REMOVAL OF GEOSMIN AND 2-METHYLISOBORNEOL FROM DRINKING WATER THROUGH BIOLOGICALLY ACTIVE SAND FILTERS

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7 PILOT STUDY ON BIOLOGICAL SAND FILTRATION FOR MIB AND GEOSMIN REMOVAL – APPARATUS AND METHODS

7.1 INTRODUCTION TO PILOT PLANT TRIALS

A pilot plant trial was conducted to investigate the removal of MIB and geosmin through biological sand filtration on a larger scale.

Previous work reported in this thesis showed that a significant period of time was required before biological sand filters utilising sands without a pre-existing biofilm were capable of MIB and geosmin biodegradation. The bacterial inoculation experiments also showed that the presence of a biofilm was an important factor in the attachment of geosmin degrading organisms to sand media. In the pilot plant, pre-ozonation was employed in an attempt to enhance the formation of the biofilm and hence minimise this acclimation period. Virgin sand was used in the pilot plant studies to further investigate the time periods required for biological degradation of MIB and geosmin to occur in sand filters.

The previous laboratory scale studies were limited in the range of flow rates which could be used. The pilot plant allows for the use of a larger range of filtration rates and subsequent EBCTs.

This chapter outlines the apparatus and methods used in the pilot plant study.

7.2 PILOT PLANT APPARATUS AND METHODS

The pilot plant consisted of two treatment trains.

- Settled water followed by biological sand filtration
- Ozonated settled water followed by biological sand filtration

The pilot plant was fed with Happy Valley settled water, which had been treated by coagulation, flocculation and sedimentation. It contained no chlorine or other disinfectants. The feed water was supplied to the pilot plant via a centrifugal pump located at the end of the sedimentation bay. The pH of the water was measured throughout the trial. It remained stable at approximately:

- pH settled water: 6.8
- pH ozonated water: 7.6

The columns were made of clear PVC and were wrapped in black builders' plastic to prevent excessive growth of photosynthetic algae.

The pilot plant dimensions are listed in Table 7-1. Table 7-2 shows the range of EBCTs used in the studies, and the corresponding hydraulic loading rates and flow

rates. A schematic of the plant is shown in Figure 7-3. Photographs of the pilot plant are presented in Figure 7-1 and 7-2.

7.2.1 Media

The pilot plant columns were mono-media sand filters. Each filter contained 1.0 m of sand with effective size of 0.55 mm and a uniformity coefficient of 1.5. This media size was chosen to replicate the particle size of the sand at Morgan WTP.

A general rule of thumb for pilot-scale filtration studies is that the column diameter (D) must be greater than the media diameter (d) according to the ratio of D/d > 50 (Logsdon *et al.* 2002). Here, the column diameter is 80 mm. The E.S of the sand is 0.55 mm. This gives a ratio of 145.45, which is acceptable.



Figure 7-1: Photograph of Pilot Plant.



Figure 7-2: Photograph of ozone generation unit.

Table 7-1: Pilot Plant Dimensions.

Ozone Contactors	Sand Columns
8 cm diameter	8 cm diameter
Height 4.2 m	Bed height 1.0 m
Flow rate 1.3 L min^{-1}	

Table 7-2: Pilot Plant Filtration Rates.

EBCT (min)	HLR (m h^{-1})	Flow Rate (L min^{-1})
10	6.0	0.5
15	5.2	0.4
30	2.6	0.2
45	1.3	0.1

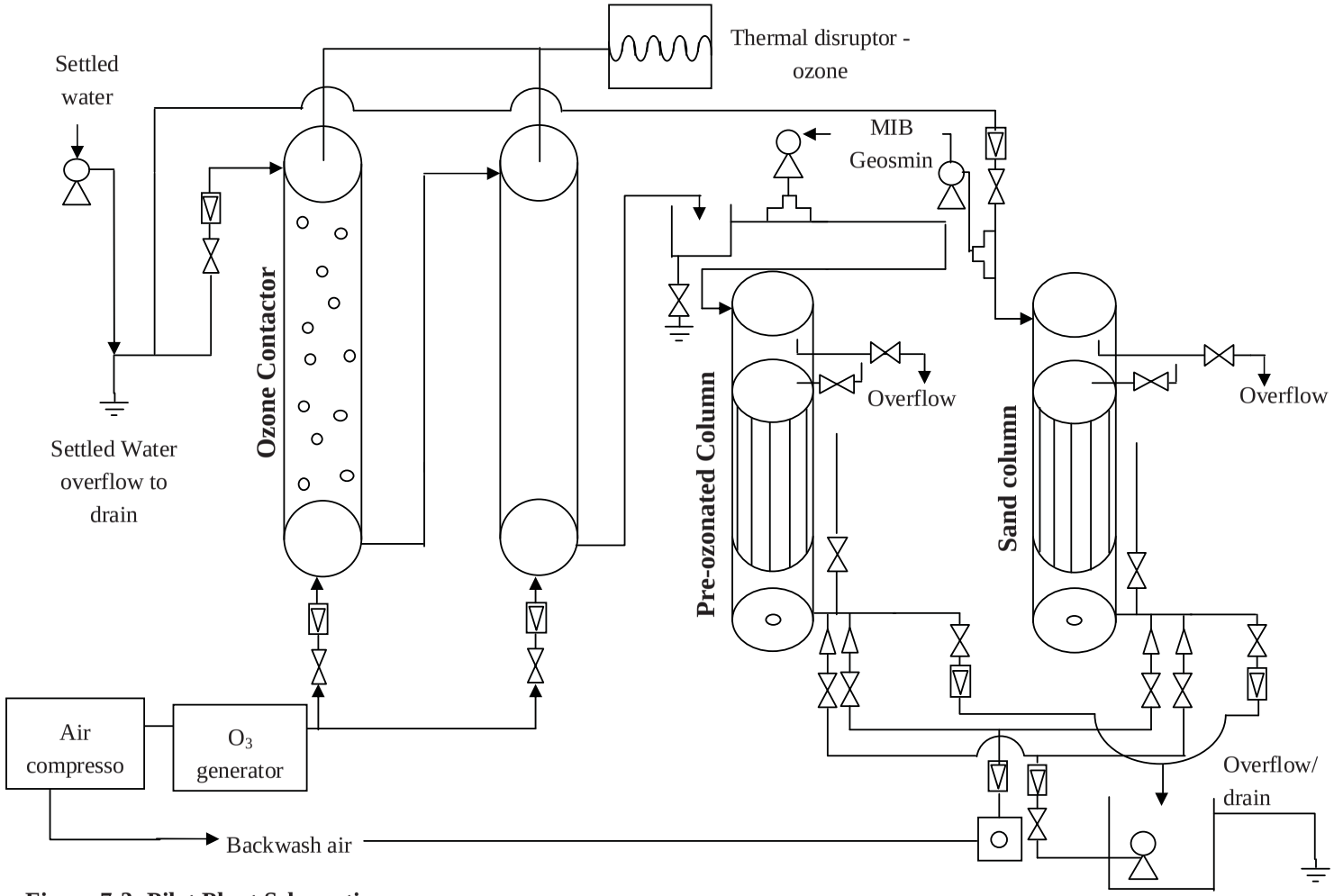


Figure 7-3: Pilot Plant Schematic.

7.2.2 Location

The pilot plant was located at the Happy Valley WTP in South Australia. Happy Valley WTP is located south of Adelaide and receives a blend of River Murray and natural catchment water from the Mt Bold Reservoir in the Adelaide Hills. It is the largest WTP in South Australia with a maximum production capacity of 850 ML per day. The WTP operates with conventional treatment - coagulation, flocculation, sedimentation and rapid gravity filtration, with chlorine disinfection. The rapid gravity filters are pre-chlorinated.

Happy Valley reservoir has frequent taste and odour issues, particularly from geosmin caused by the cyanobacteria *Anabaena circinalis*. Happy Valley WTP utilises PAC to control geosmin levels and copper sulphate dosing in the reservoir to control algal cell numbers. The raw and product geosmin concentrations at Happy Valley WTP over an 8 year period are presented in Figure 7-4. The data demonstrates that the current treatment methods are not always effective at maintaining product water below the odour threshold concentration, with many outlet data points above 10 ng L^{-1}.

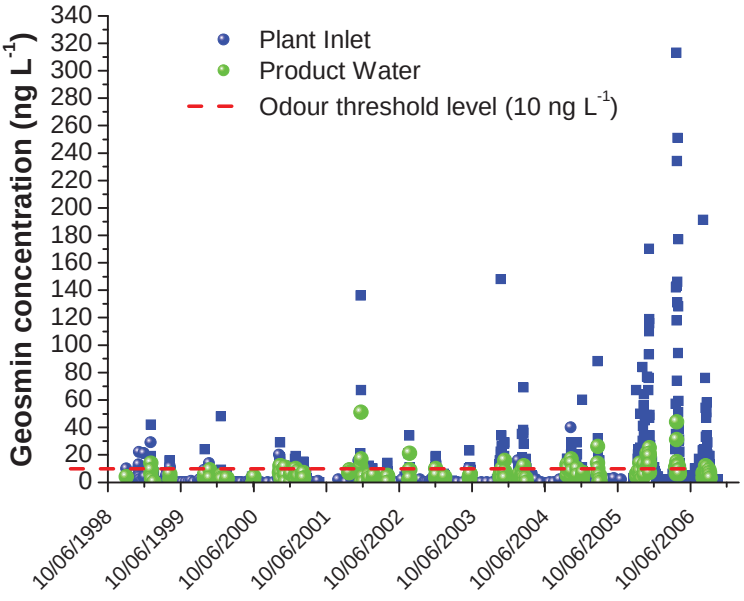


Figure 7-4: Geosmin levels (ng L^{-1}) in Happy Valley WTP.

7.3 PILOT PLANT PROCESS DESCRIPTIONS

7.3.1 Settled Water Column

The sand filters were operated using constant flow rate with effluent flow control. The constant flow rate was maintained by manually adjusting the outlet valve and rotameter during the filter cycle. Refer to Figure 7-3 for the schematic.

Inlet flow rates were controlled just prior to the column. The inlet flow rate was not monitored, but was set higher than that required by the sand filters to allow for a constant overflow. As seen in Figure 7-3, overflow pipes were used to return excess influent water to the Happy Valley WTP waste wash water tank. The inlet flow rate was maintained at a level which gave minimum overflow.

Sample ports were located just above the filter media, and just prior to the outlet rotameter.

Common filter effluent was collected in a black PVC container containing the backwash pump. Overflow from the effluent tank was sent to the Happy Valley waste wash water tank.

7.3.2 Pre-Ozonated Column

The pre-ozonated column was controlled with constant rate effluent control. The constant rate was maintained by manually adjusting the outlet valve and rotameter during the filter cycle. An overflow at the top of the filter column allowed for different flow rates through the ozone contactors and the filter column, thus maintaining a constant ozone contact time while the filter bed EBCT was varied. Refer to Figure 7-3 for the process flow diagram.

Ozone was produced using an OZAT Ozone generator, CFS-1A (Ozonia, Switzerland). The generator unit was supplied with compressed air from the Happy Valley WTP air compressor. The compressed air was passed through an air drier (Pneudri DM002, Domnick Hunter) before entering the ozone generator.

Ozone was transferred to the water by a cross–flow ozone contactor column with ceramic gas diffuser. Any excess ozone was vented at the top of the column and passed through a thermal disruption unit where the ozone was destroyed by heat.

The ozone generator and water flow rate was set to achieve an ozone residual of 0.3 mg L^{-1} after 15 minutes contact time with the gaseous ozone.

The second ozone contactor column was used to provide time for the excess ozone to react with the settled water. The ozonated water passed through a cascading flow degassing unit where any residual ozone was destroyed before it entered the column.

The approximate ozone dose was calculated from the calibration charts provided with the ozone generator unit. The ozone generator was operated with an operating voltage of 50 W and an air flow rate of approximately 0.45 m^3_{STP} h^{-1}(the actual air flow rate varied ± 0.5 m^3_{STP} h^{-1} to maintain the ozone residual of 0.3 mg L^{-1}). These settings correlated to an ozone production of 0.8 wt %. Using the equation provided with the ozone generator,

$$M_{O3} = \frac{\rho Vnc}{100} \text{ (kg h}^{-1}\text{)} \qquad (7.1)$$

where ρ = 1.293 kg Nm^{-3} (density of feed gas, air, at standard temperature and pressure); Vn = 0.45 m^3_{STP} h^{-1}; c = 0.8 wt %; an ozone concentration, M_{O3}, of 4.65 x 10^{-3} kg O_3 h^{-1} is obtained.

The transfer efficiency of the gaseous ozone to the aqueous phase was not known, therefore an arbitrary transfer efficiency of 80% was chosen, based on a previous study that reported transfer efficiencies in the range of 70 – 90% (Fonseca *et al.* 2001).

The flow rate of the ozone contactor was maintained at 80 L h^{-1}. This provided an ozone dose of 0.47 mg O_3 L^{-1}. Assuming DOCs in the range of 4.5 – 6 mg L^{-1}, this value provides an average ozone dose of 0.9 ± 0.1 mg O_3 per mg DOC.

7.4 GENERAL OPERATIONAL CONDITIONS

7.4.1 Charging of the Filter Media

The filter media was charged by unbolting the top of each column, filling each column with water and pouring in sand to approximately 15 cm higher than the desired bed height. The column was then backwashed with water only at a bed expansion of 50% for approximately 20 minutes to allow any dust and dirt to be washed out. This was followed by air scour at 50 m h^{-1} and water at 20% bed expansion for a further 20 minutes. The process was repeated until no dirt or fines were observed in the backwash effluent. A vacuum was used to remove the top 15 cm of media, which would have contained any remaining fine particles. The bed height of 100 cm was taken as the bed height directly after backwashing.

Sieve analysis was conducted on the filter media after it was loaded. This gave an ES of 0.55 mm.

7.4.2 Head Loss Monitoring

Head loss was monitored manually using water manometers.

7.4.3 Backwashing

The effluent from both columns was combined and collected in a black PVC tank. A centrifugal pump located in this tank was used for backwashing the columns.

Two methods of backwashing were used: collapse pulse and water only.

Collapse pulse backwashing was used based on the method of Elhadi *et al* (2004). Firstly, the filters were drained to 20 to 40 cm above the top of the filter media to ensure that there was no loss of media from the air scour process. Compressed air at 50 m h^{-1} was pumped in for 1 minute to break up any media clumps in the column. This was followed by water at 40% of fluidisation velocity (12 m h^{-1}) simultaneously with air at 50 m h^{-1} for 3 minutes. Finally, the filters were washed with water only at 10% bed expansion (200 L min^{-1}) for 4 minutes to allow all of the remaining particles to be washed out. The filter media was allowed to settle naturally before filtration was resumed.

For the water only backwash, the filters were backwashed at 10% bed expansion for 10 minutes. The filters were not drained prior to the water only backwash.

The filters were backwashed when head loss reached 70 cm. Filter run times varied depending on the water quality. Clean bed head loss was monitored to ensure that the filters were performing satisfactorily.

7.4.4 MIB and Geosmin Dosing

MIB and geosmin dose solution was made up by spiking 10 L of Happy Valley settled water with the required concentration of MIB and geosmin stock solution. Dosing rates were kept constant, with 8 L of stock used per 24 hours. The concentration of the dose solution varied depending on the EBCT of the filters and the target spiking concentration. The solution was made fresh each day to minimise system losses and biodegradation in the Happy Valley settled water.

The MIB and geosmin solutions were dosed to the pilot plant by dosing pumps (ProMinent Beta/4 and Gamma/L, Germany). The pumps were fitted with 6 x 4 mm low density polyethylene (LDPE) tubing (Esdan), attached to compression fittings located in the head water above each filter bed.

MIB and geosmin were dosed into the head waters of each filter; approximately 50 cm above the filter beds. This location was chosen to ensure that no MIB or geosmin were

destroyed by excess ozone, and that the dose solution was mixed with the feed water prior to reaching the filter.

In an ozone enhanced biofiltration plant, there would be a combination of removal of MIB and geosmin by ozonation and by biological degradation. However, the aim of the study was to investigate the enhancement of biodegradation by a pre-ozonated biofilm. For this reason, it was desired to have similar MIB and geosmin concentrations fed to each filter. The removal of MIB and geosmin by the ozonation process was described in detail in Chapter 2: Literature Review.

It was difficult to obtain constant inlet concentrations at the target MIB and geosmin concentrations. Difficulties with dosing MIB and geosmin in pilot plant situations have been observed previously (Elhadi *et al.* 2004a; Westerhoff *et al.* 2005). In this study the major uncertainties with the dosing were due to system losses. Another issue could be that as the flow rate declined at the end of a filter run then there could be a build up of MIB and geosmin in the head water as the dosing system was set at a constant flow rate. This issue was minimised by ensuring that the filters were backwashed regularly. Changes in feed stock concentration over the 24 hour period would also have occurred due to biodegradation, and volatilisation due to its outdoor location.

7.4.5 MIB and Geosmin Sampling

MIB and geosmin samples were taken in 500 ml PET bottles. The samples were stored headspace free during transport from Happy Valley to the laboratory to ensure no losses through volatilisation. The samples were immediately filtered through 0.22 µm to remove any potential MIB and geosmin degrading bacteria and stored at 4 ^{0}C until analysis.

Samples were also taken periodically for DOC, UV, turbidity and HPSEC. Samples were taken according to the EBCT of the filter. For example, at an EBCT 15 minutes the effluent sample was taken 15 minutes after the influent sample. All samples were taken at least 1 hour after backwashes to ensure that the filter ripening period did not impact significantly on results.

7.4.6 Ozone Residuals

Ozone residuals were routinely measured according to the method described in Chapter 3. Water samples of 80 ml were taken in 100 ml volumetric flasks containing 20 ml of Indigo reagent II. Tubing attached to the sample port was submerged in the Indigo reagent and care was taken to ensure that no air bubbles escaped, as this could interfere with the ozone residual measurement.

8 PILOT STUDY ON BIOLOGICAL SAND FILTRATION FOR MIB AND GEOSMIN REMOVAL – RESULTS AND DISCUSSION

8.1 INTRODUCTION

This chapter presents the results and discussion for experiments carried out at the pilot plant. The system was designed to represent a rapid sand filter without pre-chlorination. MIB and geosmin spiking trials were conducted to investigate the impact of pre-ozonation and empty bed contact time on MIB and geosmin biodegradation.

8.1.1 Overview of Study

Results for the pre-ozonated and settled water columns are shown separately. For each filter column, water quality data is given first. This is followed by the MIB and geosmin data. For convenience, results are presented separately according to the individual spiking trials.

As expected, the pilot scale experiments were more difficult to control than the laboratory scale studies. In some cases, apparent negative percent removals were observed. In these cases, the percent removals are shown as 0%, but the influent/effluent data shows the actual concentrations. Negative removals could be attributed to experimental errors. Although all efforts were made to sample at a sufficient time period after backwashing, it is possible that some variation in results may have arisen due to the stage of the filter cycle at the time of sampling.

A summary of the temperature of the inlet and product water after storage at Happy Valley WTP over the study period is presented in Figure 8-1. The temperature ranged from approximately 11 ^{o}C in winter to a maximum of approximately 25 ^{o}C in summer. A previous study on the effect of temperature on biological filtration concluded that it is considered to be an important parameter only if temperatures below 5 ^{o}C are experienced (Huck *et al.* 2000). A recent study found that a biological sand filter operating at 5 ^{o}C removed only 1% of the influent MIB, compared to 48% removal in an identical filter running at room temperature (Summers *et al.* 2006). However, in a separate study it was found that geosmin and MIB removals in a biological anthracite-sand filter decreased significantly at 8 ^{o}C compared to 20 ^{o}C (Elhadi *et al.* 2006). The measured water temperature in the pilot plant study did not fall below 10 ^{o}C at any time.

