the time the increase in filter media size is noticed, it is usually too late to correct by normal operational procedures, except by applying more drastic measures. Three possible drastic measures can be used to rehabilitate filter media.

- Removing the fouled media and replacing with new, properly sized media would solve the problem. This is time consuming and expensive. Not only is the new media costly, but removing and disposing of the old media is not always a simple task.
- Another alternative would be to remove the media from the filter and clean the particles, and reuse the original media. This choice of renovating the media is time consuming and expensive. Moreover this method is not very successful as it is difficult to remove inorganic chemical precipitates or crystallized deposit.
- A third alternative is *in situ* cleaning, which can eliminate handling of the media altogether. If done correctly *in situ* cleaning can be effective and relatively cheap.

Commercial grade acids, such as hydrochloric acid, are used to rehabilitate precipitate encrusted filter media. (Underwood, 1993). However the use of acid as an *in situ* method of cleaning filter media is seldom recommended, because acid may be drawn into the metal under drain and cause damage. Caustic soda can be used when the media is coated with aluminium hydroxide film resulting from the passage of abnormal quantities of floc into the filter media (Cox, 1946).

A common form of *in situ* chemical cleaning involves soaking a filter bed with a solution of chlorine. Chlorine is very effective in the removal of slime producing organisms from filter media (AWWA, 1991).

Another form of *in situ* chemical cleaning involves the use of surfactants, but this is seldom used in the water treatment industry. There are four classifications of surfactants, namely, anionic, cationic, non-ionic and amphoteric. Non-ionic surfactants are the most widely used for surface cleaning and have no charge in aqueous solution (Chad, 1996). The advantage of the surfactants is that the operator can easily see where it has been applied because it produces foam.

Surfactants however have some disadvantages when used to clean filter media. (1) It foams which is a nuisance. (2) It prevents the use of strong agitation during filter cleaning and creates waste disposal problems. (3) Surfactants in backwash water will affect the operation of recovered filter backwash water treatment plants. (4) When the surfactants are not washed away properly from the filter media, residues of it may appear in the potable water.

5.3 Experimental Work

Only media from FH3 was used to conduct the pilot scale experiments. Soaking filter media in chlorine was divided into three sections, namely:

- Bench scale experiment: to establish soaking duration
- Pilot scale experiment: experiments were conducted using pilot filters
- Full scale plant trial: experiment was conducted on a full scale plant

5.4 Pilot Scale Experiment

5.4.1 Chlorine consumption of filter media – bench scale test

From a bench scale experiment, the chlorine demand of filter media at an initial concentration the equivalent of 50mg/l (85 Ca(OCl)₂ g/m²) the chlorine consumption was determined. The results obtained are shown in Table 5.1.

Table 5.1: Chlorine demand of filter media exposed to a solution of 50 mg/l chlorine.

Chlorine concentration in soaked filter media (mg/l)				
Initial concentration	After 15 minutes	After 30 minutes	After 60 minutes	After 120 minutes
50	33	25	17	8

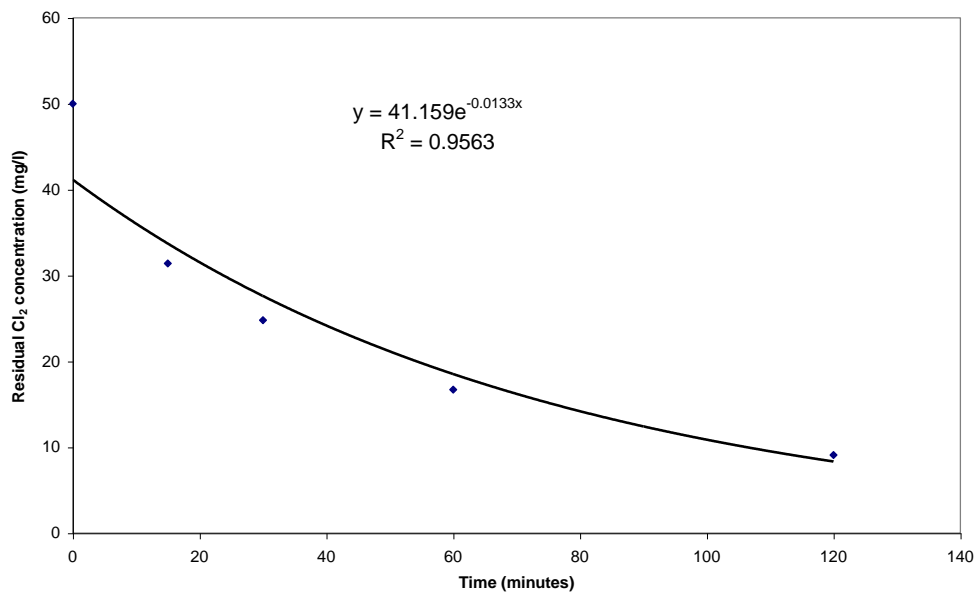


Figure 5.1: Reduction of chlorine (Cl₂) in contact with filter media against time interval.

5.4.2 Use of chlorine and chlorine dioxide to clean filter media – pilot plant study

A pilot scale experiment was conducted based on the results obtained from the bench scale experiment. Six pilot columns, (labeled A through F), were used. All columns were filled with filter media from FH3. Columns A and B were cleaned with the single procedure only (not soaked in any oxidant). This was referred to as the control. Columns C and D were cleaned and soaked with 50mg/l chlorine solution for two hours. Columns D and E were cleaned and soaked with 50mg/l chlorine dioxide for two hours. Samples of the soaking solutions were taken at a depth of 600mm, at respectively 15, 30, 60 and 120 minutes. Residual chlorine and

chlorine dioxide were measured on each sample. Figure 5.2 presents the results obtained from this experiment.

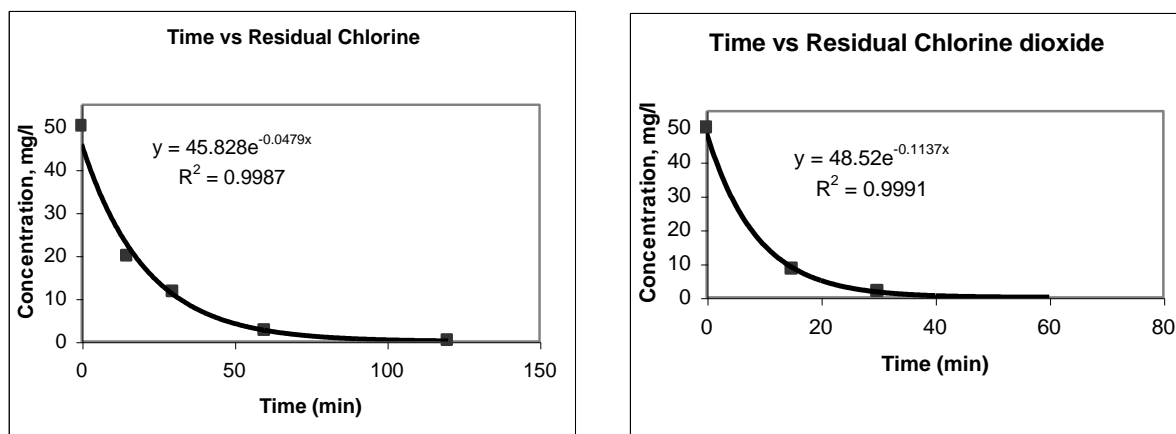


Figure 5.2: Residual chlorine (Cl₂) and chlorine dioxide (ClO₂) measured at different time intervals during the soaking of the filter media in pilot filters at a depth of 600mm.