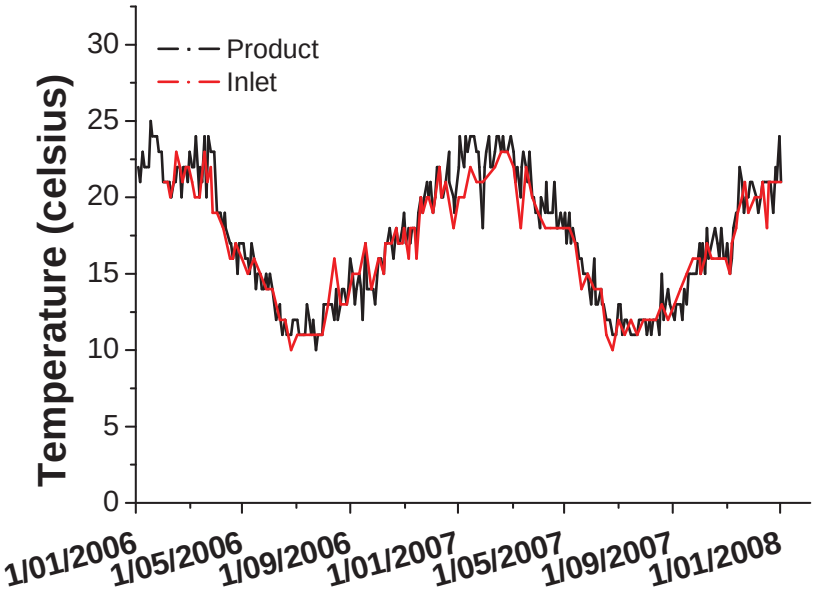


Figure 8-1: Happy Valley WTP water temperature (data courtesy United Water International).

The pilot plant was run at an EBCT of 15 minutes for 149 days before it was first spiked with MIB and geosmin. Table 8-1 shows a summary of all spiking trials conducted on the pilot plant. The pilot plant was run continuously at 15 minute EBCT between spiking events.

Approximate water temperatures for each spike were based on the Happy Valley WTP inlet water temperature (as presented in Figure 8-1). Spikes conducted in a 'low' temperature range of 14 ^{o}C and below were spike numbers 2, 3, 10, 11 and 12.

Table 8-1: Overview of spiking trials. (*) indicates first and last pre-ozonated spikes.

Trial No.	DATE	DAY	EBCT	Water temperature (^{o}C)
1	26/04/06 to 28/04/06	149-150	15	17
2*	1/08/06 to 4/08/06	246-249	15	11
3	28/08/06 to 31/08/06	273-276	15	13
4	10/10/06 to 13/10/06	316 -319	15	17
5	24/10/06 to 27/10/06	330-333	30	18
6	14/11/06 to 17/11/06	351-354	30	17
7	20/11/06 to 23/11/06	357-360	15	19
8	29/01/07 to 9/02/07	427-438	40	21
9	5/03/07 to 16/03/07	462-473	30	20
	19/03/07 to 28/03/07	476-485	15	21
10*	22/05/07 to 28/05/07	540-546	15	14
11	19/06/07 to 28/06/07	568-577	14	11
12	6/08/07 to 8/08/07	616-618	10	12
13	28/08/07 to 6/09/07	638-647	10	12

8.2 WATER QUALITY DATA FOR PRE-OZONATED COLUMN

8.2.1 Ozone Residual

Ozone was supplied to the ozonated column after 238 days of pilot plant operation and was maintained for a period of 300 days. The delay in commissioning of the ozone system was due to mechanical problems with the ozone generator and ozone dosing apparatus.

Ozone was introduced to the contactor to produce a target residual of 0.3 mg L^{-1} after 15 minutes contact time. Ozone residuals at the 15 minute contact time over the course of the ozonation trials are shown in Figure 8-2. As explained in Chapter 7, the ozone residual of 0.3 mg L^{-1} resulted from an approximate ozone dose of 0.47 mg O_3 L^{-1}, or 0.9 (± 0.1) mg O_3 per mg DOC.

Ozone residual was routinely measured in the headwater above the column to ensure that no ozone was contacting the sand. As seen in Figure 8-2, the degasser worked effectively and no ozone was detected in the filter headwater over the course of the pilot plant studies.

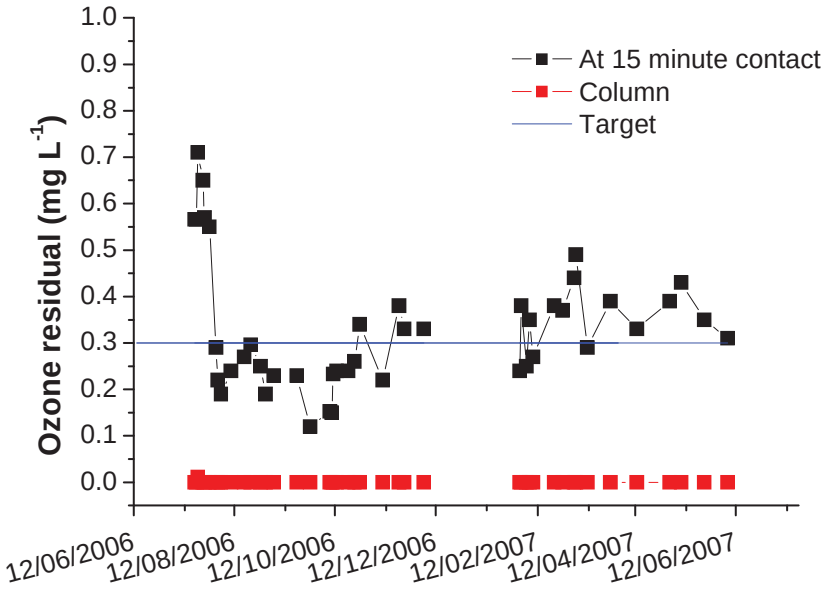


Figure 8-2: Pilot Plant Ozone Residuals.

8.2.2 DOC and UV Absorbance

Samples for DOC were taken prior to ozonation, at the inlet to the column (after the removal of ozone) and at the column outlet. The data presented in Figure 8-3 shows that the DOC of the influent water ranged from 4.0 to 8.5 mg L^{-1}. The changes in DOC are a result of changes in the water quality in the Happy Valley reservoir over the study period.

The UV absorbance of the water is shown in Figure 8-4. UV absorbance gives a greater indication of the effect of ozonation as UV absorbance measurements indicate the molecular structure of the organic matter, rather than the total concentration of organic carbon given by DOC measurements (Allpike *et al.* 2005). Again, there was minimal removal of UV absorbance by the filter column.

As explained previously, ozone changes the character of natural organic matter by breaking down larger NOM components into smaller fractions which are more easily assimilated by biofilm bacteria. Thus, there is a decrease in UV absorbance but total DOC concentration is not affected.

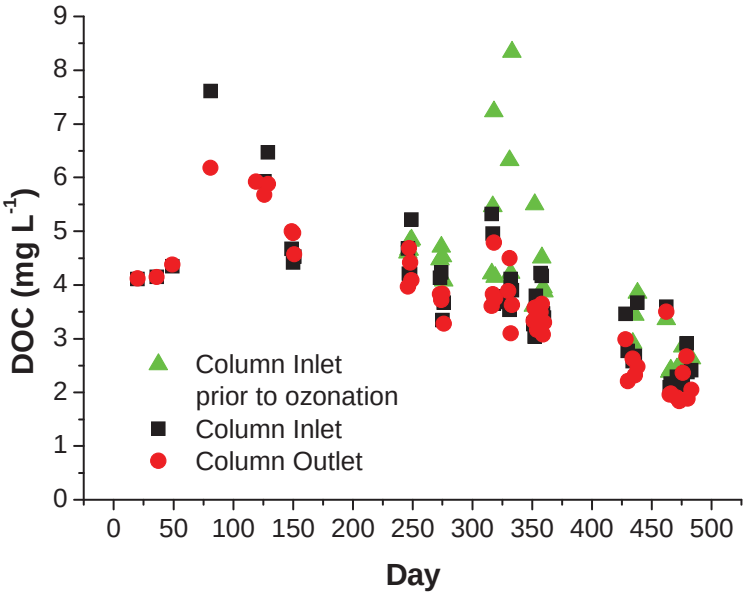


Figure 8-3: DOC of pre-ozonated column.

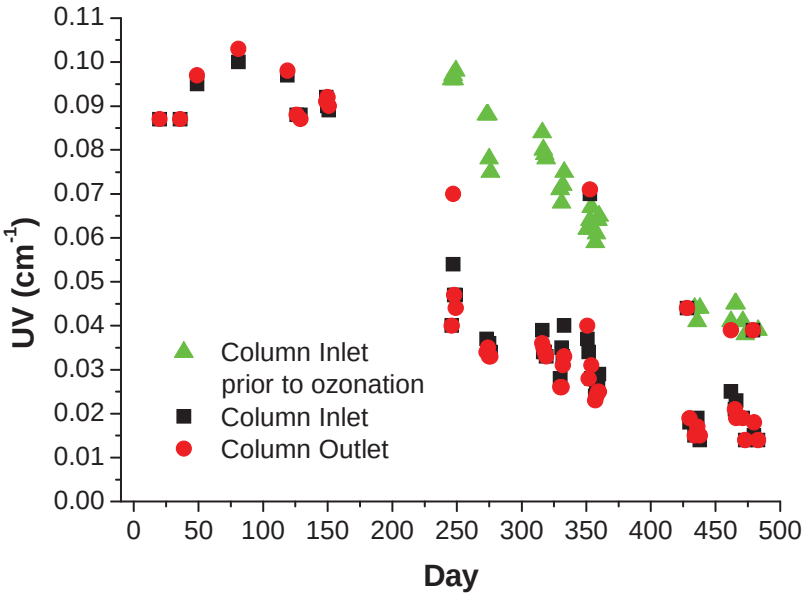


Figure 8-4: UV absorbance of pre-ozonated column.

8.3 RESULTS AND DISCUSSION FOR PRE-OZONATED COLUMN SPIKING TRIALS

8.3.1 Pre-ozonated Spiking Trial 1

In spiking trial 1, the filter was run at 15 min EBCT with target MIB and geosmin concentrations of 100 ng L^{-1}. Ozone was not applied at this time.

Raw influent and effluent data for MIB and geosmin are given in Figure 8-5 and Figure 8-6. Percentage removals of MIB and geosmin are presented in Figure 8-7. There was negligible removal of MIB and geosmin through this filter column during the first spike.

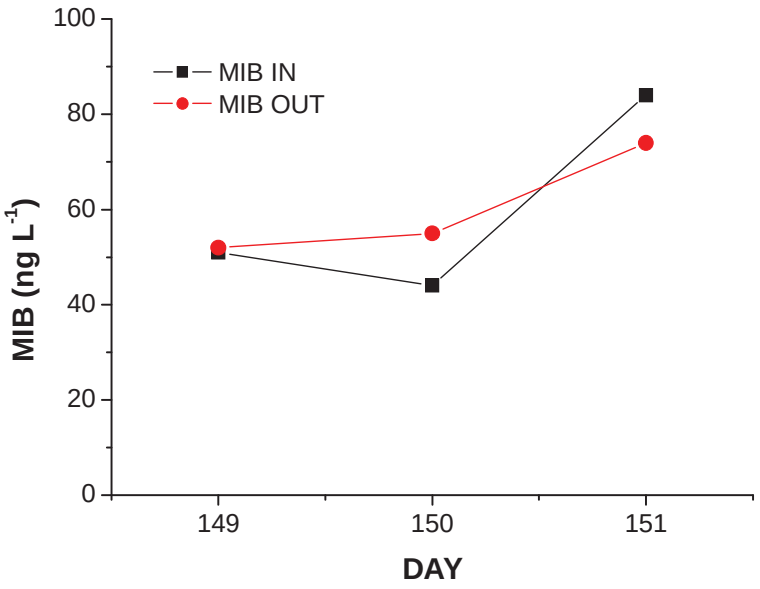


Figure 8-5: MIB concentrations (ng L^{-1}) through pre-ozonated column, spike 1.

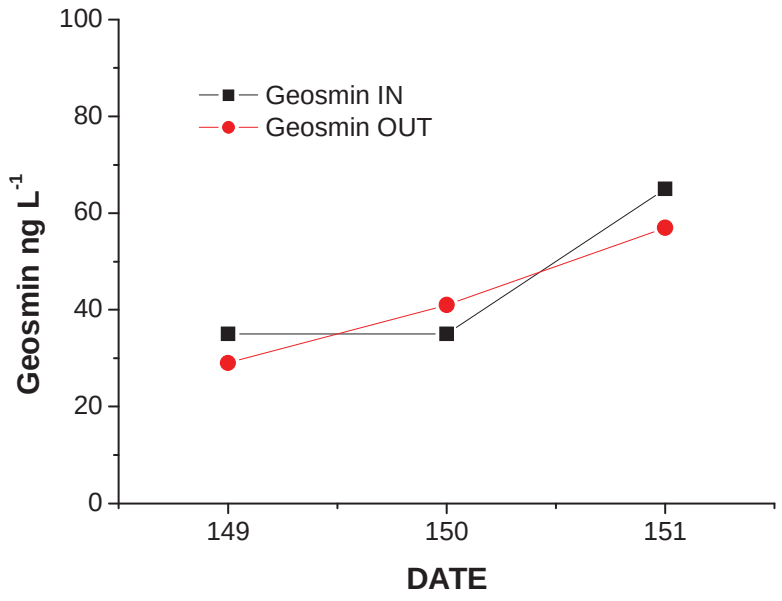


Figure 8-6: Geosmin concentrations (ng L^{-1}) through pre-ozonated column, spike 1.

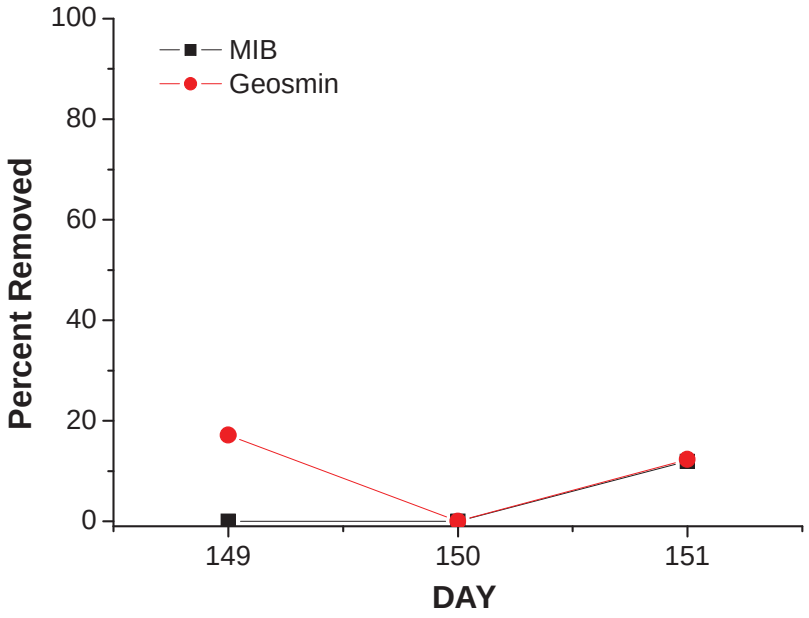


Figure 8-7: Percent removals of MIB and geosmin through pre-ozonated column, spike 1.

8.3.2 Pre-ozonated Spiking Trials 2, 3 and 4

The results from spiking trials 2, 3 and 4 are presented together. This data corresponds to day 246 to 319. Ozonation commenced on day 238. These trials were all conducted with a 15 minute EBCT and collapse pulse backwashing.

Spikes 2 and 3 had target inlet concentrations of 100 ng L^{-1} MIB and geosmin. Spike 4 had a lower target of 50 ng L^{-1}. The concentrations of MIB through the filter column during the three spikes are shown in Figure 8-8. Figure 8-9 shows the concentrations of geosmin through the filter column. The actual inlet concentrations varied from the target doses, however the trend of a decreased inlet concentration for spike 4 is evident.

Figure 8-10 gives the percentage removals of MIB and geosmin through the column. The removals of both compounds were very low, and can be considered to be background removals only.

The implementation of pre-ozonation did not result in increases in removals of either compound.

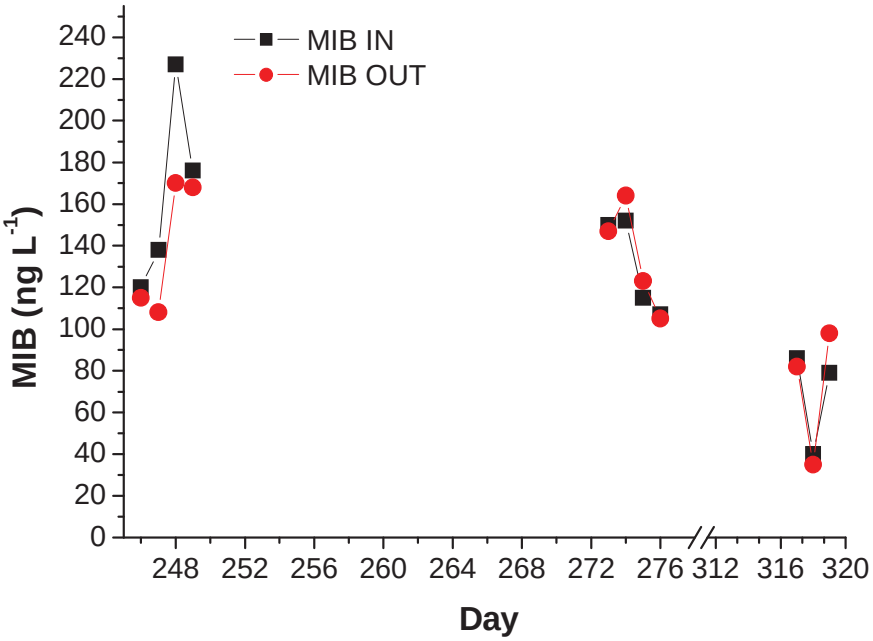


Figure 8-8: MIB concentrations (ng L^{-1}) through pre-ozonated column, spikes 2, 3 and 4.

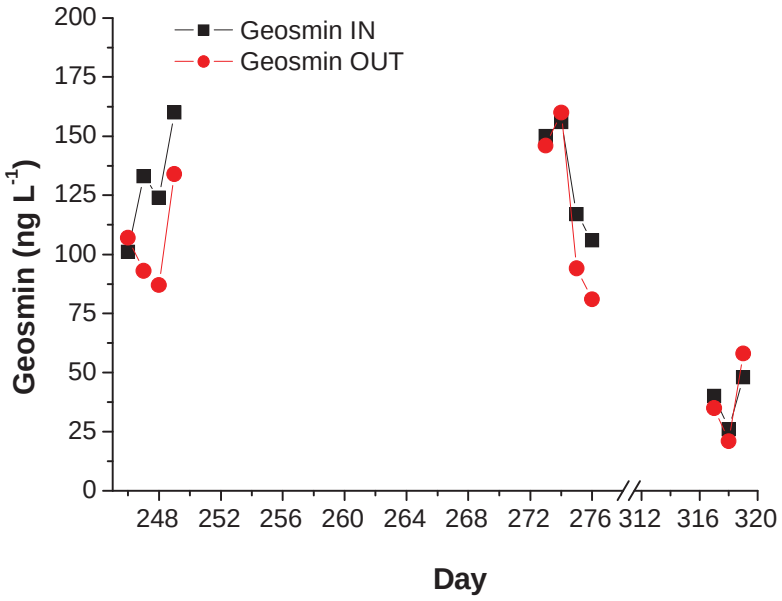


Figure 8-9: Geosmin concentrations (ng L^{-1}) through pre-ozonated column, spikes 2, 3 and 4.

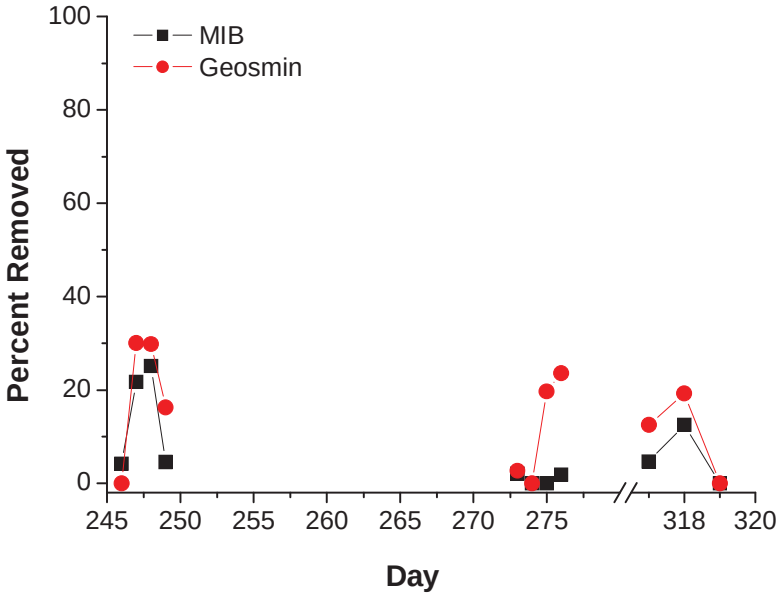


Figure 8-10: Percent removals of MIB and geosmin through pre-ozonated column, spikes 2, 3 and 4.

8.3.3 Pre-ozonated Spiking Trial 5

In spiking trial 5, the flow rate of the column was decreased to obtain an EBCT of 30 minutes. The backwashing regime was also changed to water wash only at this point and remained with water wash for the remainder of the pilot plant studies. The change in backwashing regime was made in an attempt to enhance removals of MIB and geosmin, as the plant had been running for 330 days without any appreciable removals. It was considered that the harsher abrasion caused by the air-scour may have been inhibiting growth of MIB and geosmin degrading biomass, despite noting that previous studies had found no negative impact of collapse-pulse backwashing on removal of general BOM compounds (Ahmad *et al*. 1998).

The column was spiked with a target MIB and geosmin dose of 50 ng L^{-1} for each compound. A new stock solution was used on the 2nd, 3rd and 4th days. This stock had been incorrectly labelled, and the resulting influent concentration of MIB and geosmin was higher than expected. The concentrations of MIB through the filter column during the spike are shown in Figure 8-11. Figure 8-12 shows the concentrations of geosmin through the filter column. The percentage removals of both compounds are shown in Figure 8-13.

In this spike, MIB and geosmin removals increased significantly compared to the previous spikes. Average removals over the 30 minute EBCT trial were 73% for geosmin (SD 15%, n=4) and 68% for MIB (SD 19%, n=4). Due to the lack of a non-biological control, it is not possible to determine the contribution of biodegradation versus increased physical losses to the increased removal of MIB and geosmin at this EBCT.

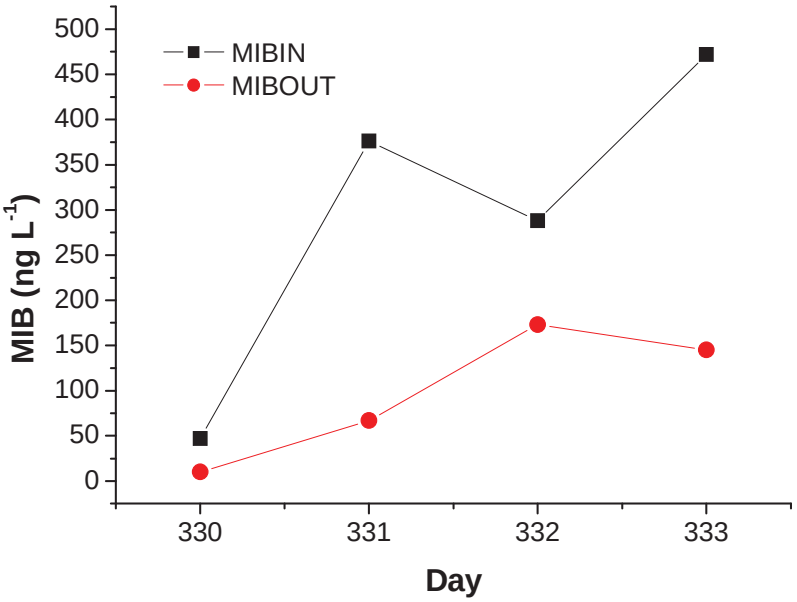


Figure 8-11: MIB concentrations (ng L^{-1}) through pre-ozonated column, spike 5.

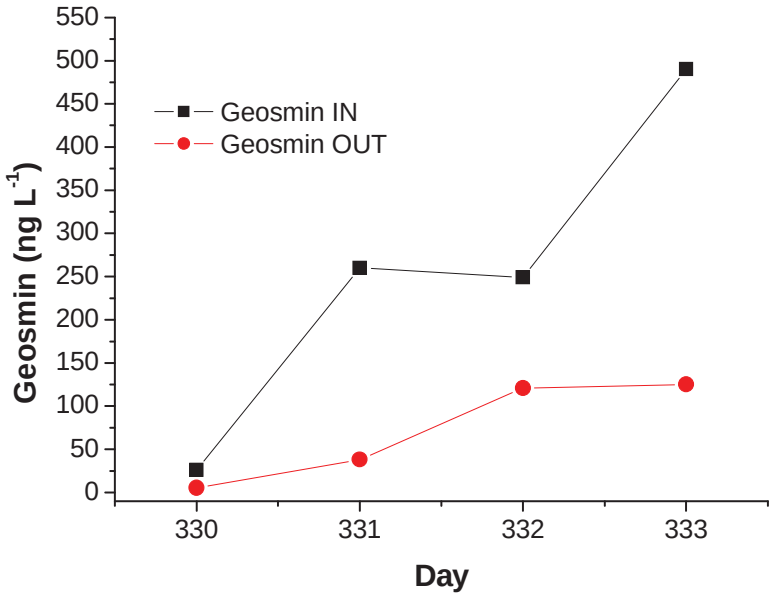


Figure 8-12: Geosmin concentrations (ng L^{-1}) through pre-ozonated column, spike 5.

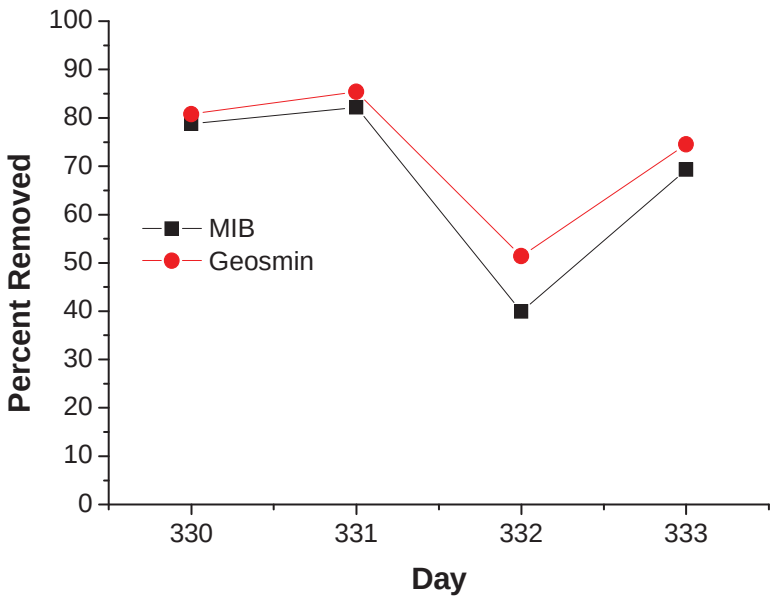


Figure 8-13: Percent removals of MIB and geosmin through pre-ozonated column, spike 5.

8.3.4 Pre-ozonated Spiking Trials 6, 7 and 8

Results from spiking trials 6, 7 and 8 are presented in this section. Spike 6 was carried out for 5 days at an EBCT of 30 minutes. It was followed by spike 7, which was carried out for 5 days at an EBCT of 30 minutes. Spike 8 involved increasing the flow rate to obtain an EBCT of 15 minutes. The data correlates to days 351 to 438. Influent and effluent concentrations of MIB and geosmin are shown in Figures 8-14 and 8-15, respectively.

The data presented in Figure 8-16 shows the percentage removals of MIB and geosmin throughout the three spikes. The impact of EBCT was not notable in spikes 6 and 7. The change from 30 minute EBCT to 15 minute EBCT had minimal impact on removals of MIB or geosmin. Geosmin removals remained higher than MIB removals throughout all three spikes.

Spike 8 (30 minute EBCT) resulted in an increase in MIB and geosmin removals to a maximum of 42% and 80%, respectively, on the final day of spike 8.

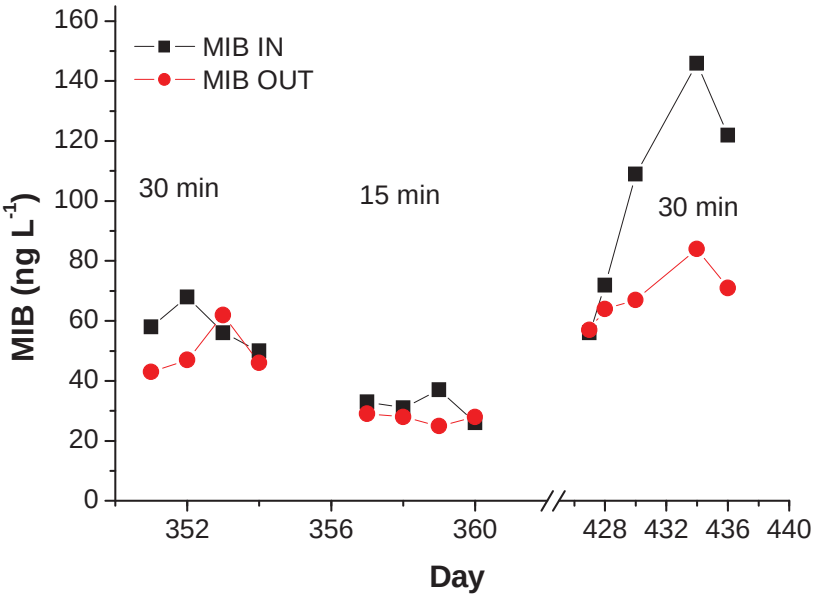


Figure 8-14: MIB concentrations (ng L^{-1}) through pre-ozonated column, spikes 6, 7 and 8.

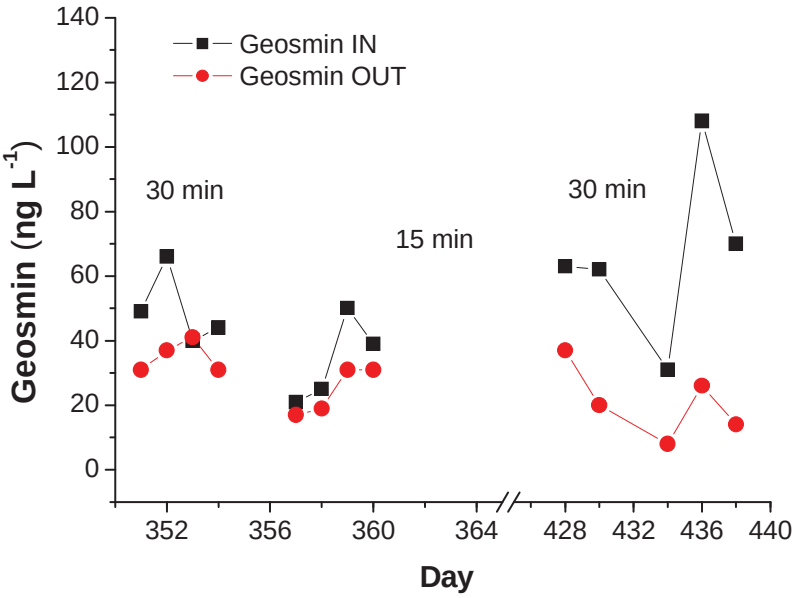


Figure 8-15: Geosmin concentrations (ng L^{-1}) through pre-ozonated column, spikes 6, 7 and 8.

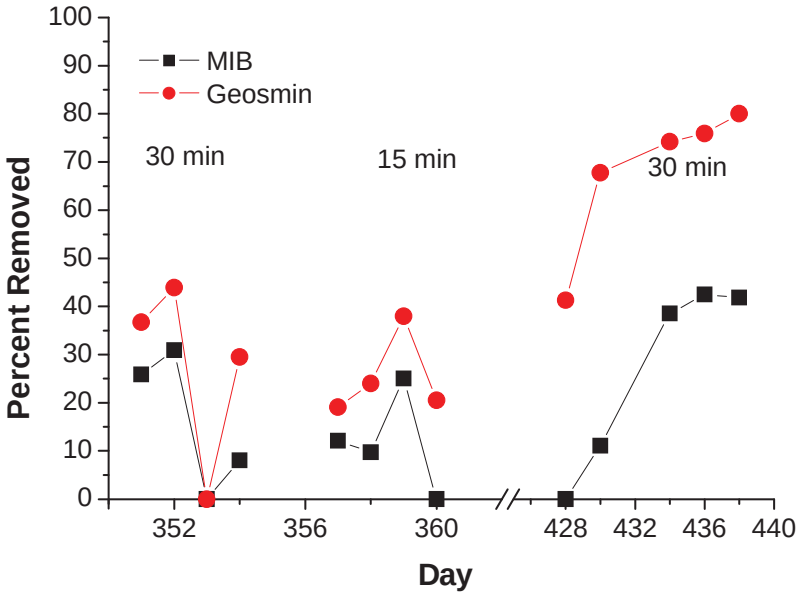


Figure 8-16: Percent removal of MIB and geosmin through pre-ozonated column, spikes 6, 7 and 8.

8.3.5 Pre-ozonated Spiking Trial 9

The preceding spiking trials were conducted for 5 day periods. Large variations in influent concentrations with these trials resulted in difficulties in interpreting the data. For this reason, the spiking time was increased to 4 weeks. Spike 9 consisted of a 2 week spike at 30 minute EBCT followed by a 2 week spike at 15 minute EBCT.

Results from the 4 week spiking trial are shown in Figures 8-17, 8-18 and 8-19. MIB and geosmin concentrations were ramped down over the 30 minute EBCT period and ramped back up over the 15 minute period.

Percentage removals of geosmin, shown in Figure 8-19, ranged from 40 to 60%. MIB removals, as presented in Figure 8-20, ranged from 24 to 55%. Figure 8-18 shows that the concentration was decreased over the two week period of the 30 minute spike then increased back up during the 15 minute EBCT trial. This did not impact on the percentage removals.

The data presented in Figure 8-19 indicates that EBCT did not have a significant effect on MIB or geosmin removal. Average MIB removals over the two EBCTs were 25% (SD 7%, n=5) at 30 minutes EBCT and 22% (SD 20%, n=5) at 15 minute EBCT. Geosmin removals averaged 44% (SD 13%, n=5) at 30 minute EBCT and 36% (SD 13%, n=5) at 15 minutes EBCT.

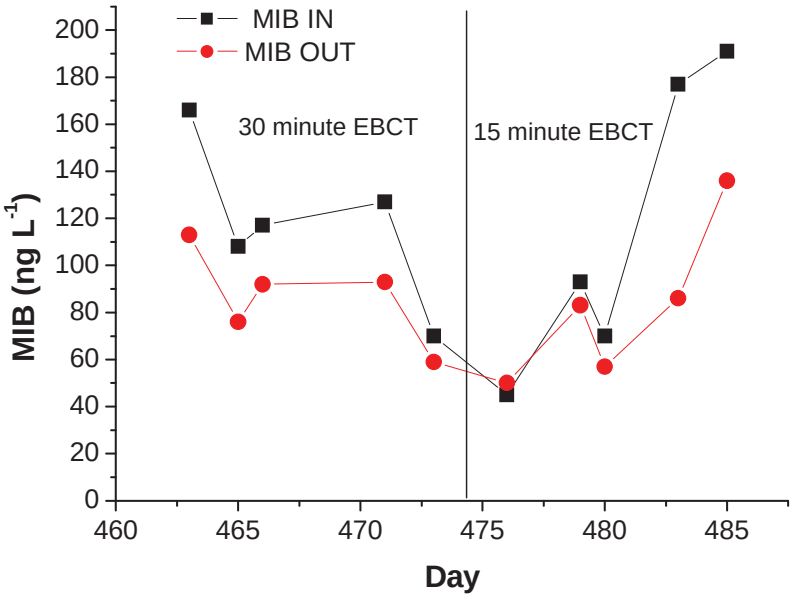


Figure 8-17: MIB concentrations (ng L^{-1}) through pre-ozonated column, spike 9.

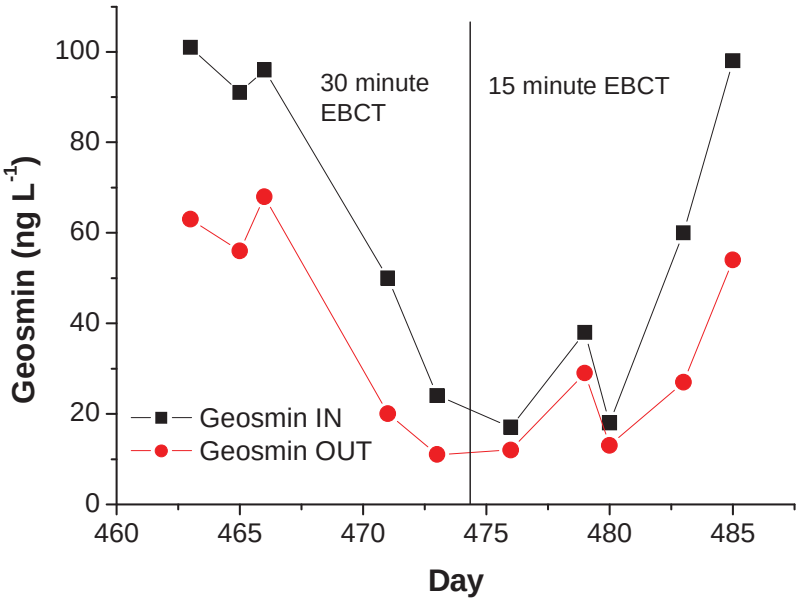


Figure 8-18: Geosmin concentrations (ng L^{-1}) through pre-ozonated column, spike 9.