Samples of filter media were taken before and after cleaning and lastly after the media had been soaked in the oxidant and cleaned. A single cleaning procedure was applied to all six pilot filters before the oxidants were added. The control to which no chemical was added was cleaned at the same time. The specific deposit concentration, EPS and HPC on the filter media were determined. (Heterotrophic plate count was expressed per gram of filter medium). “Fresh” sand was used in each experiment, which was repeated six times, the averages of the six results are shown in Table 5.2. The extracellular polymeric substances (EPS) comprised between 40% and 80% of the volatile fraction (VSS) of the specific deposit, with an average of 60%.

Table 5.2: Specific deposit, EPS and HPC present on filter media before and after backwash and soaking of filter media in Cl₂ and ClO₂ conducted on pilot filters (single cleaning procedure).

Control	Soaking	Media	TSS (kg/m ³)	VSS (kg/m ³)	EPS (kg/m ³)	HPC (cfu/g)	EPS/VSS	VSS/TSS
Control	No Chemical Added	B/BW	2.4	0.62	0.31	6800	0.50	0.26
		A/BW1	0.68	0.22	0.10	1900	0.45	0.32
		A/BW2	0.30	0.10	0.04	1010	0.4	0.33
Experiment	Cl ₂	B/BW	2.3	0.58	0.43	6400	0.74	0.25
		A/BW	0.64	0.19	0.14	3450	0.74	0.30
		A/S & BW	0.23	0.05	0.04	1245	0.8	0.22
	ClO ₂	B/BW	2.2	0.65	0.22	6850	0.44	0.29
		A/BW	0.57	0.19	0.12	6200	0.63	0.33
		A/S & BW	0.44	0.12	0.08	2290	0.67	0.27

B/BW : filter media sample taken **before the pilot filter was cleaned.**

A/BW : filter media sample taken **after the pilot filter was cleaned.**

A/S & BW : filter media sample taken **after the pilot filter media was soaked in an oxidant and cleaned.**

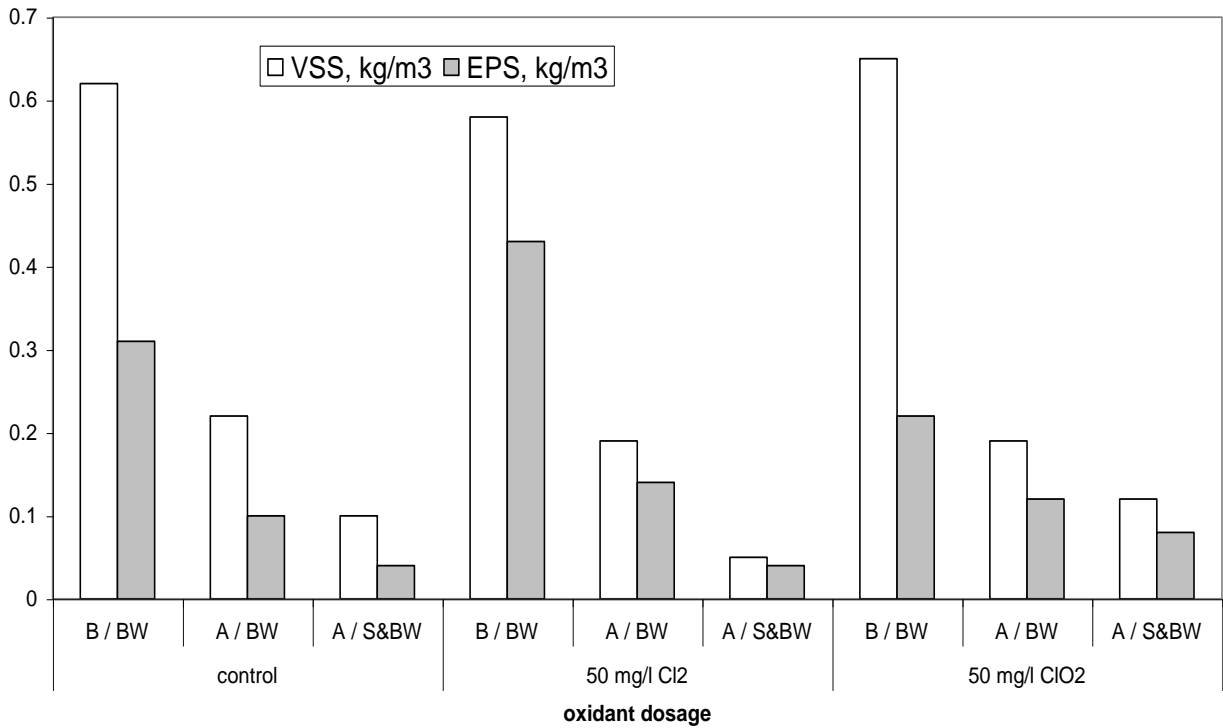


Figure 5.3: Relationship between volatile (VSS) fraction and EPS in the filter media treated with Cl₂ and ClO₂ compared with results after a single cleaning procedure.

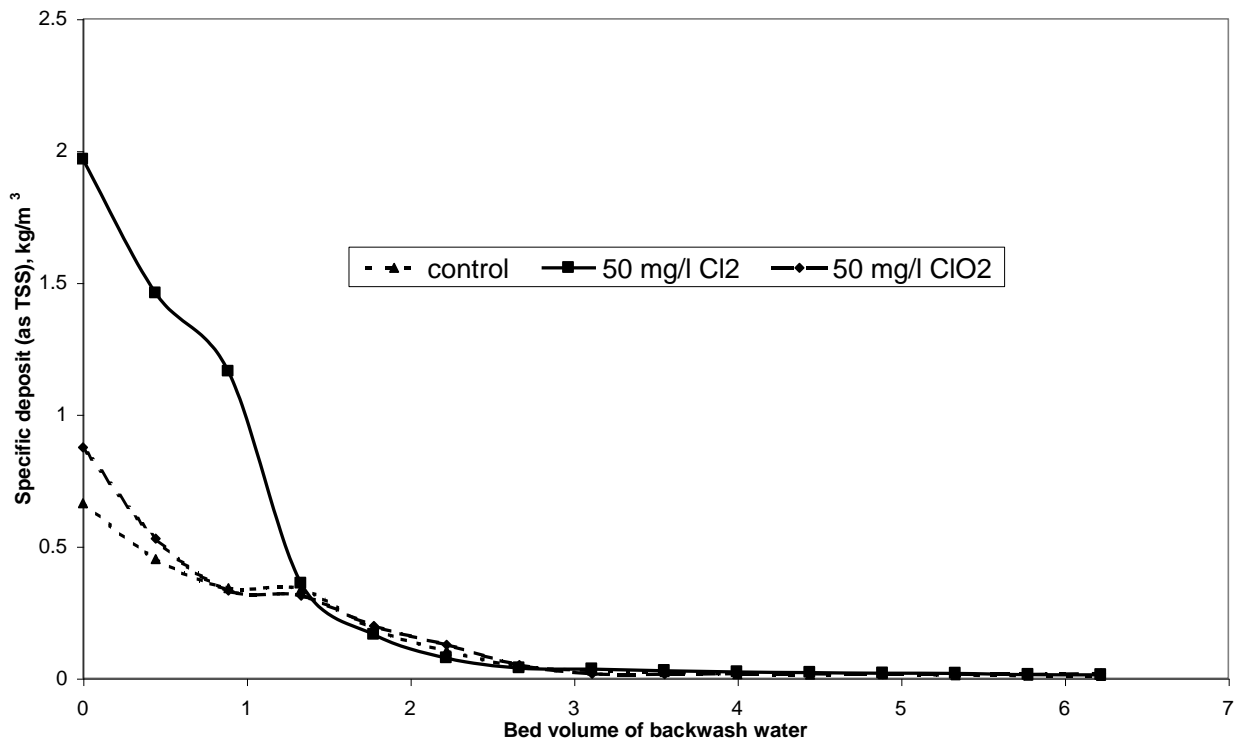


Figure 5.4: Rate of reduction of specific deposit washout after soaking filter media in oxidant.