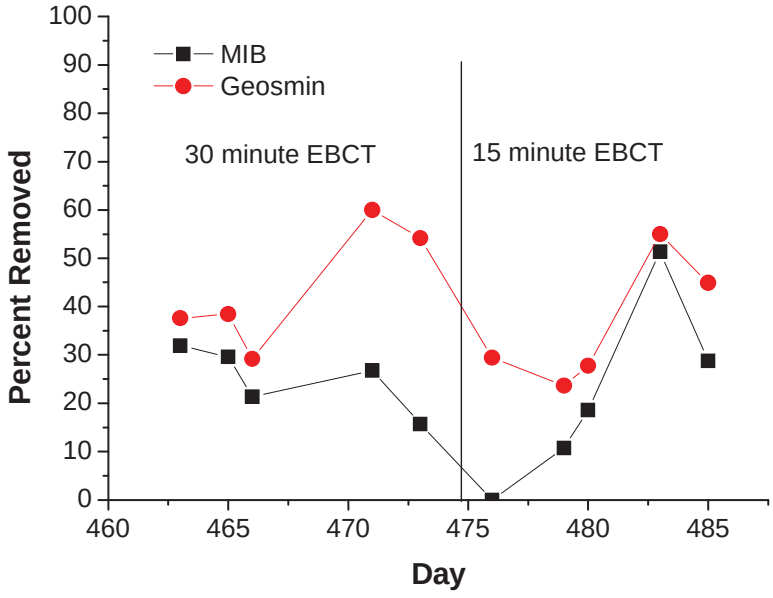


Figure 8-19: Percentage removal of MIB and geosmin through pre-ozonated column, spike 9.

8.3.6 Pre-ozonated Spiking Trial 10

In the final spiking trial for the pre-ozonated column, the column was run at an EBCT of 15 minutes. The data from this spike is shown in Figures 8-20, 8-21 and 8-22.

Figure 8-22 shows the percentage removals for the final spike. There was very little removal of MIB or geosmin. Geosmin removals ranged from 10 to 40%. MIB removals were negligible, with zero percentage removals for all but the last sample.

It is not clear why the decrease in MIB and geosmin removal in the pre-ozonated column occurred. No ozone was detected in the column influent over this period. There was a significant drop in temperature between spikes 9 and 10, decreasing from 21 ^{o}C to 14 ^{o}C. This decrease in temperature may have been a contributing factor in the decreased removals of MIB and geosmin, as previous studies have shown decreases in MIB and geosmin biodegradation with decreased temperature (Elhadi *et al.* 2006; Summers *et al.* 2006). No conclusions can be drawn with the available data, and the effect of temperature was not investigated further.

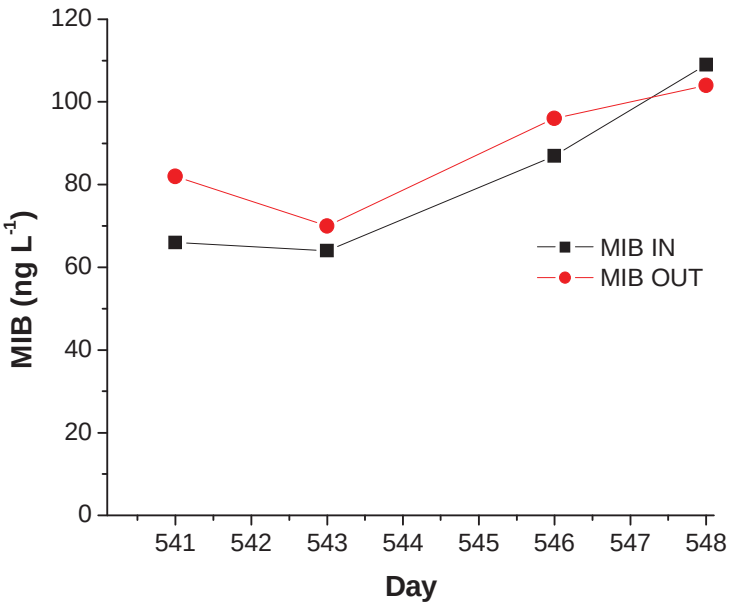


Figure 8-20: MIB concentrations (ng L^{-1}) through pre-ozonated column, spike 10.

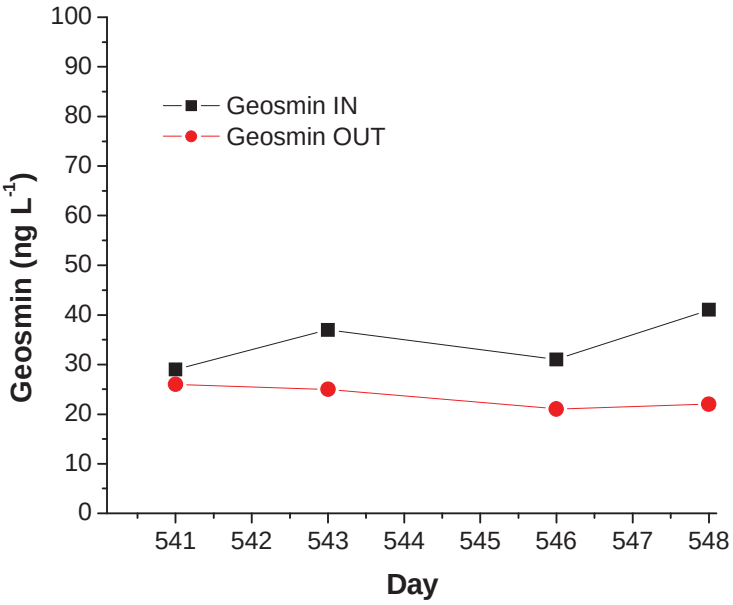


Figure 8-21: Geosmin concentrations (ng L^{-1}) through pre-ozonated column, spike 10.

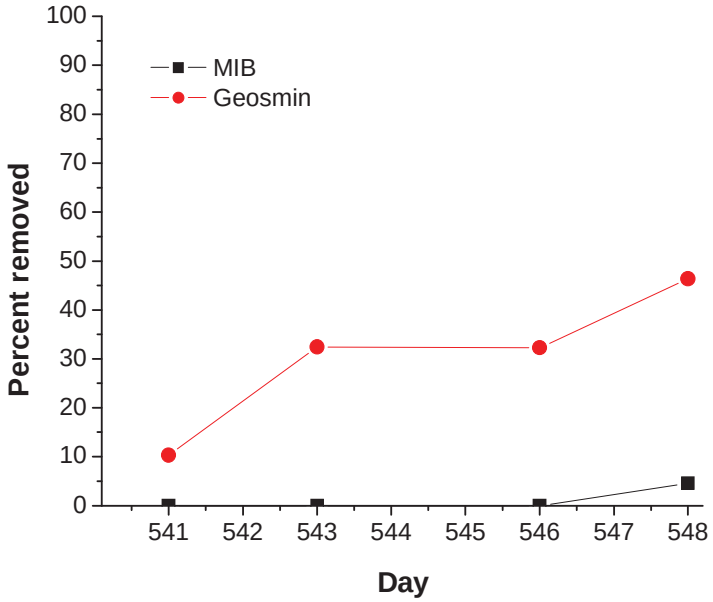


Figure 8-22: Percent removal of MIB and geosmin through pre-ozonated column, spike 10.

8.4 WATER QUALITY DATA FOR SETTLED WATER COLUMN

8.4.1 DOC and UV Absorbance

DOC concentrations in the inlet and outlet of the settled water column are presented in Figure 8-23. There was negligible removal of DOC through the sand column throughout the experiment.

Figure 8-24 presents the UV absorbance of the inlet and outlet of the settled water column. As with DOC, there was negligible change in UV absorbance through the column.

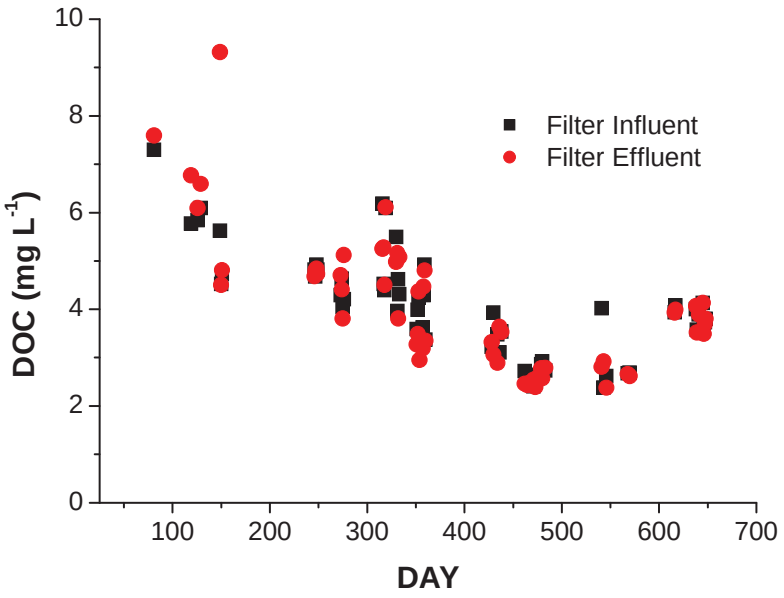


Figure 8-23: DOC of settled water column.

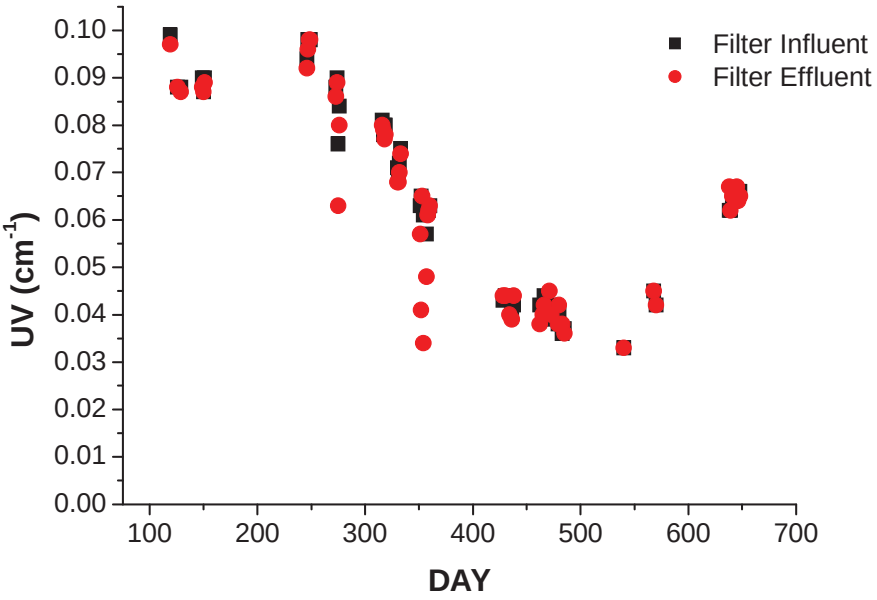


Figure 8-24: UV absorbance of settled water column.

8.5 RESULTS AND DISCUSSION FOR SETTLED WATER COLUMN SPIKING TRIALS

The following section outlines the results from the MIB and geosmin spiking trials on the settled water column. Note that the MIB and geosmin data is presented according to the spiking trials, which correlate directly to the pre-ozonated column results.

8.5.1 Settled Water Spiking Trial 1

For the first spiking period the filters were run at 15 min EBCT with target MIB and geosmin concentrations of 100 ng L^{-1}.

Results from this spike are shown in Figures 8-25, 8-26 and 8-27. There was minimal biological removal of either compound. These results mirror those of the pre-ozonated study.

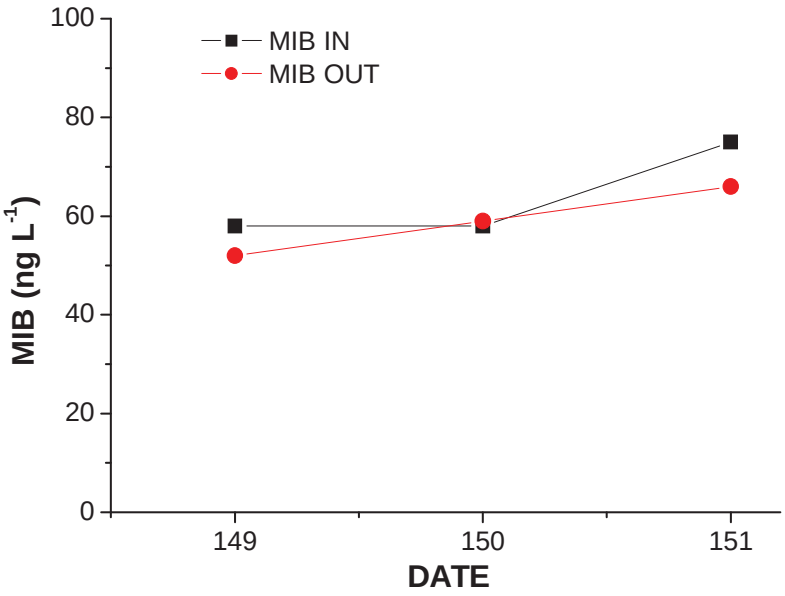


Figure 8-25: MIB concentrations (ng L^{-1}) through in settled water column, spike 1.

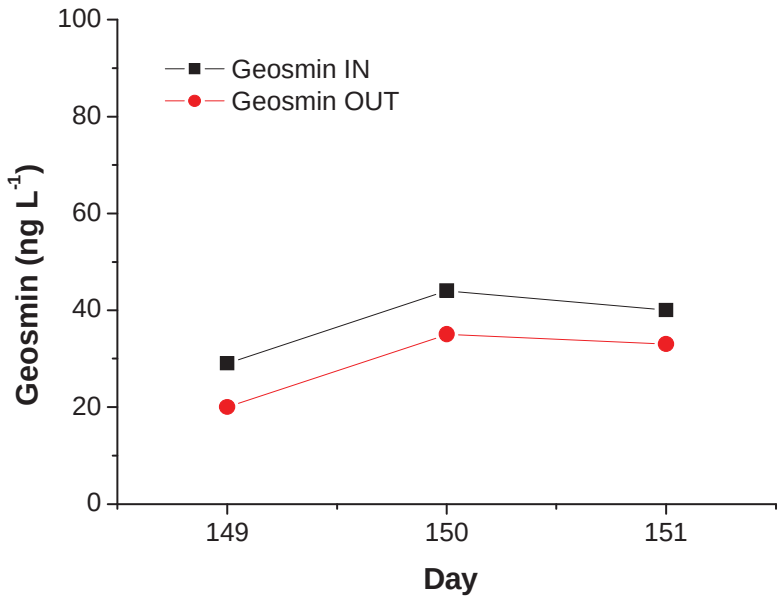


Figure 8-26: Geosmin concentrations (ng L^{-1}) through settled water column, spike 1.

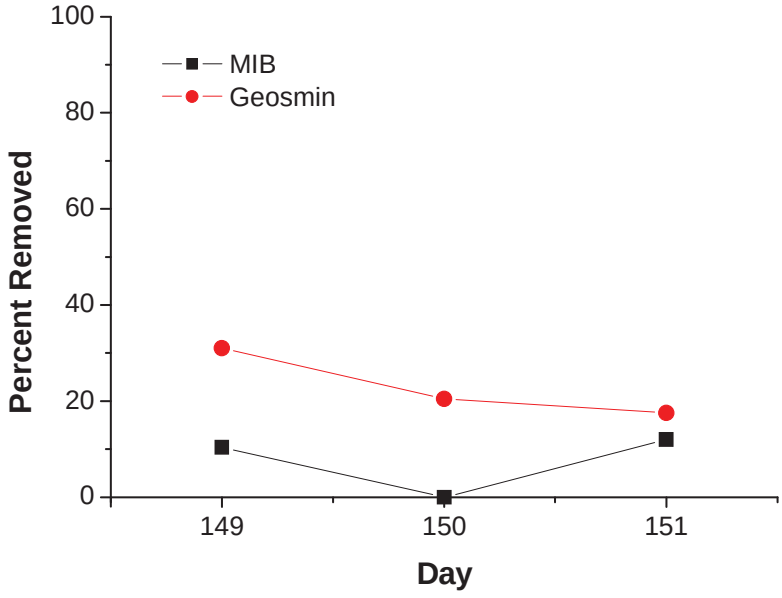


Figure 8-27: Percent concentrations (ng L^{-1}) through settled water column, spike 1.

8.5.2 Settled Water Spiking Trials 2, 3 and 4

Spiking trials 2, 3 and 4 were conducted 4 months after the initial baseline removal trial.

Three different inlet concentrations were studied. In spike 2, the inlet concentration was slowly ramped up from a low level taste and odour event to a high level odour event. This phenomenon might be observed in situations where copper dosing of a supply reservoir has resulted in a large influx of metabolites into the treatment plant. Spiking trials 3 and 4 looked at steadier inlet concentrations, with targets of 100 and 50 ng L^{-1} for each study.

Results from these spiking trials are presented together in Figures 8-28, 8-29 and 8-30. Figure 8-30 gives the percentage removals of MIB and geosmin throughout the three spikes. This figure highlights the difficulties encountered in interpreting percent removal data. Here, geosmin removals through the column averaged of 34% (SD 25%, n=12), while MIB removals averaged 17% (SD 27%, n=12). Despite these large variances, the raw MIB data presented in Figure 8-28 shows that there was negligible removal of MIB throughout the three spikes. Geosmin removals showed a similar trend, and it is difficult to suggest if any of the observed geosmin removals could be attributed to biodegradation.

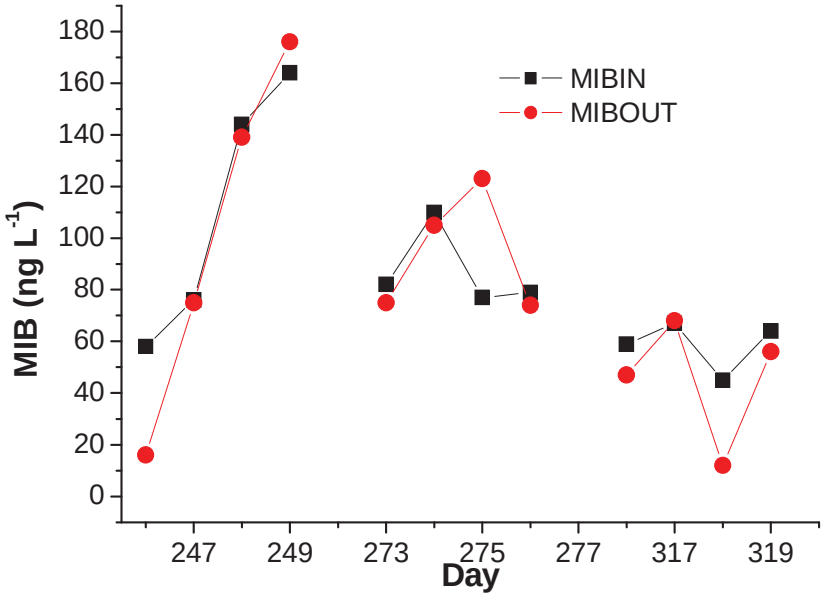


Figure 8-28: MIB concentrations (ng L^{-1}) through settled water column, spikes 2, 3 and 4.