Table 5.3: Removal efficiency of the volatile fraction after soaking filter media in an oxidant for a single backwash procedure.

	Media	VSS (kg/m ³)	% Removal	Total % Removal
Control	B/BW	0.62	64	84
	A/BW	0.22		
	A/S & BW	0.10	54	
50 mg/l Cl ₂	B/BW	0.58	66	91
	A/BW	0.19		
	A/S & BW	0.05	74	
50 mg/l ClO ₂	B/BW	0.65	70	81
	A/BW	0.19		
	A/S & BW	0.12	37	

- B/BW : filter media sample taken **before the pilot filter was backwashed**
A/BW : filter media sample taken **after the pilot filter was backwashed**
A/S & BW : filter media sample taken **after the pilot filter was soaked in an oxidant and backwashed**

The investigation was continued where the double cycle cleaning procedure (i.e. two consecutive applications of air for 2.5 minutes and water for 3.5 minutes) was applied. Six experiments were conducted in a similar manner as the single cleaning procedure and Table 5.4 contains the average of the six experiments that were conducted.

Table 5.4: Suspended solids, EPS and HPC present on filter media before and after cleaning and soaking of filter media in Cl₂ and ClO₂ conducted on pilot filters (double cycle cleaning procedure).

Control	Soaking	Media	TSS kg/m ³	VSS kg/m ³	EPS kg/m ³	HPC (cfu/g)	VSS/TSS	EPS/VSS
	Control		B/BW	5.3	1.4	0.87	31850	0.26
A/BW			1.5	0.6	0.40	13900	0.40	0.67
A/S & BW			0.9	0.26	0.20	9650	0.29	0.77
Experiment	50 mg/l Cl ₂	B/BW	5.0	1.1	0.91	41500	0.22	0.83
		A/BW	0.96	0.42	0.33	13350	0.44	0.79
		A/S & BW	0.70	0.23	0.18	605	0.33	0.78
	50 mg/l ClO ₂	B/BW	5.5	1.4	1.1	40000	0.25	0.79
		A/BW	2.5	0.69	0.49	6450	0.28	0.71
		A/S & BW	0.70	0.34	0.30	3700	0.49	0.88

Table 5.5: Removal efficiency of the volatile fraction after soaking filter media in an oxidant for a double cycle backwash procedure.

	Media	VSS, kg/m ³	% Removal	Total % Removal
Control	B/BW	1.4	57	81
	A/BW	0.60		
	A/S & BW	0.26	57	
50 mg/l Cl ₂	B/BW	1.1	62	79
	A/BW	0.42		
	A/S & BW	0.23	45	
50 mg/l ClO ₂	B/BW	1.4	51	76
	A/BW	0.69		
	A/S & BW	0.34	51	

- B/BW : filter media sample taken before the pilot filter was backwashed
A/BW : filter media sample taken after the pilot filter was backwashed
A/S & BW : filter media sample taken after the pilot filter was soaked in an oxidant and backwashed

Tables 5.4 and 5.5 show the percentage removal per backwash cycle and the overall percentage removal efficiency of the controls and the experiments. It seems as though soaking of the filter media in chlorine or chlorine dioxide had little or no benefit as the difference in overall removal efficiency is insignificant. It was therefore decided not to soak the filter media in the full scale filter in chlorine dioxide. An additional reason was the danger associated with the use of chlorine dioxide in enclosed areas and practicality of applying a chlorine dioxide solution to the filter.

5.5 Full Scale Plant Trial

5.5.1 Experimental work

Three adjacent filters that had previously been subjected to similar conditions, i.e. filter running times and rates, quality of unfiltered water and cleaning procedures, were cleaned, and then allowed to run for 72 hours. After this time, the filter beds were completely drained. In selected areas the top 10mm of the media surface was scraped off to prevent inclusion of surface debris in ten core samples of the filter media taken from each filter. From previous experiments it was determined that about 85g/m² of granular calcium hypochlorite would be required to satisfy the chlorine needs in the filter media.

Thereafter, granular calcium hypochlorite was sprinkled on two filters at concentrations of 20g/m² and 100g/m² respectively. The third filter was kept as an unchlorinated control. The water level in the filter basins was then brought up to just above the media and the air scour was applied for two minutes to mix the filter media, water and the granular calcium hypochlorite. The filters were left to soak for 24 hours and then cleaned using the single cleaning procedure. The backwash water was sampled every 30 seconds for the duration of the backwash.

The results reported earlier on in this report indicate that chlorine in contact with the filter media would dissipate rapidly in the first two to six hours. To ensure that the chlorine dissipated completely the filters were only cleaned after 24 hours.

5.5.2 Results from full scale plant trial

After the application of 100g/m² of granular calcium hypochlorite, much of the deposit and other debris that normally accumulates on the media surface had disappeared upon visual inspection. This deposit could have the potential to develop into mudballs if not removed from the filter media. The composition and the fate of oxidized deposit were not the focus of the investigation, but could be a productive avenue for future research.

5.5.2.1 Filter media grading after soaking filter bed in calcium hypochlorite for 24 hours

The characteristics of the filter media after soaking the filter bed in calcium hypochlorite for 24 hours was evaluated by measuring the grain size distribution and grain size. Table 5.6 and Figure 5.5 respectively depict the grain size distribution of filter media and Table 5.6 gives the grain sizes after soaking the filter beds in calcium hypochlorite for 24 hours.

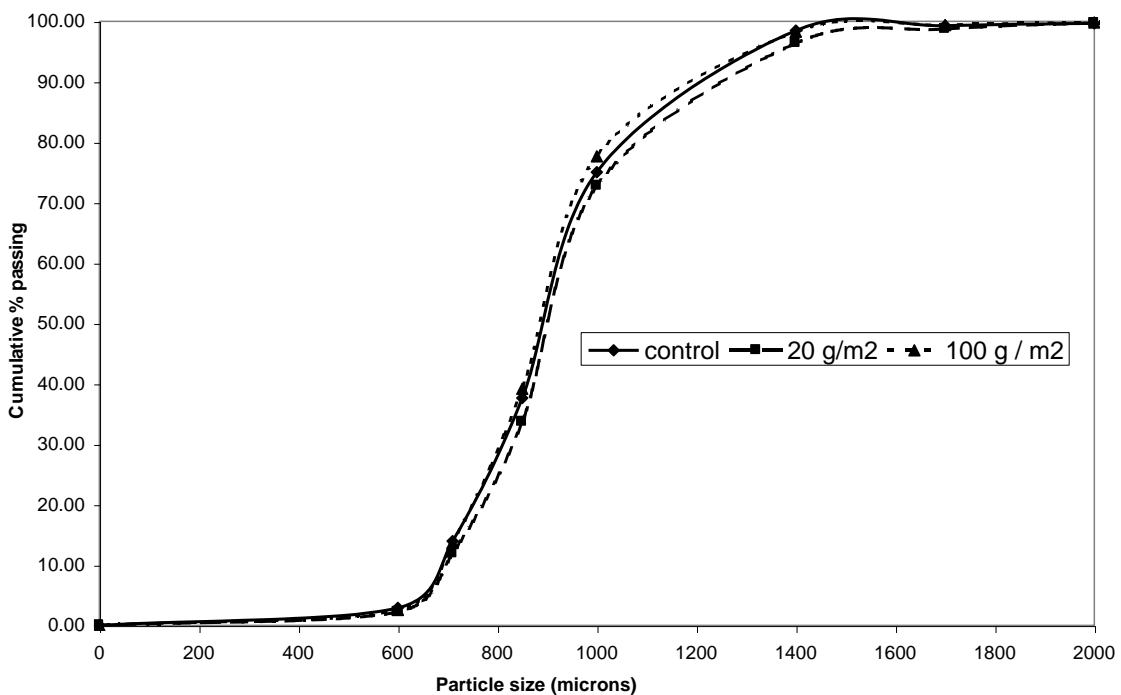


Figure 5.5: Grain size distribution in filter media after soaking beds in calcium hypochlorite for 24 hours.

Table 5.6: Grain size distribution in filter media after soaking filter beds in calcium hypochlorite for 24 hours.

HTH Dose (g/m ²)	d ₁₀ (micron)	d ₆₀ (micron)	UC
Control	690	950	1.38
20 g/m ²	670	940	1.40
100 g/m ²	670	930	1.39

Although there seems to be a slight decrease in the grain size of the filter media treated with chlorine, for all practical purposes, there is no difference between the media of the two filters in which the chlorine soaking test was done and the control.

5.5.2.2 Analysis of the stripped specific deposit

Table 5.7 gives the removal efficiency of the specific deposit from the filter media that was soaked in chlorine for 24 hours and cleaned, and changes in TSS and VSS concentrations in filter media.

Table 5.7: Specific deposit removal efficiency after soaking filter bed in HTH chlorine for 24 hours.

HTH Dose (g/m ²)	Sample	TSS (kg/m ³)	VSS (kg/m ³)	VSS/TSS	% VSS Removed
Control	B/BW	8.53	2.08	0.24	12
	A/BW	2.78	1.84	0.66	
20	B/BW	8.56	2.36	0.28	70
	A/BW	1.66	0.70	0.42	
100	B/BW	7.95	2.27	0.29	75
	A/BW	1.61	0.56	0.35	

5.5.2.3 Specific deposit washout profile

In figure 5.6 and 5.7, the number of bed volumes of wash water against amount of specific deposit washed out is given. This demonstrates that very little additional specific deposit was washed out after two bed volumes of wash water had been applied. Most of the specific deposit was removed within two bed volumes of wash water irrespective of whether the media was soaked in calcium hypochlorite or not.

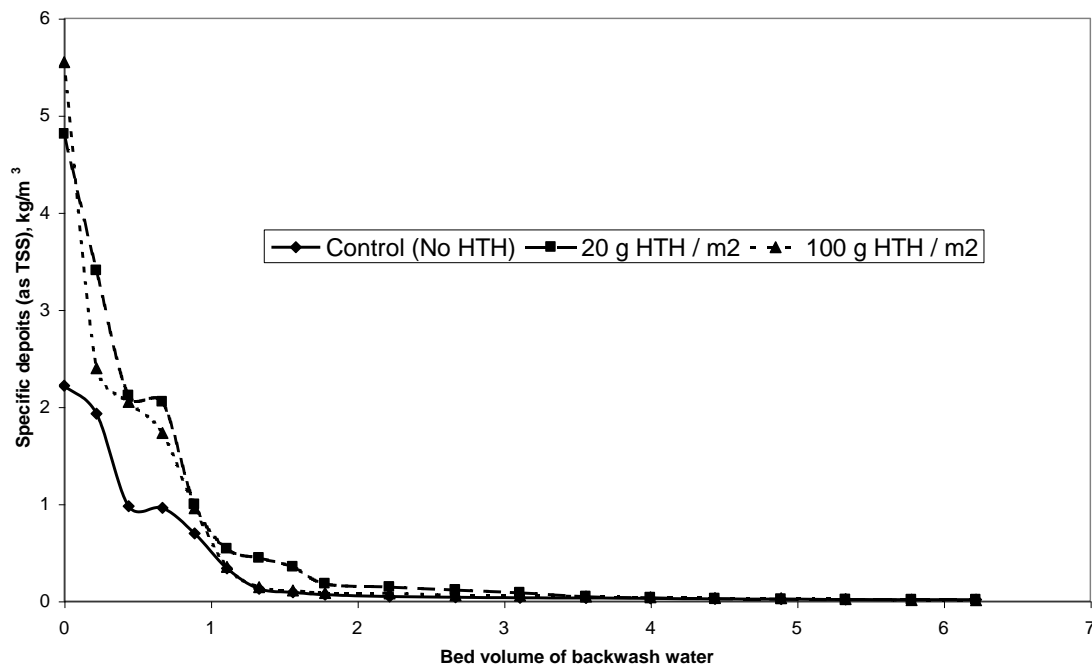


Figure 5.6: Wash out profile of specific deposit (expressed as TSS) in the backwash water after soaking the filter bed in calcium hypochlorite chlorine for 24 hours.