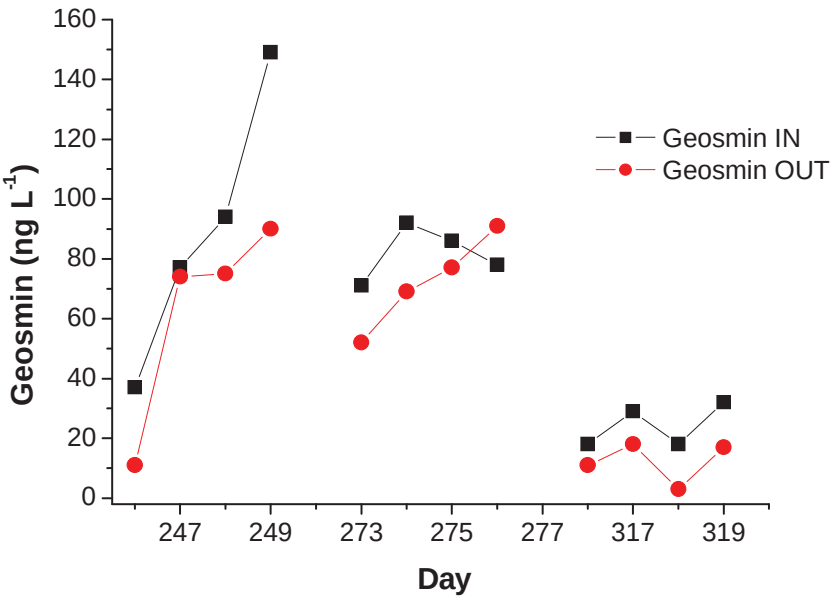


Figure 8-29: Geosmin concentrations (ng L^{-1}) through settled water column, spikes 2, 3 and 4.

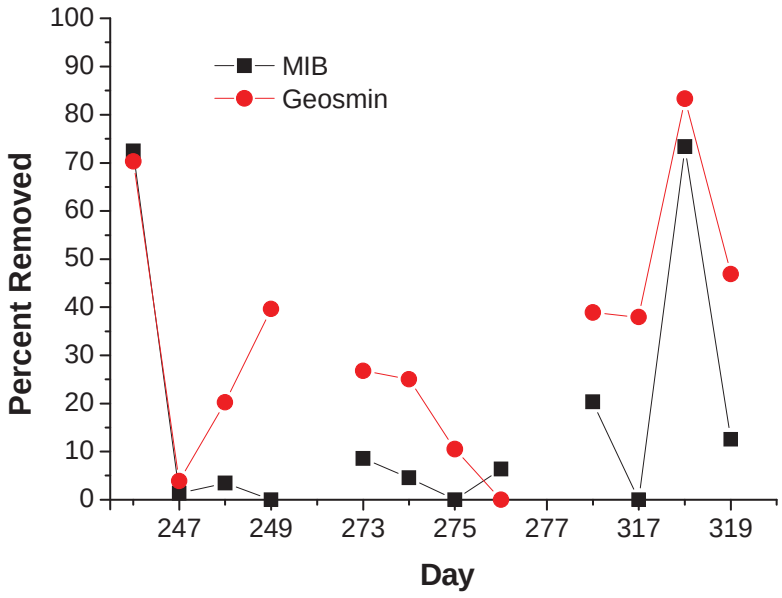


Figure 8-30: Percent removal of MIB and geosmin through settled water column, spikes 2, 3 and 4.

8.5.3 Settled Water Spiking Trials 5, 6, 7 and 8

The EBCT of the columns was increased from 15 minutes to 30 minutes for spikes 5 and 6. This was followed by spike 7 at 15 minute EBCT, and spike 8 at 30 minute EBCT. The results are shown in Figures 8-31, 8-32 and 8-33. As with the pre-ozonated column, air scour backwash was ceased at this time and the columns were run on water only backwash for the remainder of the study.

Percentage removals of MIB and geosmin for the 4 spikes are shown in Figure 8-33. Again, it is observed that it is difficult to ascertain the degree of MIB and geosmin removals which can be attributed to biological processes. The raw MIB data, shown in Figure 8-31, shows that there was negligible removal of MIB in each of the four spikes. Figure 8-33 indicates that there was a greater removal of geosmin, however it was still variable and conclusions on the degree of biodegradation are difficult. These results indicate that EBCT did not have a large impact on the column performance.

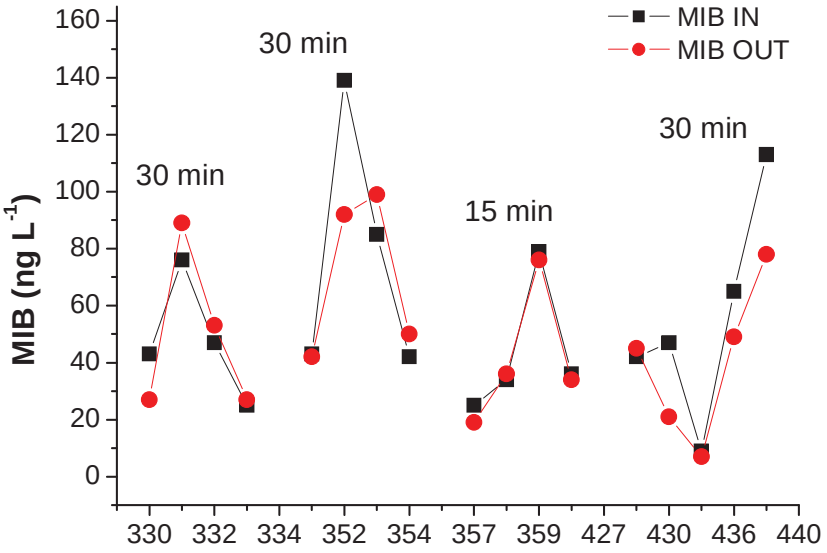


Figure 8-31: MIB concentrations (ng L^{-1}) through settled water column, spikes 5, 6, 7 and 8.

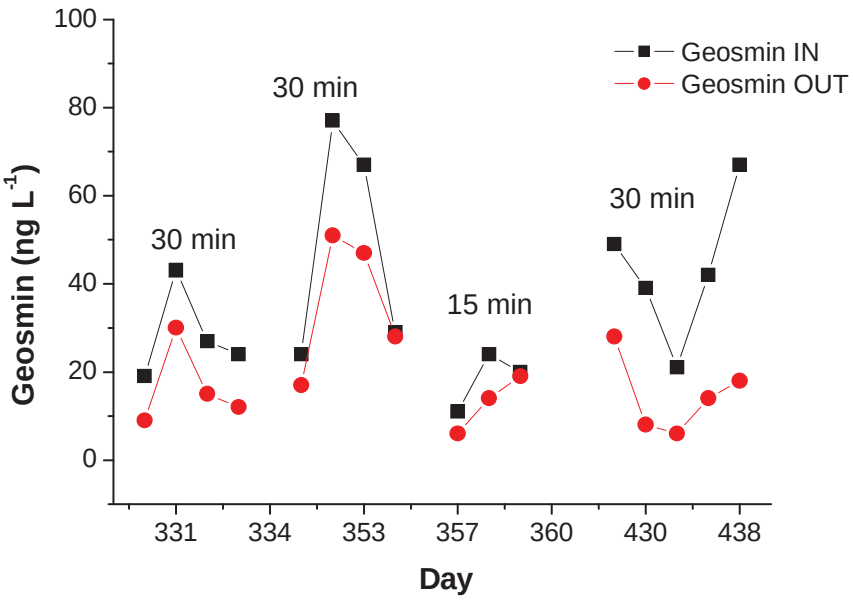


Figure 8-32: Geosmin concentrations (ng L^{-1}) through settled water column, spikes 5, 6, 7 and 8.

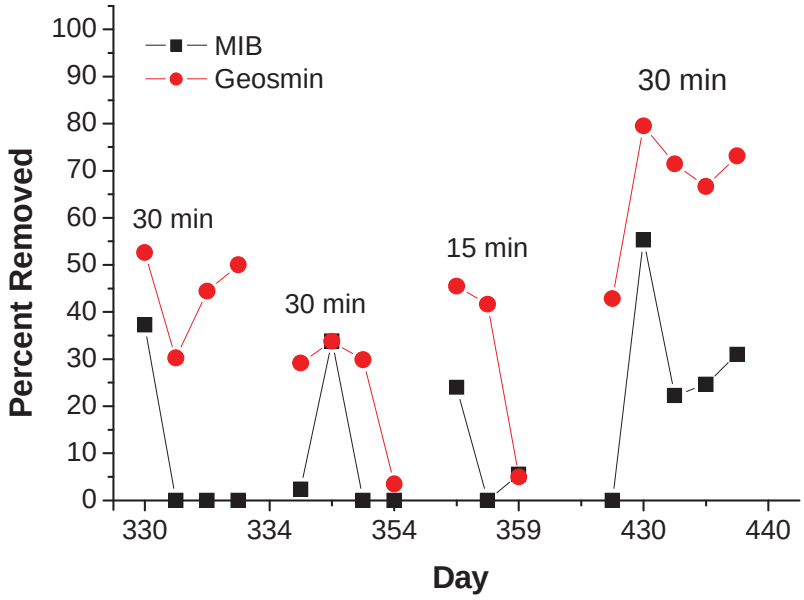


Figure 8-33: Percent removal of MIB and geosmin through settled water column, spikes 5, 6, 7 and 8.

8.5.4 Settled Water Spiking Trial 9

The preceding spiking trials were conducted for 5 day periods. In spike 9, the spiking time was increased to 4 weeks with 2 weeks at 30 minute EBCT followed by 2 weeks at 15 minute EBCT.

Again, the effect of EBCT was not significant. The percentage removals of MIB and geosmin are shown in Figure 8-36. Influent and effluent concentrations of MIB and geosmin are shown in Figures 8-34 and 8-35, respectively. MIB removals averaged 20% (SD 9%, n=5) for the 30 minute EBCT and 21% (SD 3%, =4) during the 15 minute EBCT. This is a negligible difference. Geosmin removals averaged 41% (SD 12%, n=5) for the 30 minute EBCT followed by 50% (SD 8%, n=4) for the 15 minute EBCT. These differences are negligible considering the variations within the data points for each EBCT.

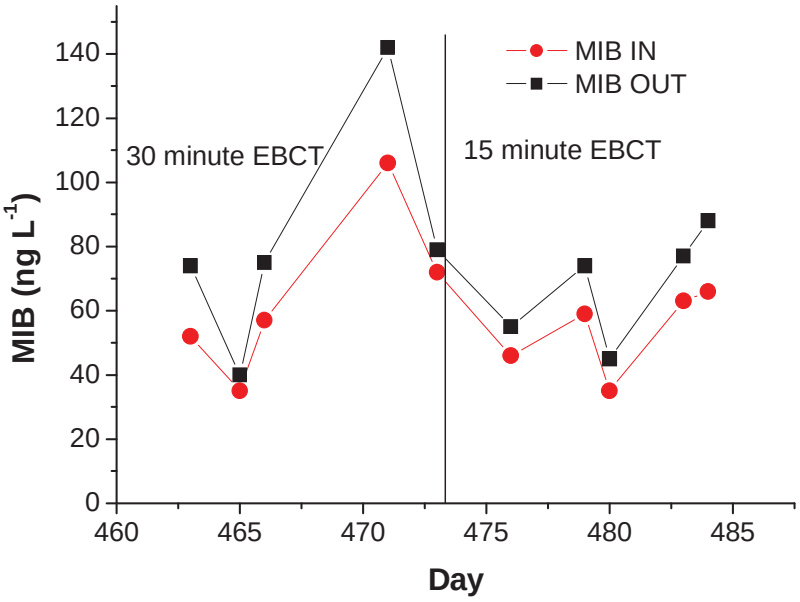


Figure 8-34: MIB concentrations (ng L^{-1}) through settled water column, spike 9.

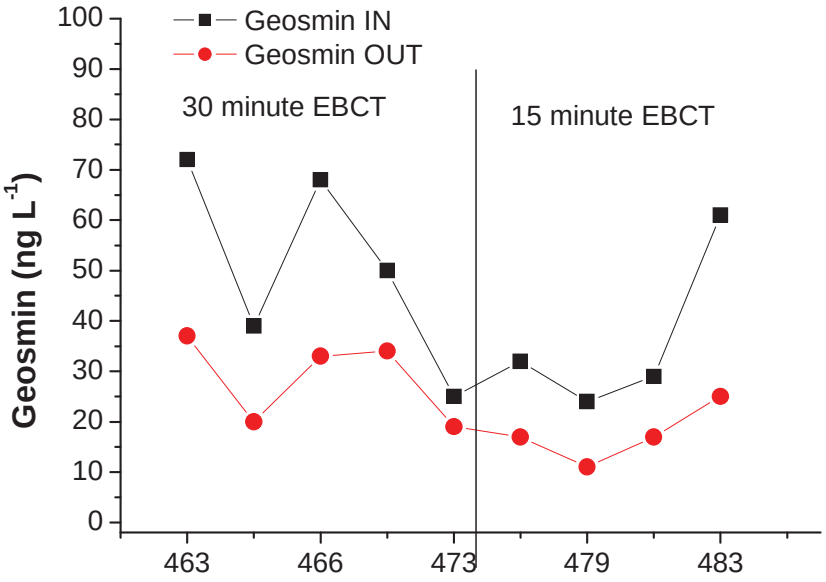


Figure 8-35: Geosmin concentrations (ng L^{-1}) through settled water column, spike 9.

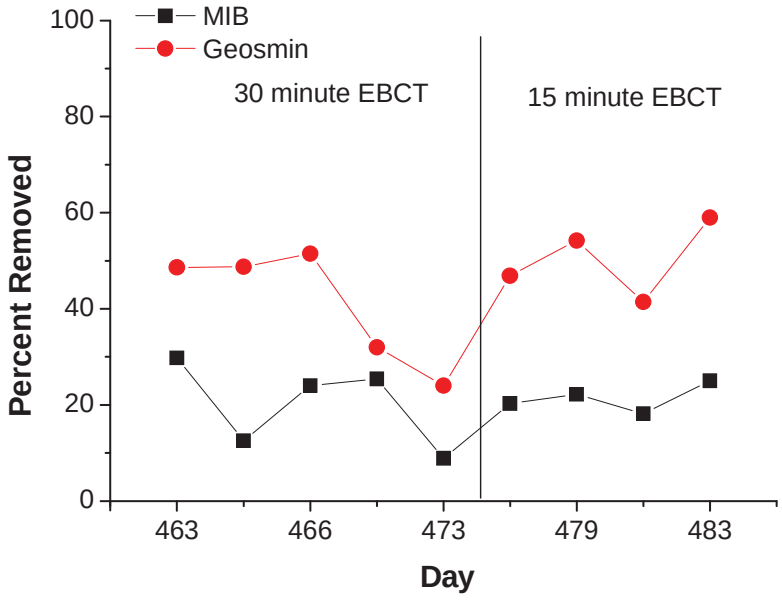


Figure 8-36: Percentage removal of MIB and geosmin through settled water column, spike 9.

8.5.5 Settled Water Spiking Trial 10

The tenth spiking trial on the settled water column was conducted at a 15 minute EBCT over a period of 7 days. Results from this spike are shown in Figures 8-37, 8-38 and 8-39.

A significant increase in biodegradation of MIB and geosmin occurred during this spiking trial. The data presented in Figure 8-39 shows the percentage removals of MIB and geosmin throughout the trial. MIB removals averaged 64% (SD 9%, n=4), while geosmin removals averaged 82% (SD 11%, n=4). For the first time for the pilot plant study, the effluent geosmin concentrations remained close to the odour threshold concentration of 10.0 ng L^{-1}, averaging 7.3 ng L^{-1} (SD 3.3 ng L^{-1}, n=4) over this trial.

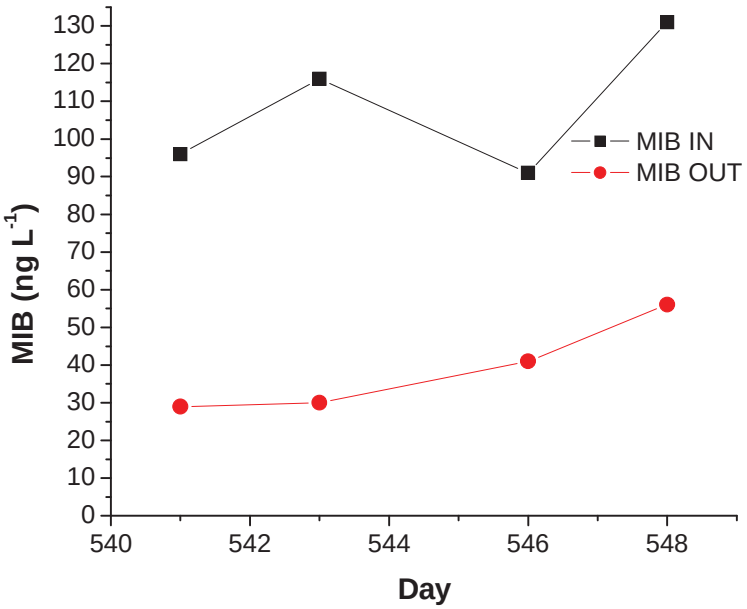


Figure 8-37: MIB concentrations (ng L^{-1}) through settled water column, spike 10.

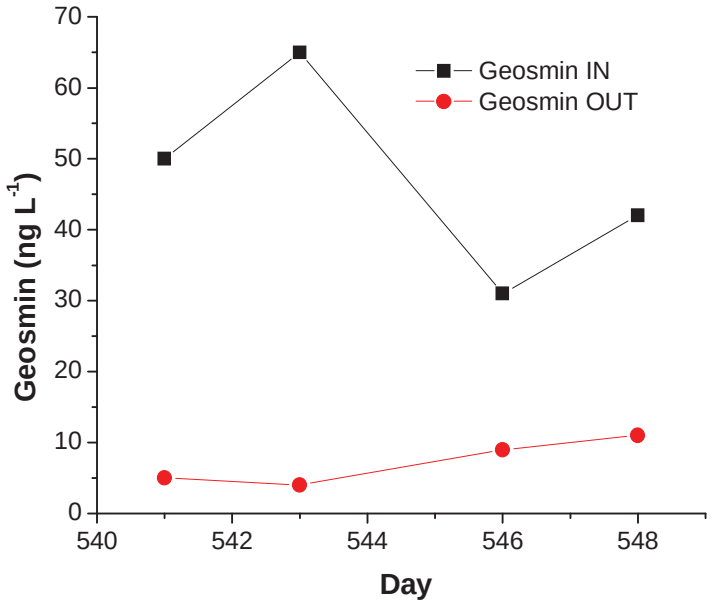


Figure 8-38: Geosmin concentrations (ng L^{-1}) through settled water column, spike 10.

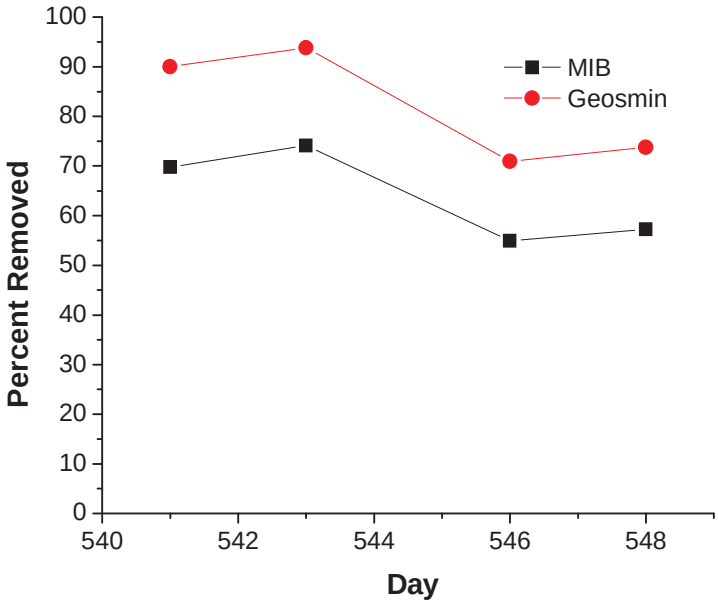


Figure 8-39: Percentage removal of MIB and geosmin through settled water column, spike 10.

8.5.6 Settled Water Spiking Trial 11

The previous spike showed promising MIB and geosmin removals at a 15 minute EBCT. For spike 11, the flow rate was increased to give an EBCT of 10 minutes, or a filtration rate of 6.0 m h^{-1}. This is within the low range of rapid gravity filtration. The spike was conducted over 9 days, correlating to days 568 to 577.

Influent/effluent data for MIB and geosmin are shown in Figures 8-43 and 8-44. Percentage removals of both compounds through the columns are shown in Figure 8-45.

Day 1 of sampling gave outlying results. This may have been due to an insufficient time period between the start of the dosing pumps and the sampling. With the exception of the first day's results, MIB removals averaged 32% (SD 10%, n=4) over the 9 days, while geosmin removals averaged 53% (SD 6%, n=4). These results suggest that the settled water column was developing a biomass which was capable of taste and odour removal as the removals are above that considered to be background removal alone.

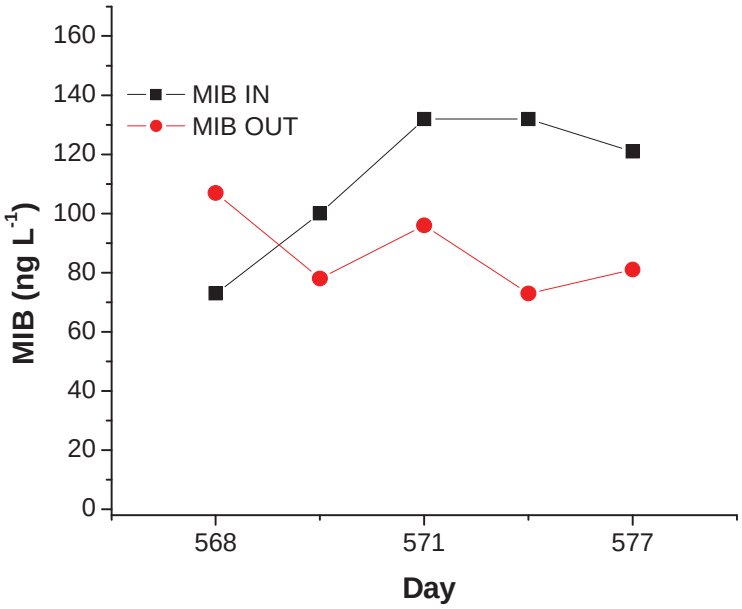


Figure 8-40: MIB concentrations (ng L^{-1}) through settled water column, spike 11.

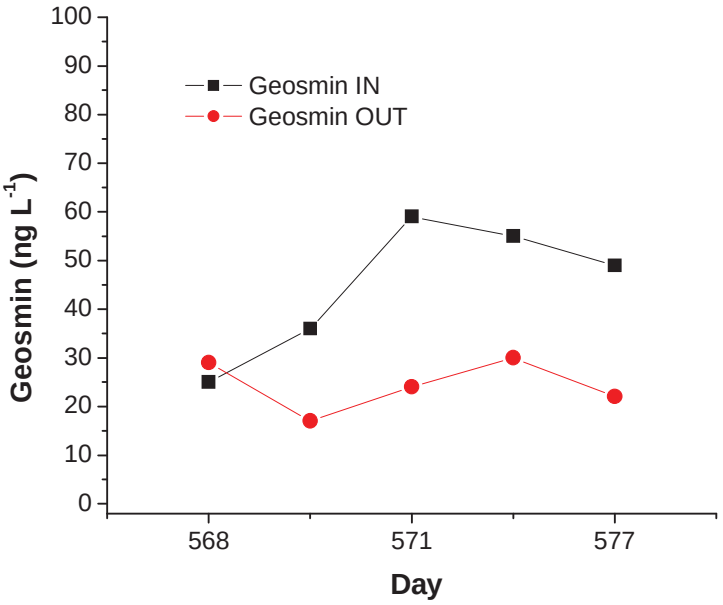


Figure 8-41: Geosmin concentrations (ng L^{-1}) through settled water column, spike 11.

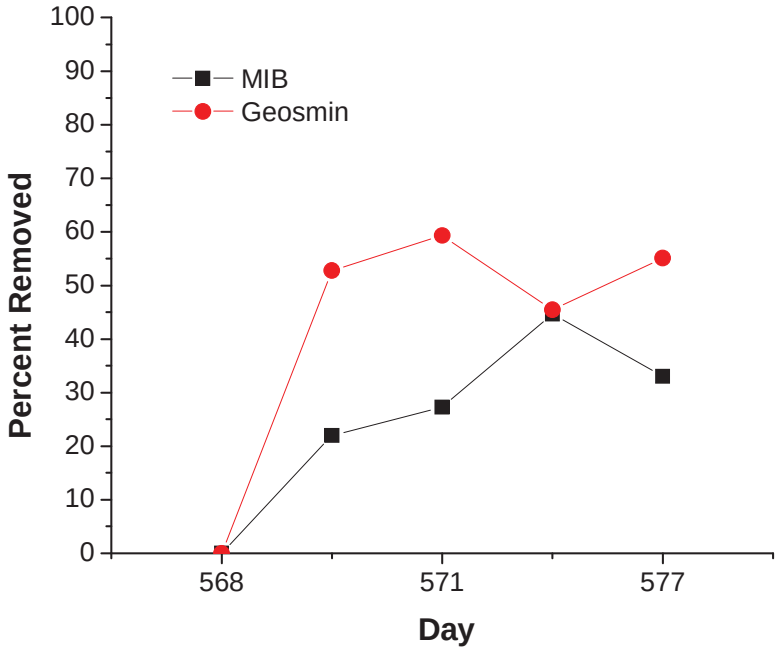


Figure 8-42: Percentage removal of MIB and geosmin through settled column, spike 11.

8.5.7 Settled Column Spiking Trial 12 and 13

Spike 12 was carried out for 3 days at a 10 minute EBCT. The spike was stopped after 3 days due to power failures to the pilot plant due to Happy Valley plant maintenance.

Spike 13 was carried out for 9 days at a 10 minute EBCT. Figure 8-43 gives the MIB concentrations through the column for spikes 12 and 13. Geosmin concentrations are given in Figure 8-44. The percentage removals of MIB and geosmin are shown in Figure 8-45. As with the previous spiking trials, the percentage removals of MIB and geosmin in trials 12 and 13 were scattered, coinciding with the fluctuating inlet concentrations of the two compounds. However, geosmin removals were consistently above 50%, indicating some degree of biological removal was occurring.

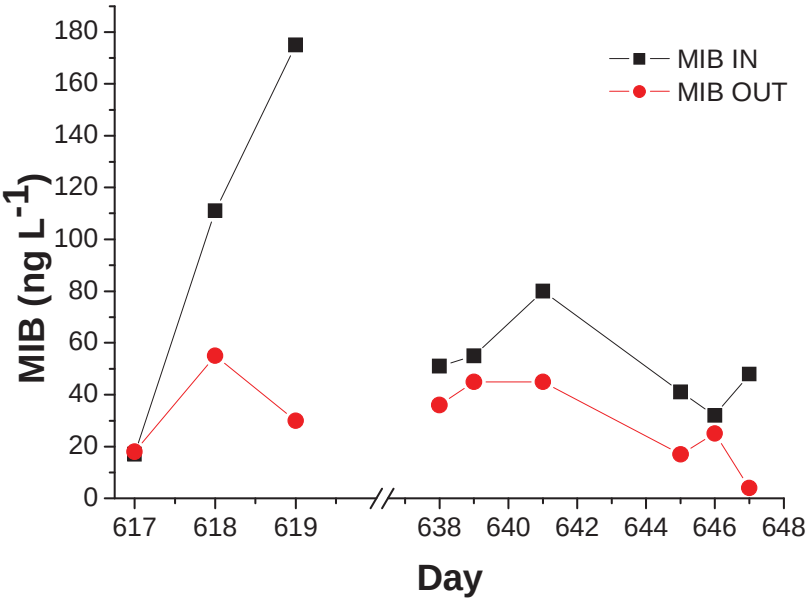


Figure 8-43: MIB concentrations (ng L^{-1}) through settled water column, spikes 12 and 13.

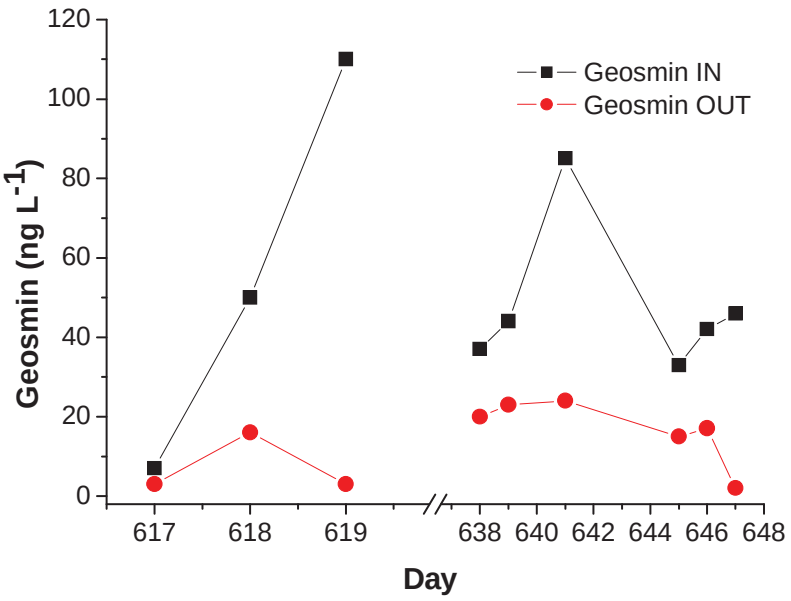


Figure 8-44: Geosmin concentrations (ng L^{-1}) through settled water column, spikes 12 and 13.

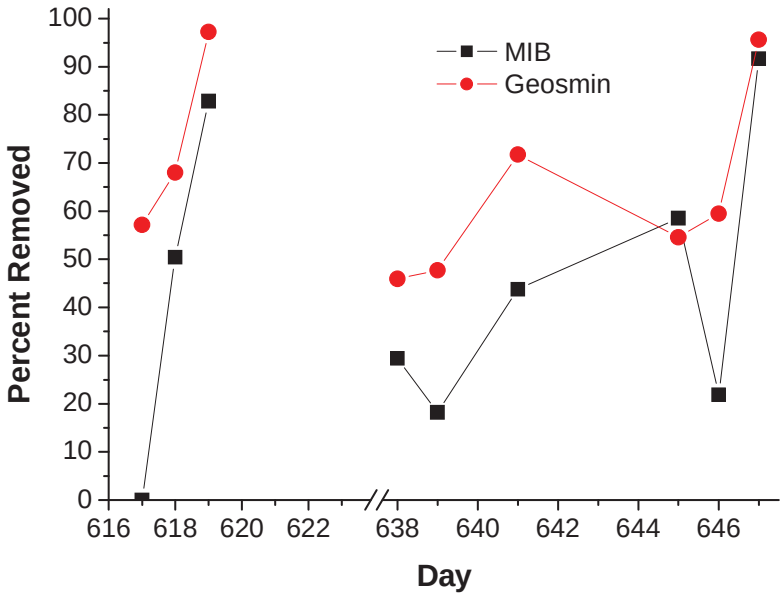


Figure 8-45: Percentage removal of MIB and geosmin through settled water column, spikes 12 and 13.

8.6 BIOFILM STUDY

Scanning electron microscopy, flow cytometry and the ATP assay were used to study the biofilm developed on each of the filters. As the ATP assay was in method development during parts of the pilot plant study, it was not used throughout the duration of the study.

8.6.1 Flow Cytometry on Biofilms

Flow cytometry was used on two occasions to estimate the numbers of active bacteria on the filter media. Approximate biomass levels were calculated by removal of the biofilm from a sand sample, with subsequent bacterial enumeration by flow cytometry. The first sample was taken 23 days after the implementation of ozonation. The second sample was taken 302 days after the start of ozonation. The cell numbers are shown in Figure 8-46. The biomass increased significantly for the second sampling period. There was no difference between the biomass levels on the ozonated column and the settled water column, which was not as expected.

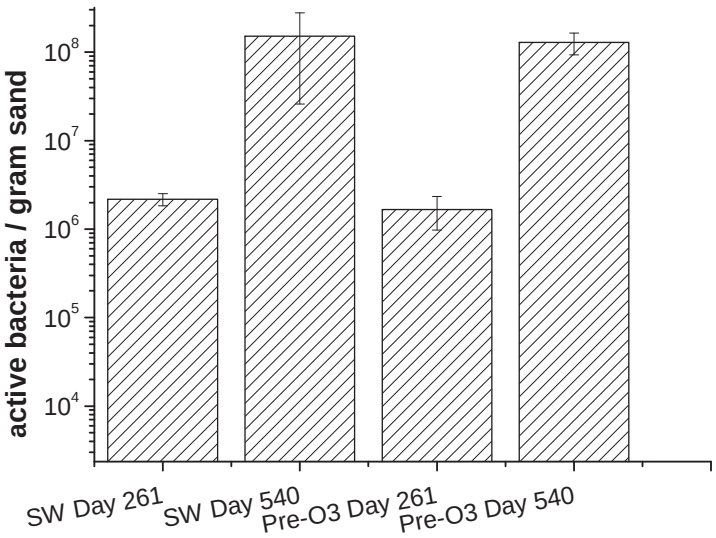


Figure 8-46: Biomass levels on sand media by flow cytometry. SW indicates sand taken from settled water column; Pre-O3 indicates sand taken from pre-ozonated column.

8.6.2 Biomass Activity

The ATP assay was carried out periodically over the course of the pilot plant study. Results are shown in Figure 8-47. Contrary to the majority of studies on pre-ozonation, the column subjected to pre-ozonation showed a lower biomass activity during the period in which ozonation was operating. The two columns showed very similar biomass activities after the cessation of pre-ozonation.

The ATP values of the pilot plant media were at the lower end of that observed in previous biofiltration studies in this thesis. In comparison, the laboratory scale Happy Valley settled water column, shown in Chapter 5, had ATP levels of greater than 1000 nmol ATP per unit filter volume after 300 days in operation. This column was removing greater than 90% of the influent MIB and geosmin concentration. The pilot plant biomass remained lower than 800 nmol ATP per until filter volume, even after 550 days of operation.

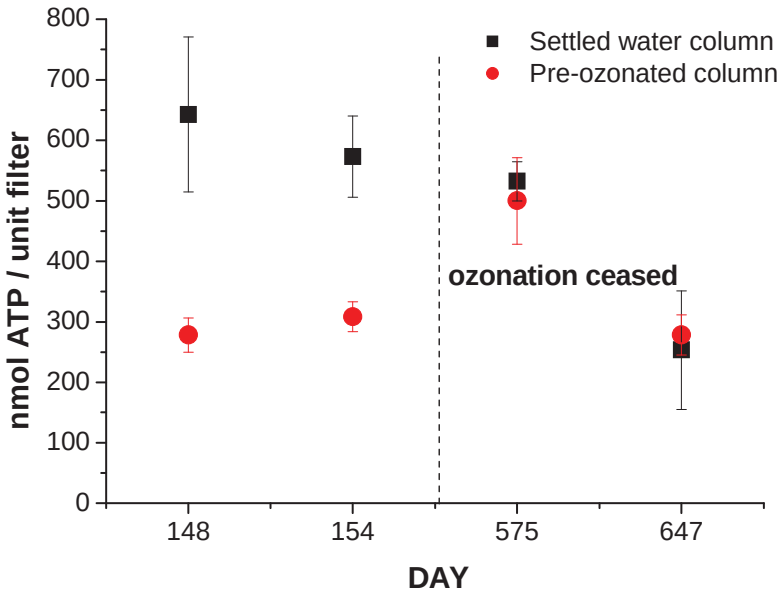


Figure 8-47: Biomass activity on pilot plant sand (nmol ATP per until filter volume). Error bars indicate standard deviations from triplicate analysis.

8.6.3 SEM on Pilot Plant Sand

Sand was sampled from the pilot plant after 532 days of plant operation. The SEM pictures show that a thick biofilm had developed on the media from both columns during the study.

Visually, the biofilms on each column were similar. However, previous studies have shown that pre-ozonation changes the microbial composition of drinking water biofilms (Moll *et al.* 1999; Fonseca *et al.* 2001). These changes are not evident by the SEM, flow cytometric or ATP assay methods of studying biofilms.

The scale for each scan is shown on the figures.

SEM of Virgin Sand

Figures 8-48 and 8-49 are SEM scans of the virgin sand, prior to use in the pilot plant. The scans showed the sand to have a rough surface with no discernable microorganisms.

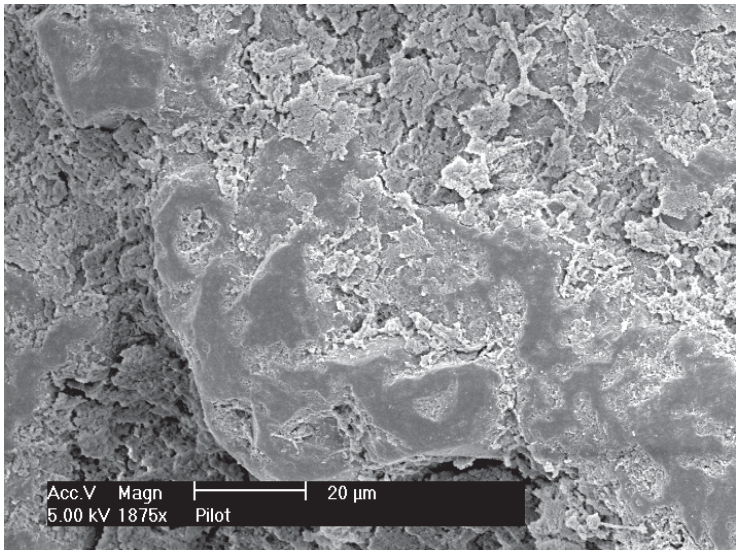


Figure 8-48: SEM image of Virgin Pilot Plant sand, scan 1.

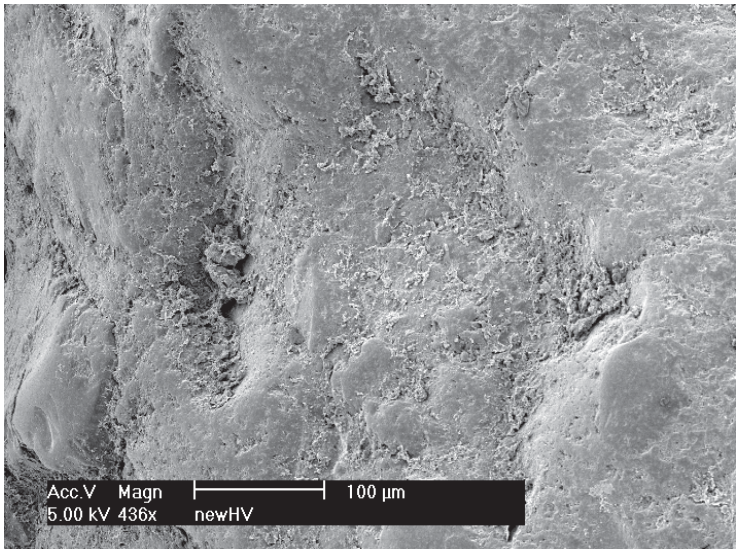


Figure 8-49: SEM image of Virgin Pilot Plant sand, scan 2.