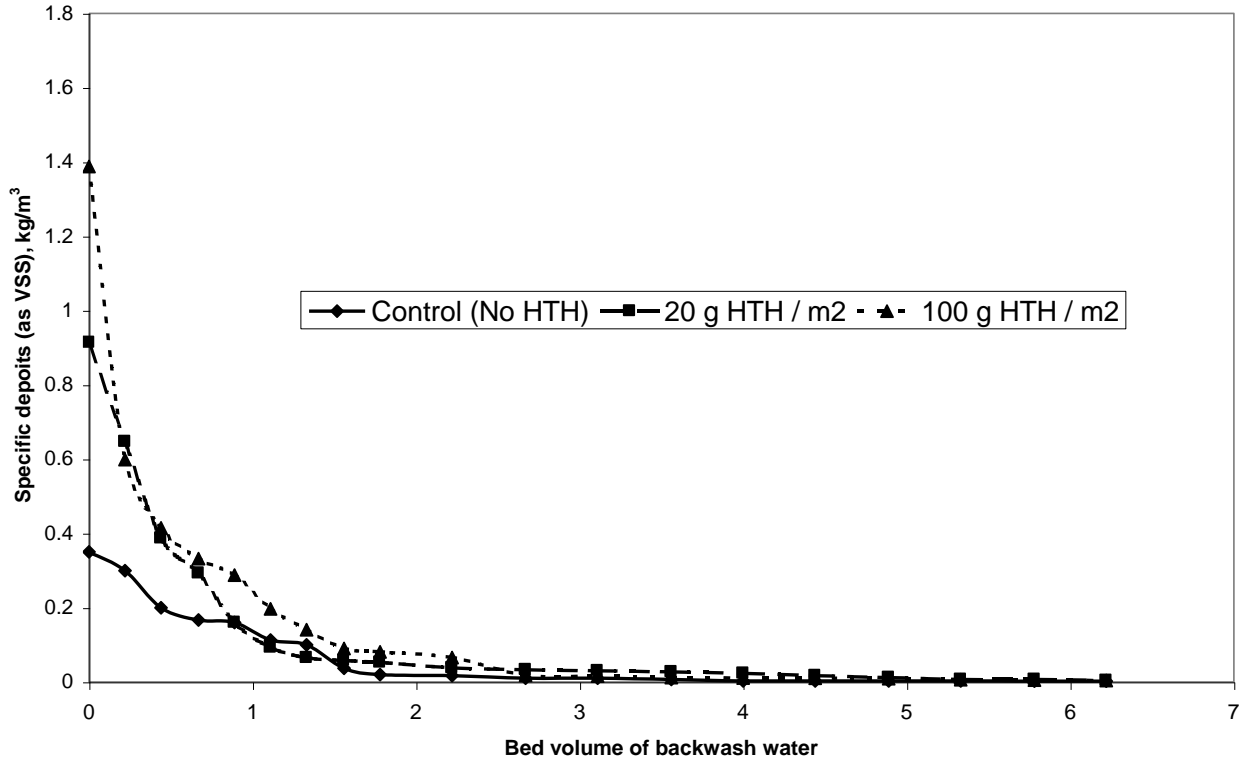


Figure 5.7: Wash out profile of specific deposit (expressed as VSS) in the backwash water after soaking the filter bed in calcium hypochlorite chlorine for 24 hours.

Table 5.8 and Figures 5.8 and 5.9 depict the cumulative specific deposit per bed volume of backwash water. After 2.7 bed volumes, the cumulative specific deposit remained similar. The total cumulative specific deposit (expressed as TSS) after 2.7 bed volumes was 1.3kg/m³, 1.8kg/m³ and 2.4kg/m³, and for the control, 20g/m² and 100g/m² respectively.

Table 5.8: Cumulative specific deposit in backwash water after soaking filters in calcium hypochlorite (HTH).

Bed Volume of Backwash Water	Control (No HTH)		20g HTH / m ²		100g HTH / m ²	
	TSS, kg	VSS, kg	TSS, kg	VSS, kg	TSS, kg	VSS, kg
0	0	0	0	0	0	0
0.2	57.8	5.9	47.1	12.7	66.9	11.8
0.4	96.2	13.8	127.9	27.9	150.1	28.1
0.7	153.7	23.8	231.6	45.5	273.0	48.0
0.9	209.2	36.5	307.7	58.2	352.2	70.9
1.1	242.6	47.7	342.7	67.5	405.5	90.5
1.3	257.7	59.6	359.8	75.2	458.2	107.2
1.6	270.3	64.8	375.1	83.3	507.4	119.8
1.8	280.9	67.9	388.5	91.7	535.7	132.7
2.2	290.5	71.3	404.2	99.3	564.1	145.8
2.7	300.0	73.7	418.5	101.1	567.1	150.1

3.1	309.7	74.5	420.4	102.5	570.0	150.5
3.6	319.9	75.7	421.3	103.2	570.3	150.8
4.0	322.9	76.8	422.6	103.2	572.8	152.2
4.4	325.7	78.0	423.7	103.9	573.7	154.1
4.9	327.4	78.3	424.8	104.4	574.6	157.0
5.3	329.5	79.7	425.4	104.8	575.2	157.9
5.8	330.3	80.8	426.5	105.1	576.5	160.6
6.2	333.6	81.9	428.0	105.3	578.7	161.7

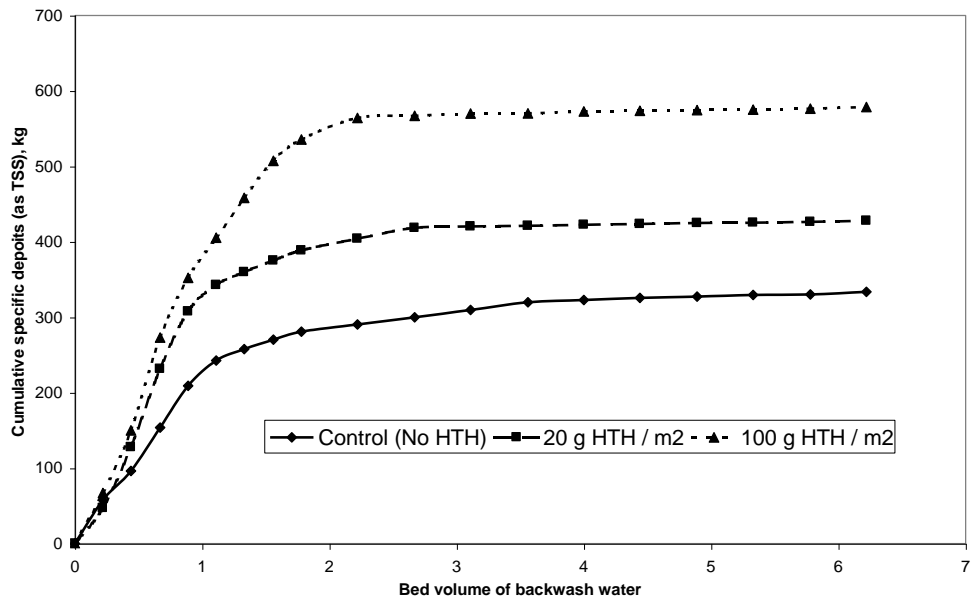


Figure 5.8: Cumulative specific deposit (expressed as TSS) in the backwash water after soaking the filter bed in HTH chlorine for 24 hours.

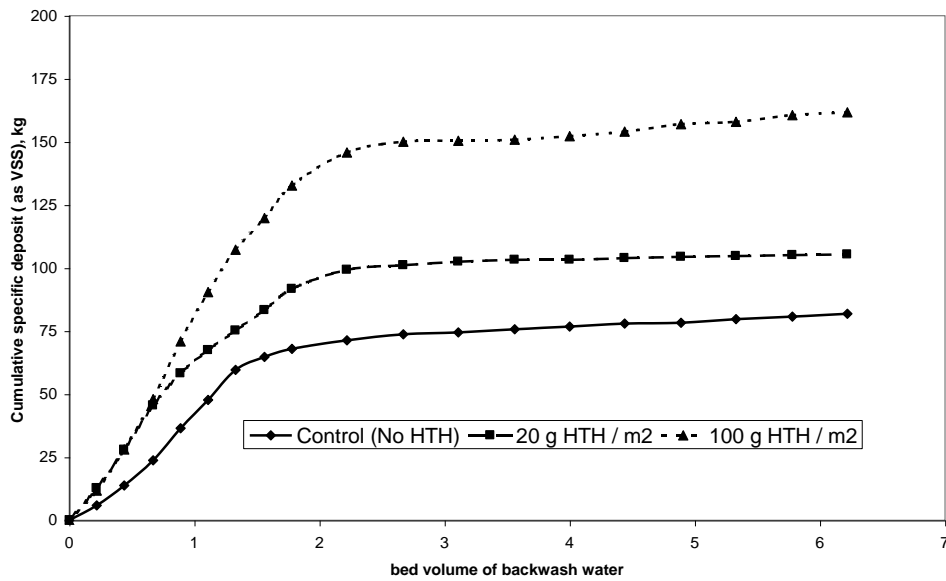


Figure 5.9: Cumulative specific deposit (expressed as VSS) in the backwash water after soaking the filter bed in HTH for 24 hours.