SEM of Ozonated Column

Figures 8-50, 8-51 and 8-52 are a selection of SEM scans of the pre-Ozonated column. The sands were sampled after 530 days of pilot plant operation, 290 days after the start of ozonation. The scans demonstrated that a biofilm had developed on the sand, comprised of a diverse range of microorganisms.

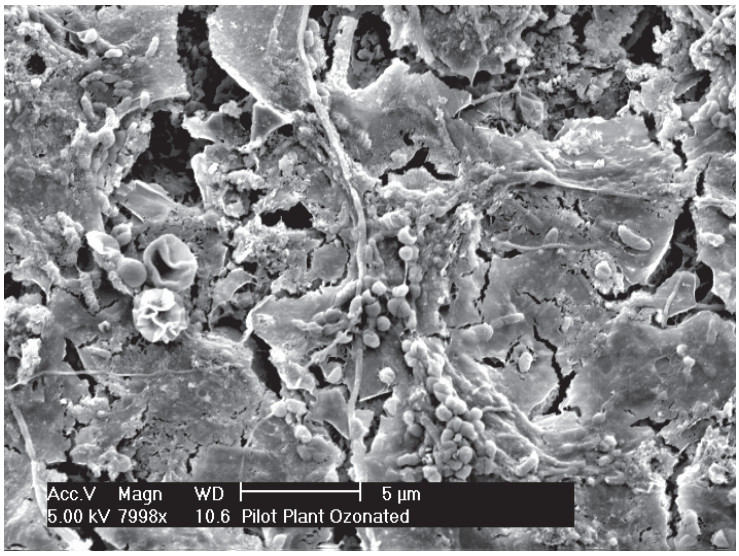


Figure 8-50: SEM image of pre-ozonated column sand, scan 1.

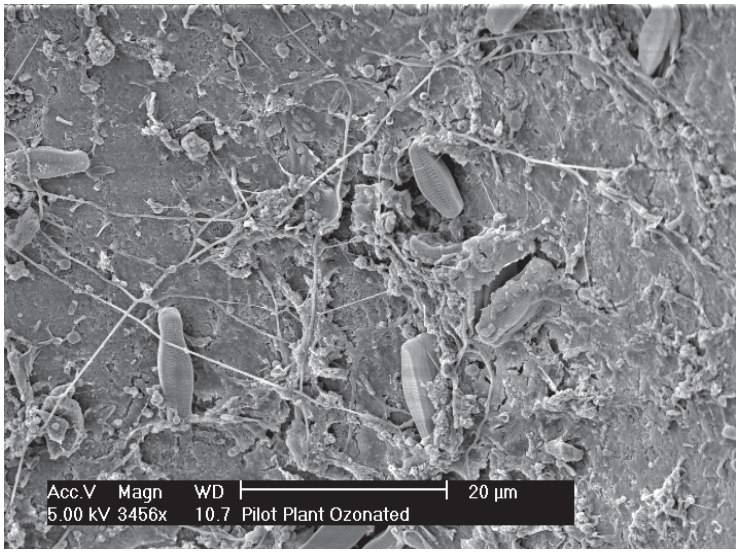


Figure 8-51: SEM image of pre-ozonated column sand, scan 2.

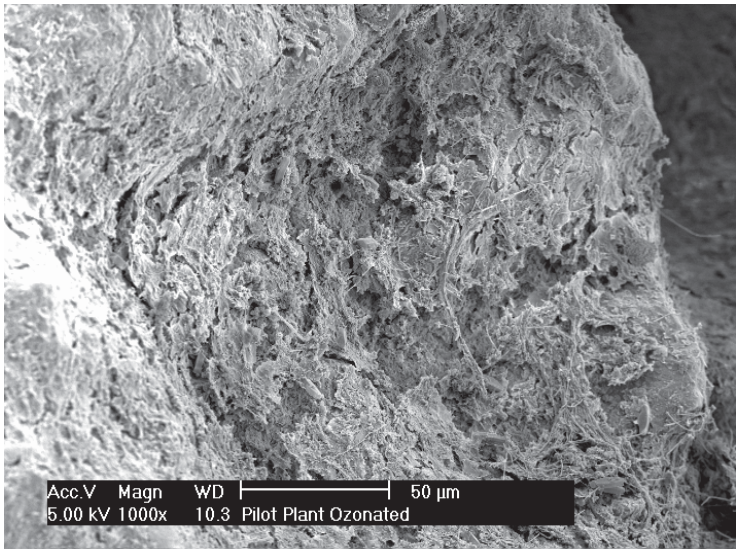


Figure 8-52: SEM image of pre-ozonated column sand, scan 3.

SEM on Settled Water Column

Figures 8-53, 8-54 and 8-55 are the SEM scans of the settled water column. In these scans, it can be observed that the settled water column sand had also developed a substantial biofilm.

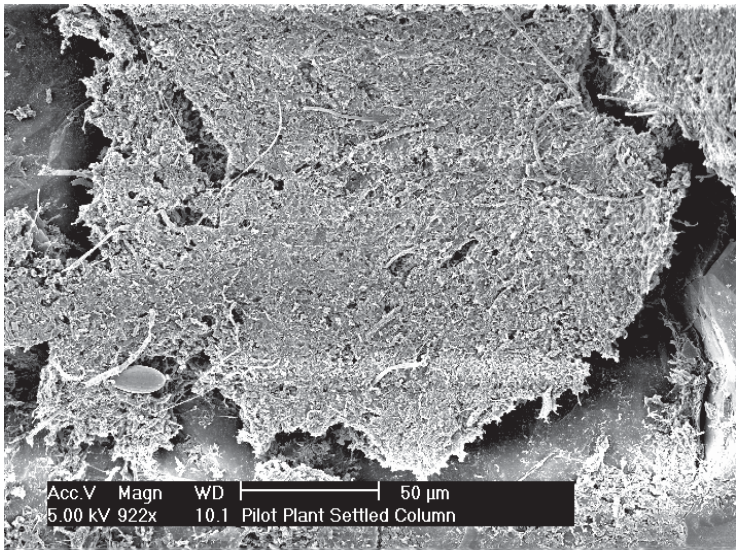


Figure 8-53: SEM image of settled water column sand, scan 1.

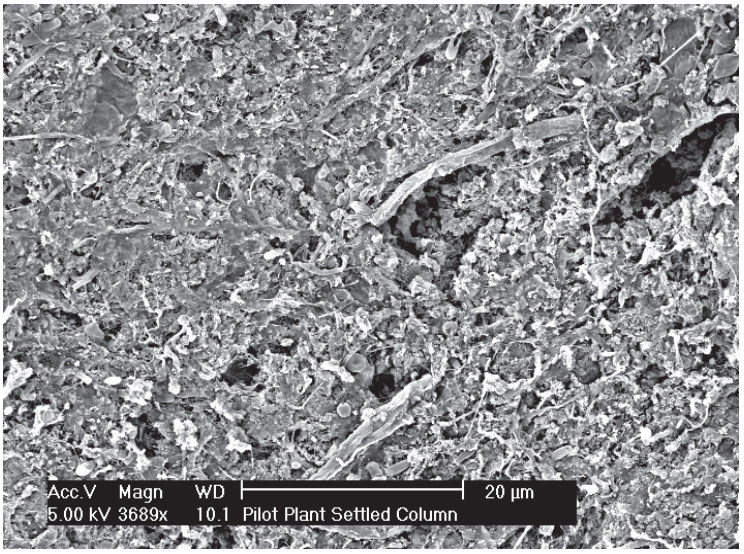


Figure 8-54: SEM image of settled water column, scan 2.

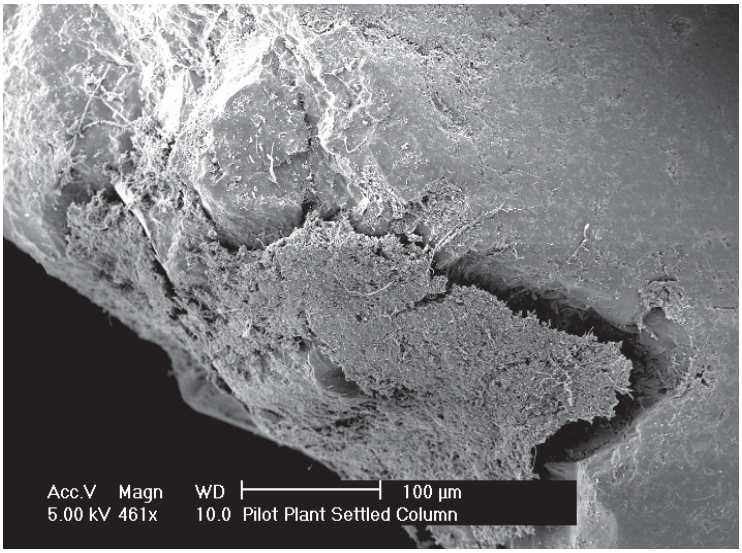


Figure 8-55: SEM image of settled water column, scan 3.

8.7 FILTER RUN TIMES AND TURBIDITIES

The settled water column built up head loss depending on the Happy Valley WTP settled water quality. Head loss also increased with higher filtration rates. On average, the settled water filter required backwashing every 3 days. At this point, terminal head loss was reached and the filtration rate would decline. In some instances, large flows of highly turbid water entered the pilot plant, causing head loss to build up within hours. In these cases, more frequent backwashing was required.

The implementation of ozone resulted in a marked decrease in the head loss of the ozonated column. In periods when no head loss was observed the filter was backwashed every 2 weeks. In a previous study, ozonation of settled water prior to sand filtration improved particle removal by 90% at ozone doses between 2 to 4 mg L^{-1}, in the particle size range of 2-10µm (Bourgine *et al.* 1998). Bourgine *et al.* (1998) suggest that the reason for the increase in particle removal is due to particle destabilisation, improving removal by attachment mechanisms on the sand surface. However, Bourgine *et al.* (1998) noted that the ozonation process aided the filtration, but did not affect the particle sizes and concentration prior to filtration.

Clean bed head loss was monitored throughout the study. It did not decrease, remaining at an average of 20 cm for the duration of the study. This indicated that the columns were operating well, despite variations in backwash frequency and method.

Turbidities of the pre-ozonated column are shown in Figure 8-56. Effluent turbidities were between 0.1 and 0.2 NTU, which is slightly higher than the ADWG value of 0.1 NTU (NRMMC 2004). It is not known why the ozonation process itself decreased turbidities. This is contrary to that observed by other researchers, who found that particle size and concentration was not affected by ozone (Bourgine *et al.* 1998). It is possible that the hydraulic conditions in the pilot plant caused some settling of the turbidity before reaching the head water of the column.

Turbidities of the settled water column are presented in Figure 8-57. Again, effluent turbidities did not go below 0.1 NTU, showing that the filtration process did not produce water of the recommended standard.

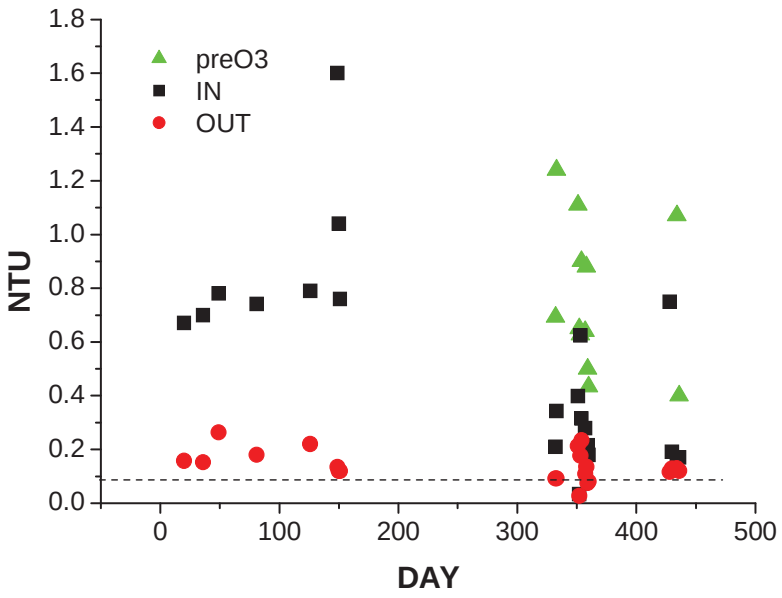


Figure 8-56: Pre-ozonated column turbidities (NTU). Dotted line indicates ADWG value.

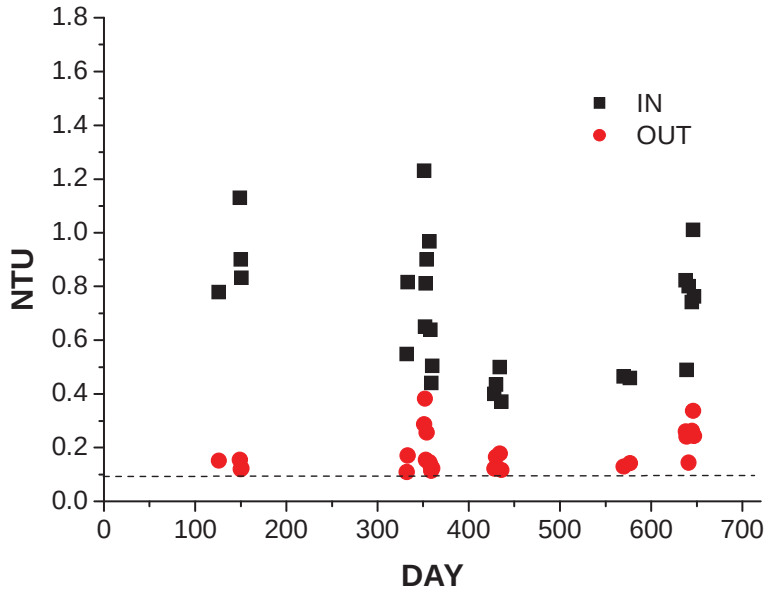


Figure 8-57: Settled water column turbidities (NTU). Dotted line indicates ADWG value.

8.8 SUMMARY OF RESULTS

8.8.1 DOC Removals

A summary of the percentage removals of DOC by the filter columns is presented in Figure 8-58. The removal of DOC gives an indication of the amount of biodegradable organic carbon (BDOC) which was removed by biological activity within the filter. The data presented in the figure is based on the DOC concentration at the influent of the columns, after the quenching of ozone. These values are thus independent of any DOC removal by the ozonation process itself.

From the figure, it can be seen that there was not a large difference in the DOC removal of each column. The average DOC removal for the settled water column was -1.0% (SD 15%), while the pre-ozonated column gave an average DOC removal of 6% (SD 14%).

A previous pilot plant study, utilising biofilters containing sand media, achieved 14% removal of DOC in a non-ozonated filter compared to approximately 25% DOC removal in a pre-ozonated filter operated at a 17 minute EBCT (Fonseca *et al.* 2001). The pre-ozonated column in that study was exposed to an ozone dose of approximately 1.3 (± 0.25) mg O_3 per mg DOC, which is slightly higher than the dose of 0.9 (± 0.1) mg O_3 per mg DOC that was approximated in the Happy Valley pilot plant study.

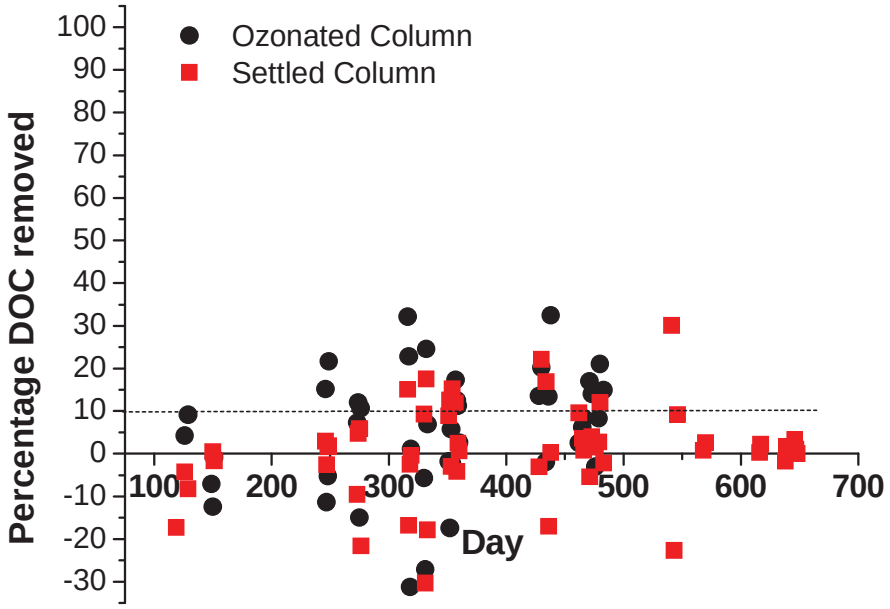


Figure 8-58: Percentage DOC removed in pilot plant trials.

8.8.2 MIB and Geosmin Removals

The pre-ozonated column was run for a period of 546 days with 10 spiking periods. Pre-ozonation was used from day 238 to day 546, or spikes 2 to 10. The settled water column was run for a period of 647 days with 13 spiking periods. The individual spiking trials were described in Sections 8.3 and 8.5. There are many interacting factors associated with the pilot plant study that would have contributed to the observed MIB and geosmin removals. These include sampling error at the pilot plant, the effect of biomass development with time, changes in temperature and water quality over the period of the study, fluctuations of filtration rates due to head loss in the filters, and the effect of the change in backwashing regime. It is impossible to establish the individual contributions of each of these factors to the results of the study using the available data. Thus, only general observations will be discussed.

Percentage removal data of MIB and geosmin in both columns were collated and box plots were constructed. The presentation of the data in this manner is very useful for making comparisons between each contact time and each column. In the box plots, the boxes indicate the upper and lower quartiles, with the whiskers indicating the maximum and minimum data points. The upper quartile is the middle value of the data points above the median, while the lower quartile is the middle value of the data points below the median, thus the length of the box represents the inter quartile range (IQR) of the data. The solid squares inside each box indicate the mean of the data.

Box plots of the MIB and geosmin percentage removals are presented in Figure 8-59 and Figure 8-60, respectively. The plots show the differences in the percentage removals of MIB and geosmin through each column at 15 minute and 30 minute EBCTs. The purpose of these plots is to investigate any differences in the performance of the pre-ozonated and settled water columns. The plots also allow for a comparison of the effect of EBCT on removals in each column.

The data presented in Figure 8-61 shows that the effect of EBCT on MIB removals was more pronounced in the pre-ozonated column than the settled water column. The IQRs for the settled water column overlapped, indicating that EBCT did not have a significant effect on MIB removals in the settled water column. Removals of MIB at the 15 minute EBCT were at the level of background removals for both columns. It is likely that increased removals seen at 30 minute EBCT were due to increases in background losses at the higher EBCT.

The spread of the geosmin data was larger than that of MIB, as seen by the large boxes seen in Figure 8-60. This is as expected, with greater system losses of geosmin compared to MIB being observed throughout the studies described in this thesis. Again, there was a more pronounced effect of EBCT for the pre-ozonated column than

for the settled water column. Mean geosmin removals at 15 minute EBCT did not greatly exceed background removals for either column. The mean removals for geosmin at 30 minute EBCT were similar for both columns, although the settled water column data exhibited a greater data spread.

Significant increases in the pre-ozonated column were not evident, indicating that pre-ozonation did not enhance biological removal. In fact, pre-ozonation may have had a negative impact as mean geosmin removals at the 15 minute EBCT were superior for the settled water column. The observation that ozonation may have a negative impact on geosmin biodegradation was also noted in Chapter 5, where ozonated settled water exhibited a lower geosmin biodegradation rate than settled water. It was suggested that the production of BDOC by the ozonation process may have provided a more preferable substrate to the MIB and geosmin degrading organisms, hence impairing the removals of MIB and geosmin.

The greatest performance in both columns was observed at the 30 minute EBCT, with mean values close to 50%. This is not acceptable performance, as removals of greater than 50% would be required at Happy Valley WTP to provide water of acceptable odour quality. Filtration rates to achieve 30 minute EBCT would not be used in a first-stage full-scale rapid gravity filter unless very deep beds are used. Thus, this work has demonstrated that biological MIB and geosmin removal by the elimination of pre-chlorination of existing rapid gravity filters is not a valid treatment method over the time period studied.

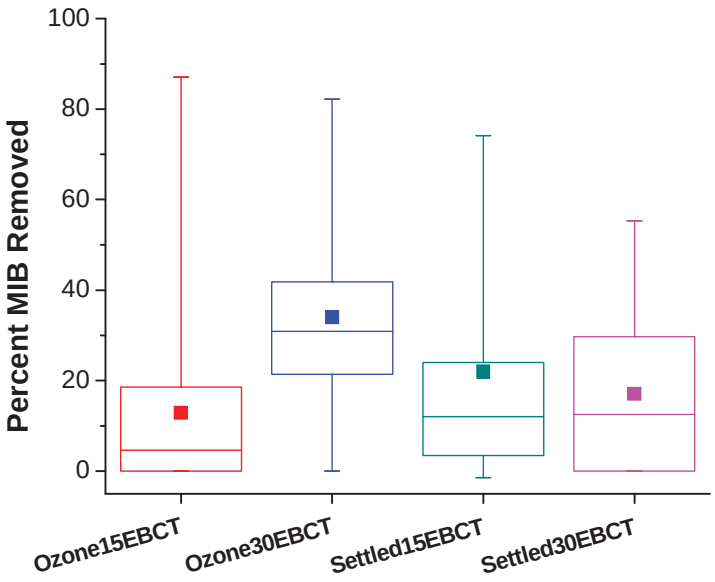


Figure 8-59: Box plot of MIB pilot plant data over total spike period.

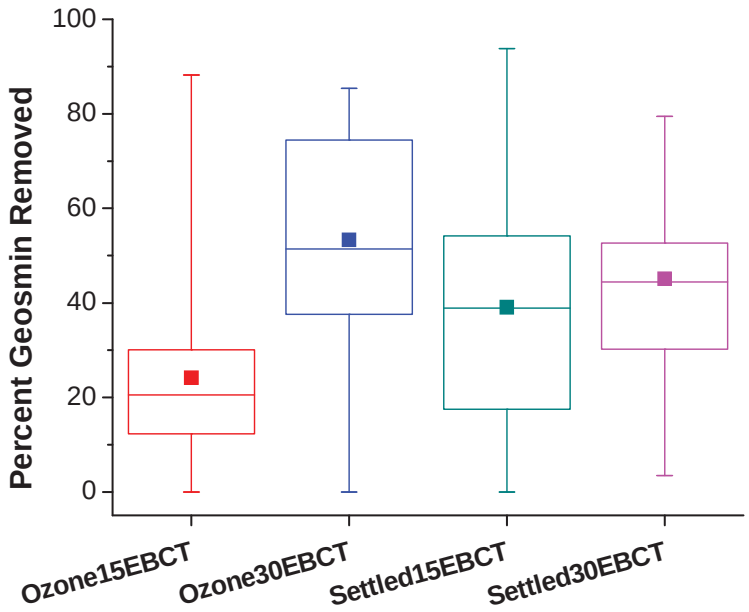


Figure 8-60: Box plot of geosmin removal over total spike period.

Previous studies in this thesis concluded that a long acclimation period is required before biofilms capable of MIB and geosmin develop in rapid sand filters. The sand media from Morgan WTP had been in operation since 1986 before it was exposed to the chlorinated backwash, a period of 22 years. It is not known how long this media took to develop its robust MIB and geosmin degrading biofilm. It may be that the sand media used in this pilot plant study would develop an efficient biofilm if the columns were operated for a longer period of time. To investigate this, the data from the pilot plant was separated according to spikes 1 to 6 and spikes 7 to 10, and box plots were constructed. Arrangement of the data in this manner allows the reader to observe the effect of time on the development of an MIB and geosmin degrading biofilm. MIB data at these separate time periods is presented in Figure 8-61. Geosmin data is presented in Figure 8-62. Removals of MIB and geosmin in both columns up to spike 6 (day 355) were at the level of background removal only. The mean removal of MIB in the settled water column increased after day 355, while the mean removal of MIB in the pre-ozonated column did not increase. The increase in the settled water column may be due to the development of a biofilm. Despite this increase, neither column gave removals of MIB that were sufficient to produce water of acceptable odour quality. Geosmin removals were higher, although the large spread of the data indicates that the removals fluctuated greatly.

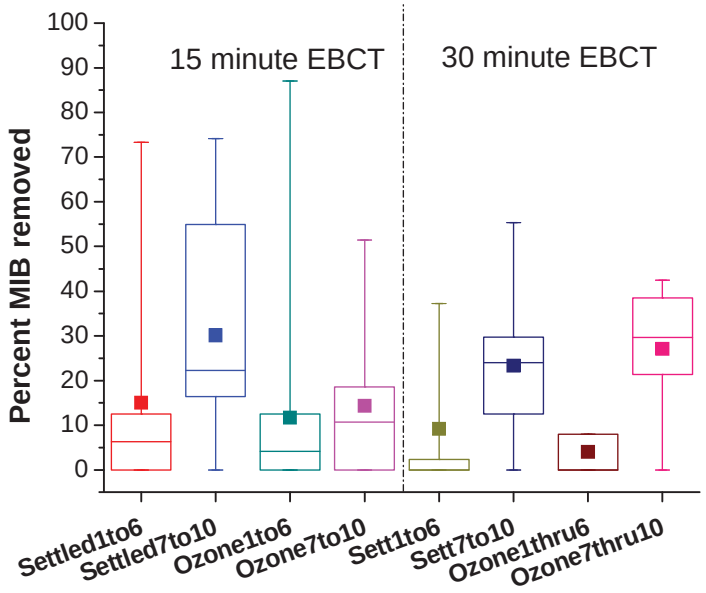


Figure 8-61: Box plot of MIB removals over two time periods.

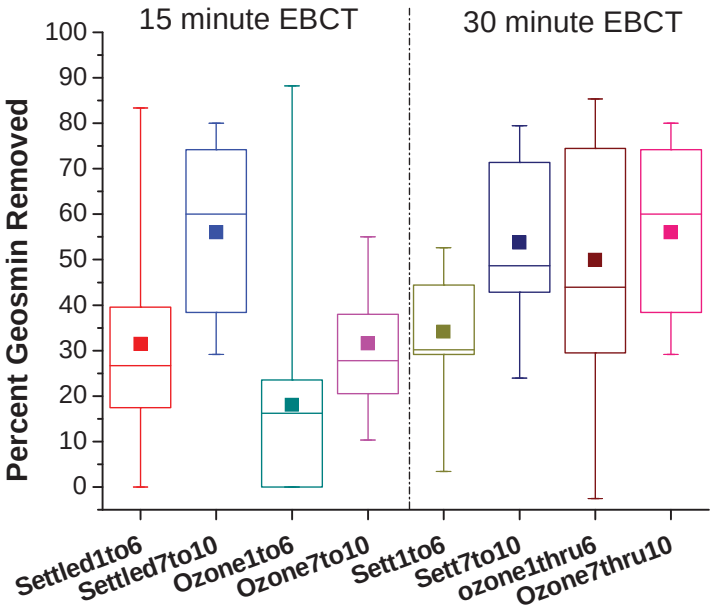


Figure 8-62: Box plot of geosmin removals over two time periods.

The trend of increasing removals of MIB and geosmin can be extrapolated to infer that the sand media may develop an efficient biofilm if operation was continued over a longer time frame. The results of the final three spiking trials on the settled water column were not included in the box plots, as these studies were conducted at an EBCT of 10 minutes. A box plot of that data is shown in Figure 8-63. These spikes correspond to days 568 to 647. It is seen that geosmin removals averaged 59%, which is higher than that observed previously for the higher contact time of 15 minutes. This suggests that the settled water column was starting to remove geosmin biologically. MIB removals remained below 50%, and it is not clear how much of the MIB removal was by biological processes.

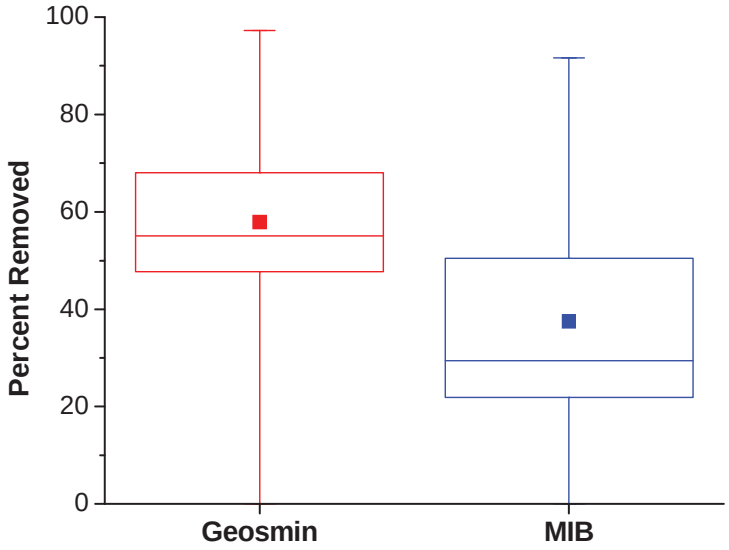


Figure 8-63: Box plots of settled water column, spikes 11 to 13.

8.9 CONCLUSIONS ON CHAPTER 8

The overall performance of the pilot plant in terms of MIB and geosmin removal was unpredictable and highly varied. Neither treatment train gave stable removals at a sufficient level to produce water of an acceptable odour quality.

The pilot plant study highlighted the long periods of time required for biological removal of MIB and geosmin to occur in rapid gravity filters. Separation of the data into two time periods, spikes 1 to 6 and spikes 7 to 10, established that geosmin removals were increasing over time. The final spikes in the settled water column were conducted from days 568 to 647. These spikes gave the greatest removals of MIB and geosmin despite the plant being run at a lower EBCT of 10 minutes. This suggests that the plant may produce efficient biological removals if it were to be operated over an extended time period.

Pre-ozonation did not aid in the development of a biofilm capable of MIB and geosmin biodegradation. In some cases, removals of MIB and geosmin were greater in the column fed with settled water. The biofilm analysis, by the ATP assay, flow cytometry and SEM, also did not show a significant difference in biofilm activity between the two columns.

The only advantage of pre-ozonation was increased filter run times. The ozonation process itself also decreased the turbidity of the water. However, neither column produced water of acceptable turbidity standard, indicating that the filters were not performing satisfactorily in terms of conventional filtration for particle removal. DOC removal was poor for both columns, with average removals below 10%.

In general, the pilot plant did not give adequate MIB and geosmin removal to be considered a replacement to PAC usage. Removals of MIB did not exceed the level of background removals. Geosmin removals fluctuated greatly and average removals did not reach the level required to produce odour free water. Additionally, the water did not meet the ADWG standard for turbidity. It was found that removals of geosmin and MIB were increasing and it was suggested that the plant might begin to operate efficiently if it were operated for a longer time period. A WTP that chose to invest the time required for a biofilm to develop may have to implement additional strategies to mitigate the decreases in water quality caused by elimination of the pre-chlorination step. However, the levels of MIB and geosmin removals during this time may be sufficient so as to reduce the amount of PAC required and therefore be of economical advantage to water utilities.

9 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

9.1 SUMMARY AND CONCLUSIONS

The studies presented in this thesis demonstrate the potential of biological sand filtration for removal of MIB and geosmin. However, the results highlighted the requirement for a method to enhance the formation of MIB and geosmin degrading biofilms in rapid sand filters without pre-existing biofilms. A review of historical data from the Morgan WTP confirmed that a biologically active rapid sand filter can remove MIB and geosmin effectively in a conventional rapid gravity filter which had not been exposed to chlorine. Backwashing with chlorinated water decreased the biological performance of the filter, however the biological activity and resultant MIB and geosmin removal returned once chlorinated backwashing was ceased. Laboratory studies confirmed that the MIB and geosmin removal was by biodegradation. Anthracite and sand were both shown to be carriers for MIB and geosmin degrading organisms within the filter. The Morgan filter sand had been in the filter since the commissioning of the WTP in 1986, allowing for the development of a very robust biofilm.

Attempts to replicate this removal in laboratory and pilot studies with new filter sands demonstrated that excessively long periods of time were required to develop biofilms capable of effective MIB and geosmin removal. The presence of MIB or geosmin degrading organisms in the influent water did not result in faster biofilm development. Periods in excess of 300 days were required before geosmin removals over 80 % were observed in a laboratory column, despite biological geosmin removal being observed in the influent water.

Laboratory column studies demonstrated that smaller particle size was advantageous in the development of biofilms. It was postulated that this allowed for greater biomass concentration per unit filter volume.

An ATP assay, for the analysis of biofilm activity, was optimised for use on sand media. Flow cytometry was used to gain an indication of biomass concentration while the ATP assay was in development. It was found that higher ATP activity did not correlate to increased removals of MIB and geosmin, as media with similar biomass levels (as shown by ATP assay) had different MIB and geosmin degrading abilities. Thus, these methods were insufficient for providing an indication of MIB and geosmin degrading potential of a biofilm.

Two methods were used to enhance the biodegradation of MIB and geosmin and to minimise the biofilm development period: pre-ozonation and inoculation with geosmin degrading organisms.

Pre-ozonation was studied at a pilot plant, which was run for 650 days. The pilot plant consisted of two sand filters fed with settled water and pre-ozonated settled water. Results from the pilot plant study indicated that pre-ozonation did not enhance the formation of MIB and geosmin degrading biofilms. It was suggested that the ozonation process resulted in the production of other small organic compounds which were preferable substrates for biofilm organisms. Poorer degradation of geosmin in ozonated water was also observed in bioreactor studies with ozonated Happy Valley settled water, strengthening this theory.

Another method utilised for enhancing biofilm formation was the inoculation of laboratory sand filters with geosmin degrading organisms. Laboratory columns were inoculated with a consortium of three Gram-negative bacteria that had previously been isolated from biofilm sampled from the Morgan WTP filter media and shown to be capable of geosmin biodegradation. It was shown that the inoculation process could successfully improve the biological removal of geosmin, with removals of up to 70 % observed. The attachment of the degrading organisms to the filter was superior in filters with pre-existing biofilms. The inoculation study only consisted of preliminary studies, and a more thorough investigation was recommended.

Biological sand filters which were well acclimated for MIB and geosmin removal could perform satisfactorily in the range of EBCTs commonly found in rapid gravity filtration. Biofilms developed in shorter time periods were less able to cope in the full range of EBCTs. This was demonstrated in the full scale and laboratory scale studies. Morgan WTP, which operated at an EBCT of approximately 3.5 minutes, was shown to give highly effective MIB and geosmin removals. Laboratory studies utilising sand media sampled after the biofilm had been damaged and subsequently allowed to recover, showed that the recovered biofilm was less able to cope at lower EBCTs. The pilot plant work demonstrated that there was not a significant impact of EBCT in the range of 10 to 30 minutes.

9.2 GENERAL DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study has shown that biological sand filtration for MIB and geosmin removal can be a cost-effective and reliable process, as demonstrated by the Morgan full-scale study. However, the long start-up periods associated with the development of robust MIB and geosmin degrading biofilms on new sands and the difficulties with maintaining good removals with newer biofilms at lower EBCTs means that the process can not be confidently implemented before methods to enhance the biofilm development are further developed.

Although it is generally accepted that pre-ozonation enhances the performance of biological filtration systems, it was not known whether the enhanced biological activity commonly associated with pre-ozonation would benefit the organisms involved in the biodegradation of MIB and geosmin. The results from the pilot plant study indicated that pre-ozonation did not enhance the biological component of MIB and geosmin removal in the ozone-biofiltration tandem. In fact, poor removals were observed in filters with and without pre-ozonation, again highlighting the difficulties in the formation of MIB and geosmin degrading biofilms. Hypothetically, if cost was not an issue, it would be preferable to incorporate pre-ozonation due to its ability to remove a proportion of the MIB and geosmin. The removal by ozonation, coupled with the removal by the biological processes, may result in water with acceptable levels of MIB and geosmin. However, in reality the implementation of an ozonation system in a treatment plant would require significant retrofitting and high costs to the facility.

The laboratory studies highlighted the importance of pre-existing biofilm on the attachment of the degrading organisms within the filter beds. Previous work in this study and in studies by other researchers (Liu *et al.* 2008) highlighted the impact of a pre-existing biofilm to the attachment of bacteria inoculated onto porous inert media. The attachment of geosmin degrading organisms, both inoculated and naturally occurring, was more successful in filters with inactivated pre-existing biofilms.

There are two options that warrant further exploration. Firstly, more work should be conducted into the inoculation of filters with MIB and geosmin degrading organisms. However, as this study showed, the attachment of these organisms is reliant on the state of the biofilm into which they are inoculated. For this reason, a more useful approach may first be to develop methods to grow biofilms on new sands, which will then provide an EPS substrate onto which the naturally occurring degrading organisms can attach to. This may be achieved by a once-off inoculation with an organism known to form biofilms and excrete EPS more readily, such as the *P. aeruginosa* used in the study by Liu *et al.* (2008). However, as the study by Liu *et al.* (2008) highlighted, different organisms excrete EPS of different composition, and the composition of the EPS can affect the attachment and sustenance of biofilm. For this reason, more work is required to determine the optimum EPS composition for attachment of MIB and geosmin degrading organisms.

It is recommended that biological treatment cannot be used to replace PAC addition at this stage. However, the used of biological treatment may lower the required PAC concentrations, or act as a second barrier to breakthrough of taste and odour.

9.2.1 Recommendations for Further Work

This study has highlighted a number of areas for future work. In particular,

- Greater research into compounds and or organisms which may promote the formation of biofilms and the factors involved in the formation of biofilms on sand;
- Isolation of MIB degrading organisms;
- Isolation of a single geosmin degrading organism;
- Identification of genes responsible for geosmin and MIB biodegradation;
- Development of molecular tools to track the presence and activity of MIB and geosmin degrading organisms within a biofilm. This would be a more useful tool than total biomass measurements such as the ATP assay and FCM;
- Development of an inoculation method which can be employed on the full scale; and
- Further study of operational conditions on MIB and geosmin degradation in well-acclimated pilot scale biological sand filters
    - The pilot plant did not reach steady state removals at the higher contact time, hence study of the effect of operational parameters such as rapid gravity filtration EBCTs, backwashing technique were not adequately studied in this project
    - Particular emphasis on effect of higher filtration rates (lower EBCTs) in the range of rapid gravity filtration.