The total cumulative specific deposit removed in a filter soaked in 100g/m² calcium hypochlorite, was 1.8 times more than the control for both TSS and VSS. And the total cumulative specific deposit removed in a filter soaked in 20g/m² calcium hypochlorite was 1.3 times more than the control for both TSS and VSS. Visual inspection of the filters after soaking and backwash show that the amount of specific deposit on the media surface decreased as the higher dosage of calcium hypochlorite was applied.

5.5.2.4 Analysis of the deposit collected on the surface of the filter after backwashing

Samples of the specific deposit accumulated on the surface of the filter bed were collected, dried and pulverized. The deposit was analysed by XRF analysis. The results were compared with suspended matter extracted from Vaal Dam water. Tables 5.9A and 5.9B contain the results.

Table 5.9A: Analysis of the deposit collected from the surface of the filter bed.

Phase	SiO ₂	CaO	Fe ₂ O ₃	Al ₂ O ₃	MgO	K ₂ O	Mn ₃ O ₄	TiO ₂	P ₂ O ₅	WO ₃	Cr ₂ O ₃	ZrO ₂	HfO ₂
%	55.4	23.3	11	8.2	0.7	0.6	0.2	0.2	0.2	0.06	0.04	0.01	0.00

Table 5.9B: Analysis of the suspended matter extracted from Vaal Dam water.

Phase	SiO ₂	CaO	Fe ₂ O ₃	Al ₂ O ₃	MgO	K ₂ O	Mn ₃ O ₄	TiO ₂	P ₂ O ₅	WO ₃	Cr ₂ O ₃	ZrO ₂	HfO ₂
%	59.4	1.3	10.9	25.7	1.8	2.3	0.2	0.7	0.3	0.04	0.03	0.02	0.00

The chemical composition of the deposit from the filter media is similar to that of the suspended matter extracted from Vaal Dam water. The higher proportions of CaO in the deposit from the filter media could be attributed to the use of hydrated lime as a coagulant.

5.6 Summary and Conclusions

- A combination of a single cleaning procedure and soaking of filter media in chlorine dioxide showed no benefit in any of the experiments?. The reason for the inefficiency of chlorine dioxide could be its rapid decay rate and instability in light.
- A combination of a single cleaning procedure and soaking filter media in chlorine, improved the removal efficiency of the volatile fraction of the specific deposit by twelve percent.
- A combination of a double cycle cleaning procedure and soaking filter media in chlorine or chlorine dioxide showed no benefit over the application of the single cleaning procedure.
- Extended backwashing of more than two bed volumes had no significant effect on removing more of the specific deposit.
- Analysis of the wash out water indicate that significantly more specific deposit was removed following soaking with chlorine.

CHAPTER 6 – PREOXIDATION

6.1 Purpose

The purpose of these experiments was to investigate the effect of chlorinating water before filtration, on the filtrate quality. It is stated by William *et al*, 2004, that preoxidation can alter the grain size distribution of suspended matter in clarified water, which could thereby influence particle removal by filtration. Although this aspect was not the focus of the investigation it could be a topic for future research.

6.2 Experimental Work

Only chlorine was used as preoxidant in this experiment, which was repeated six times. The chlorine dose applied during prechlorination was such that it exceeded the 20 minute chlorine demand of water by 1mg/l. As the average chlorine demand for the clarified water was 1.24mg/l after 20 minutes of contact time a dose of 2.24mg/l was used in all six experiments. Calcium hypochlorite was used to make up a chlorine stock solution, and then added proportionally to the water to maintain the desired chlorine concentration. The residual chlorine concentration in the filtrate was measured following the standard chlorine determination method, using DPD as an indicator (Standard method 4500 Cl).

The following analyses were performed on the water before filtration and the filtrate, with and without preoxidation: free viable chlorine residual, turbidity, dissolved organic carbon (DOC), total organic carbon (TOC), and UV₂₅₄ absorption. The concentration of specific deposit on the filter media was measured using the cylinder inversion test.

6.3 Results from the Experiment on the Chlorination of Water Prior to Filtration

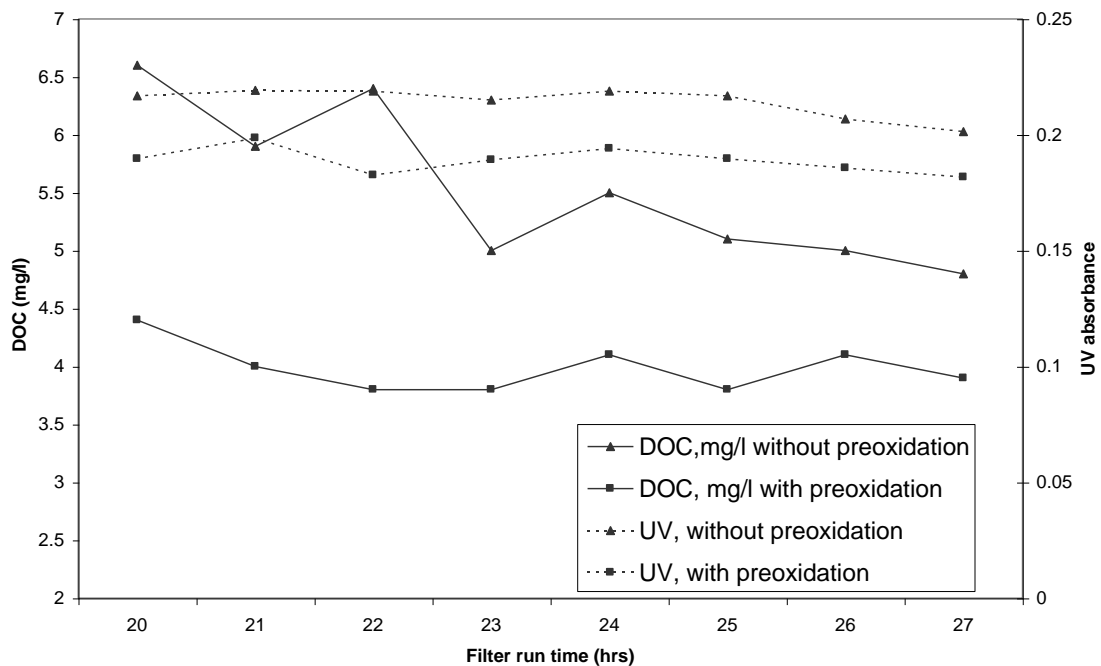


Figure 6.1: DOC concentration and UV₂₅₄ absorbance of the filtrate following chlorination of water prior to filtration.

6.3.1 Reduction of DOC concentration and UV₂₅₄ absorbance in filtrate as the result of chlorination (average of six experiments)

Figure 6.1 presents DOC (in milligrams per litre) and UV₂₅₄ absorbance of the filtered water with and without preoxidation against filter run time. Table 6.1 summarises the average concentrations of DOC and UV₂₅₄ absorbance measured. From the reduction in the levels of the determinants, it seems as though the preoxidation had a beneficial effect on the filtrate quality.

Table 6.1: DOC and UV₂₅₄ absorbance of the clarified water and filtrate measured (average of six experiments).

	DOC, mg/l	UV ₂₅₄ absorbance	*SUVA l/m.mg
<i>Clarified water</i>	6.7	0.99	14.8
Control	5.4	0.21	3.9
<i>Prechlorination</i>	3.9	0.19	4.9

$$* \text{SUVA} = \left[\frac{\text{UV}_{254} \times 100}{\text{DOC}} \right] \text{ l/m.mg}$$

Typically, a specific ultraviolet absorbance (SUVA) result of less than 3 l/m.mg corresponds to largely the presence of fulvic material, whereas SUVA in the range of 4-5 l/m.mg corresponds to mainly the presence of humic material. Because humic material is more easily removed through coagulation than fulvic material, higher SUVA values should indicate water that is more amenable to enhance coagulation.

6.3.2 Analysis of the specific deposit of the filter media (as TSS) after 48 hours of filtration with and without prechlorination

Table 6.2: Specific deposit after 48 hours of filtration before backwash.

	Specific deposit, kg/m ³	Volume of water filtered, l
Without Preoxidation	1.8	1033
With Preoxidation	2.5	973

The difference in the amount of water filtered by each pilot column was six percent, which could be considered negligible. The amount of specific deposit trapped by the media in the pilot filter where preoxidation was applied, was 42 percent more than the amount of specific deposit trapped by the media in the pilot filter where preoxidation was not employed.

6.3.3 Residual chlorine in the filter bed

The residual chlorine was also monitored at different depths of the filter media. Samples were taken at 50mm above the media surface, and at 300mm and 600mm below the surface of the filter bed. Figure 6.2 depicts the results obtained.

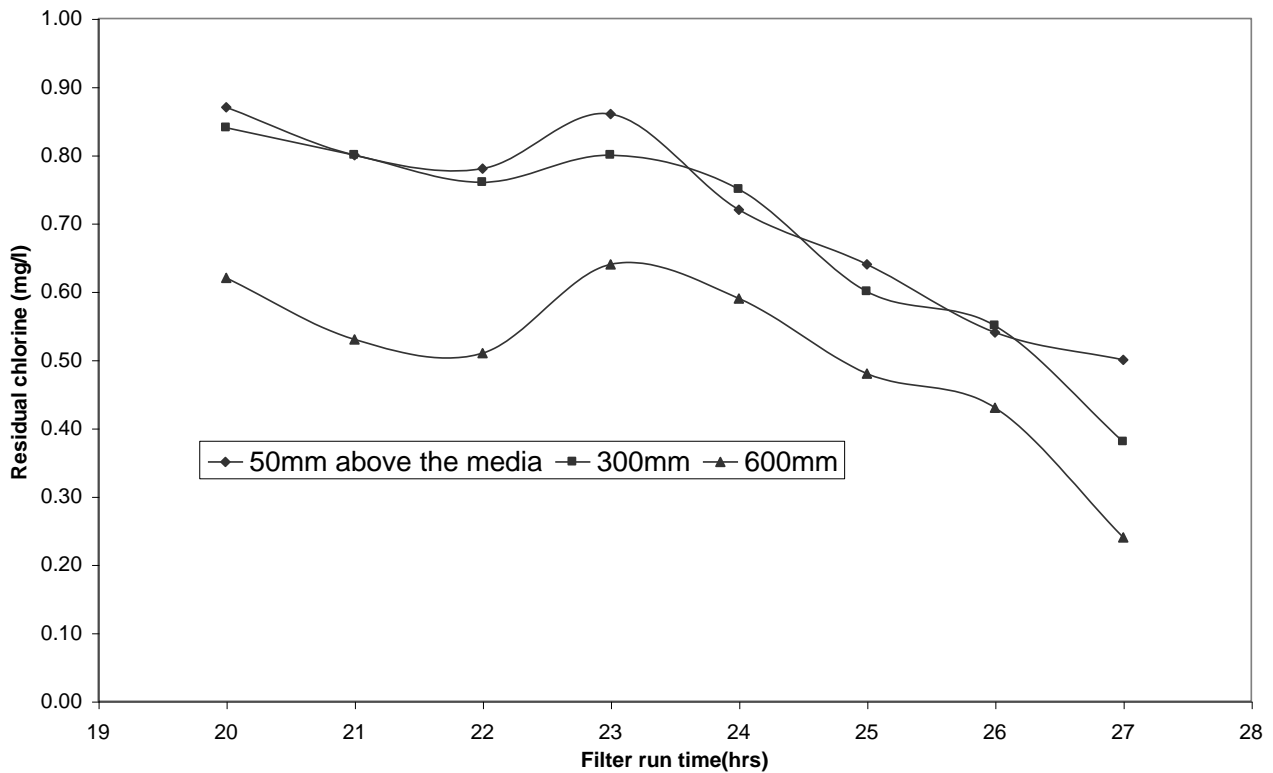


Figure 6.2: Residual chlorine concentration at different depths in the filter media related to the duration of the filter run.

Although it would have been ideal to keep the chlorine concentration in the water before filtration constant, it decreased over time. The chlorine concentration at 300mm and 600mm to the filter bed, followed the same pattern but at the lower concentrations. This would indicate that the filter media consumed the chlorine, but also that it is possible that chlorine would penetrate through the filter media.

6.4 Summary and Conclusions

- From the reduction in the levels of the determinants it seems as though the preoxidation had a beneficial effect on the filtrate quality.
- Significantly more specific deposit accumulated in the filter media following preoxidation compared to the situation where no preoxidation was done.

CHAPTER 7 – ECONOMIC ANALYSIS

7.1 Economic Aspects of Filter Media Cleaning

An economic analysis of the single and double cycle cleaning procedure was conducted. As explained earlier, these two cleaning procedures consisted of separate air scours and water washes (backwashes). The time delay between air scouring and backwashing was approximately 10 seconds. The single cleaning procedure comprises an air scour of five minutes and a backwash of seven minutes. The double cycle cleaning procedure consists of two consecutive cleaning cycles, each comprising an air scour of 2.5 minutes followed by a backwash of 3.5 minutes.

For both these cleaning procedures operational and capital requirements were analysed as shown in Tables 7.1 and 7.2 below. It can be seen that the total volume of air and water used when applying single backwash and double cycle procedures remains the same. The figures quoted pertain to equipment and conditions as in a large filter house and are used as an example only. The costs are expressed as ZA cents per m² of the filter.

Although the control equipment will be used twice as much when applying the double cycle cleaning procedure compared to the single cleaning procedure, it seems as though the additional maintenance cost will be little and of no significance over the useful life of a filter plant.

Table 7.1: Economic analysis for single cleaning procedure.

OPERATIONAL PARAMETERS		Calculation
Air scour rate (mm/sec)	7.5 (27 m/h)	
Backwash scour rate (mm/sec)	8.9 (32 m/h)	
Air scour time (min.)	5	
Backwash time (min.)	7	
Bed volume of backwash water	6.2	
Delay time between air and water (s)	10	
Air scour pump power rating (kW)	90	
Backwash pump power rating (kW)	225	
Volume of compressed air used for air scour (m ³ of compressed air / m ² filter area)	2,250	Air scour rate multiplied by air scour time
Volume of water used for backwash (m ³ of backwash water / m ² filter area)	3,370	Backwash rate multiplied by Backwash time
Energy required to air scour (kW/h)	7.5	Air scour pump power multiplied by Air scour time
Energy used to backwash (kW/h)	26.25	Backwash pump power multiplied by Backwash time
Filter run time (hrs)	48	

OPERATING COSTS		Calculation
Cost of purified water (m ³)	270	
Energy cost (c/kW/h)	24	
Amount spent on backwash (c/m ² filter area)	910	Volume of water used for backwash multiplied by cost of water
Amount spent on air scouring (c/m ²)	180	Unit cost of energy multiplied by Energy used for air scouring
Energy costs for backwashing (c/m ²)	630	Unit cost of energy multiplied by Energy used for backwashing
Total cost of consumables to perform Single cleaning procedure (c/m ²)	1720	

Table 7.2: Economic analysis for double cycle cleaning procedure.

OPERATIONAL PARAMETERS		Calculation
Air scour rate (mm/sec)	7.5 (27 m/h)	
Backwash scour rate (mm/sec)	8.9 (32 m/h)	
Air scour time (min.)	2.5	
Backwash time (min.)	3.5	
Bed volume	3.1	
Delay time between air and water (s)	10	
Air scour pump power rating (kW)	90	
Backwash pump power rating (kW)	225	
Volume of compressed air used for air scour (m ³ of compressed air / m ² filter area)	1,125	Air scour rate multiplied by air scour time
Volume of water used during backwashing (m ³ of backwash water / m ² filter area)	1,865	Backwash rate multiplied by Backwash time
Energy during air scouring (kW/h)	3.75	Air scour pump power multiplied by Air scour time
Energy during backwashing (kW/h)	13.13	Backwash pump power multiplied by Backwash time
OPERATING COSTS		Calculation
Cost of purified water (c/kl)	270	
Energy cost (c/kW/h)	24	
Amount spent on backwash water (c/m ² filter area)	455	Volume of water used for backwash multiplied by cost of water
Amount spent on air scouring (c/m ²)	90	Unit cost of energy multiplied by Energy used for air scouring
Energy costs for backwashing (c/m ²)	315	Unit cost of energy multiplied by Energy used for backwashing
Cost of consumables to perform single backwash or double cycle backwash procedure (c/m ²)	860	
Total cost of consumables to perform Single cleaning procedure (c/m ²)	1720	

7.2 Direct Cost Analysis

The first backwash of the double cycle cleaning procedure removed most of the deposit. The results of the cylinder inversion test conducted after the first cleaning procedure met the suggested SA guideline for this test. This suggests that air scour and backwash time could be reduced. If the conditions for the single cleaning procedure is changed, so that the air scour time is reduced from 5 minutes to 3 minutes and the backwash time from 7 minutes to 4 minutes, which equates to approximately 3.5 bed volumes of wash water, a saving of respectively 40 and 43 percent in the direct costs of cleaning filters is possible. Total operating costs include:

- Electrical consumption during air scouring and backwashing
- Volume of water used during backwashing
- Reduction on the wear and tear on the air scour blowers or compressors, and backwash water pumps with their associated maintenance.

7.3 Indirect Cost Analysis

The indirect cost savings and other long term benefits that may result from improved filter cleaning procedures were not investigated in this study. It would only be possible to evaluate and quantify the effect of alternative cleaning procedures following a dedicated controlled study. From the rather superficial observations that were made in this regard during this study, it can be speculated that benefits as listed below may be derived.

- Cleaner filter media implies longer filter run time, an improvement in the filtrate quality, a reduction in the frequency of operating and servicing the air scour and backwash water compressor and pumps and a reduction in the frequency of replacing filter media. A longer filter run time would reduce the frequency at which the filter has to be cleaned, provided that the filter media cleaning procedure is adequate to prevent the build-up of deposit in the media.
- Suitably cleaned filter media should produce an improvement in the filtrate quality. This implies a reduction in the chlorine demand of the water and maintaining the chlorine residual in reticulation systems for a longer time.
- Filter media that is adequately cleaned time and time again, results in an increase in the lifespan of the filter media.

Factors such as grain encrustation must be investigated, to ensure that reducing the backwash duration does not cause the grain size to increase rapidly. This occurs when:

- Most of the deposit is not removed during backwash.
- Inadequate backwashing results in mudball formation.
- Metal salts are employed as coagulants.

7.4 Summary and Conclusions

Although there may not be a direct saving in using the double filter cleaning procedure, long-term benefits may be derived from cleaner filter media, more consistent grain size of media and longer periods between cleaning.

CHAPTER 8 – CONCLUSIONS & RECOMMENDATIONS

8.1 Conclusions

Conclusions presented here are based on the results and observations made when various investigations were done on the full scale plant, pilot scale experiments and *in situ* chemical method of filter rehabilitation. These conclusions pertain to the specific objectives of this study.

8.1.1 The effect of single and double cycle cleaning procedures without the addition of chemicals on used and virgin filter media.

Results from pilot plant experiments

- Double cycle cleaning procedure improved the removal efficiency of the specific deposit from the virgin media by twenty two percent compared to the single cleaning procedure. There was very little difference in the amount of specific deposit removed from used media from FH1 and FH3 by the single cleaning procedure compared to the double cycle cleaning procedure. The specific deposit that remained on the filter media as determined by the cylinder inversion test after applying both the single and double cycle cleaning procedures, was within class I of the suggested guidelines for filter cleanliness.
- The double cleaning procedure removes substantially more captured matter from the virgin media compared to the single cleaning. For the used media from FH1 and FH3 there was little difference between the amount of captured matter removed by the single cleaning compared to the double cycle cleaning procedures.
- The turbidity of the filtrate from media which was cleaned with either the single or double cycle procedure was consistently below or close to 0.5 NTU which is the Rand Water production standard. It seems however as though the turbidity of the filtrate from the virgin media was slightly lower than the turbidity of filtrate from used media.

8.1.2 The effect of multi cycle sequential washing operations and single cycle washing operations, with and without the addition of chemicals, on used filter media.

Results from full scale plant experiments

- Combination of single cleaning and soaking of filter media in chlorine dioxide showed no benefit. Combination of the single cleaning procedure and soaking filter media in chlorine improved the removal efficiency of the volatile fraction of the specific deposit by twelve percent.
- Combination of the double cycle cleaning procedure and soaking filter media in chlorine or chlorine dioxide showed no benefit.

8.1.3 Operating and capital costs associated with the implementing of the multi-cycle sequential filter cleaning procedure.

- The total amount of air and backwash water consumed during the single and double cleaning procedure is the same and therefore no saving is possible.
- During this study it was not possible to draw any conclusions on the effect of the more frequent operation of the compressors or blowers producing scour air, or backwash

water pumps on increased operational costs due to higher maintenance. It seems as though the additional costs would be negligible over the life of the equipment.

- It was not possible to quantify the long term benefits of improved filter media cleanliness on items such as: increase in filter run times, quality of filtrate and sustained quality of filter media.

8.2 Recommendations For Future Research

- Investigation into the long term effects of single *versus* double cleaning procedures in combination or without oxidation on the quality of the filtrate and filter media as well as operational costs.
- Investigate the difference in the performance of virgin media compared to used or encrusted media in terms of the removal efficiency of suspended matter in order to determine criteria to replace spent filter media.
- Investigate the effect of an *in situ* chemical method of filter rehabilitation on filtrate quality and subsequent filter run time.
- Investigate the composition and the fate of deposit remaining in or on filter media after soaking of the filter media with an oxidant.
- The effect of the chlorination of water prior to filtration on the sand's affinity to trap suspended matter and the effect of such oxidation on factors that may influence the removal of suspended matter.
- Removal efficiency of algae and invertebrates by sand filters and the efficiency of different cleaning procedures to remove these organisms from the filter media.

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