

GRANULAR ACTIVATED CARBON
MANAGEMENT AT A WATER TREATMENT
PLANT

By

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ABSTRACT

The Rietvlei Water Treatment Plant was extended with a granular activated carbon (GAC) filtration system after an exhaustive series of tests, which were started in 1994. Upon commissioning towards the middle of 1999, a year of close monitoring followed to measure the GAC performance at full-scale. After verification that the GAC does indeed ensure a high quality product under all conditions, the emphasis shifted to the optimisation of the GAC handling and regeneration system. Frequently moving the entire GAC inventory from the filters to an off-site regeneration plant and back requires significant operational effort and contributes a major part of the total cost of the GAC system. A number of systematic investigations were carried out in response to a number of practical questions that arose at Rietvlei.

The first part of the study was directed towards tracking and quantifying the GAC on and off site. The main findings were that 10.0% of the GAC is lost from the filter during backwashing (0.3%) and removal of GAC from the filter for regeneration (9.7%). The sump traps not all this GAC and 2.3% of the total inventory is lost to the river. Inserting a sieve at the outlet of the sump can eliminate this loss. A further 80.3% of the GAC in a filter is removed for regeneration, of which 18.7% is lost during the regeneration process. The minimising off this loss can only be achieved through the optimisation of the regeneration process, which falls within the domain of the regeneration contractor.

The second part of the study was directed at the behaviour of the GAC whilst within the filter bed. The porosity and sphericity was determined by laboratory tests and calculations. The porosity was found to be 0.69 for the 12 x 40 size carbon and 0.66 for the 8 x 30 size carbon and the sphericity was found to be 0.67 for the 12 x 40 size carbon and 0.66 for the 8 x 30 size carbon. By using a calibrated bed expansion model, the bed expansion could be calculated at 9°C and 23°C for the two carbons gradings; the maximum temperature range experienced at Rietvlei. The main finding of this part of the study was that the average available freeboard is 650 mm for the 12 x 40 grading and 430 mm for the 8 x 30 grading, and therefore no GAC should wash over the weir at all during backwashing.

The third part of the study measured the physical changes of the GAC found at different points in the GAC cycle. The main findings were that the small fraction of GAC washed out of the bed during backwashing and removal has a finer grading, higher apparent density and lower adsorption capacity than the GAC in the filter bed. There seems to be no marked attrition of the carbon or generation of fines during the removal and transport of the GAC to the regeneration plant. After regeneration, there was a 7% decrease in apparent density and a 30% increase in adsorption capacity.

The final part of the study correlated the adsorption capacity of the GAC with its time in use as well as UV254 removal. After regeneration, UV254 removal begins at approximately 20% and declines to 14% after 400 days of operation, and to 10% after 600 days. After regeneration, the iodine number begins at approximately 800, declines to 600 after 400 days of operation, and to 500 after 600 days.



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LIST OF SYMBOLS

Symbol	Description
V_{mf}	Velocity of minimum fluidisation
ε	The porosity of the expanded bed L
ε_o	The fixed bed porosity
DF	Dilution factor – if run under standard conditions
M	Mass of carbon, g
V	Volume of water used (m^3)
$h_{supply/drain}$	Difference in level (m) in the supply and drain tanks
$V_{supply/drain}$	Volume of water used (m^3) for backwash
$A_{supply/drain}$	Area (m^2) of the supply and drain tanks
$Q_{backwash}$	Backwash rate (m^3/h)
Q_{rise}	Rise rate (m/h) of the backwash water
Δh_{rise}	Difference in level of each tank from time start to time stop from marker to marker
Δh	Difference in level of each tank
Δt_{rise}	Difference in time from marker to marker
t_{water}	Total time during which water was used (hours)
A_{filter}	Area of filter bed (m^2)
L_o	The bed depth at rest (m)
\emptyset	Diameter of the column (m)
L	The average depth (m) of the media after fluidisation
m_{cyl}	Mass of the cylinder (g)
V_s	Top-up required for each filter ($m^3/cycle$)
V_b	Backwash loss ($m^3/backwash$)
n_b	Number of backwashes / regeneration cycle
V_h	Handling loss ($m^3/cycle$)
η_s	Trap efficiency of the on-site sump (-)
η_r	Volumetric efficiency of the regeneration plant (-)
V_r	Volume removed to the regeneration plant ($m^3/cycle$)

d_{eq}	Grain size
g	gravitational acceleration
μ	dynamic viscosity (N.s/m ²)
ρ	water density (kg/m ³)
ρ_s	media density (kg/m ³)



CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Rietvlei Dam has been supplying the city of Pretoria with drinking water since 1934.

Through the years the population around the Hennops River has grown, and the quality of the water in the dam has deteriorated. For this reason the water treatment plant was upgraded in 1988, which improved the performance of the plant for some years. Because of extensive agricultural activities in the catchment area, increasing concentrations of nitrogen and phosphorus pass into the dam. These elements increased the growth of algae, especially in the summer seasons.

Van Staden (1996) did a pilot plant study for 192 days, on different auxiliary treatment possibilities at Rietvlei. Granular activated carbon (GAC) and ozone possibilities were investigated. His results indicated that an auxiliary GAC plant would be the optimum choice, when considering the economics and quality of the water. To improve water quality, particularly in terms of taste and odour caused by the algae, the GAC plant was built in 1999. The GAC plant was commissioned on 22 November 1999.



Upon commissioning, a year of close monitoring by De Kloe (2000) followed to measure the GAC performance at full-scale. After verification that the GAC does indeed ensure a high quality product under all conditions, the emphasis has now shifted to the optimisation of the GAC handling and regeneration system.

1.2 PROBLEM

The first indications were that the GAC losses are higher than originally expected, and that most of these losses occurred during the regeneration cycle. If these preliminary findings could be verified by more rigorous measurement and closer monitoring, it could have important implications for the specification of virgin carbon and the specification of future GAC regeneration contracts.

The relatively high operational cost is due to two main factors. Firstly, the activated carbon is expensive and its losses (which can never be completely eliminated) have to be minimised. Secondly, the activated carbon has to be physically removed from the filters from time to time, thermally reactivated off-site by a commercial concern, and placed back in the filter. Operational costs can be sharply reduced if the activated carbon is only reactivated when UV breakthrough point is reached.

The problem is to find the most cost-effective way to operate and maintain the process – once again in search for optimal local solutions, which may be substantially different from other places in the world where the process is operating. The GAC plant at Rietvlei is the only working plant of its kind in South Africa. There is currently no local data available on the expected losses during plant operations, handling and regeneration of the GAC, and when GAC should be removed.

1.3 OBJECTIVES

This dissertation will report on a number of systematic investigations carried out in response to the following practical questions that arose at Rietvlei:

- How should carbon be specified and how should selection criteria be weighted?
- What are the in-plant GAC losses due to washout, and how can the backwash cycle be modified should these losses be excessive?
- What are the GAC handling losses, and how can these losses be minimised?
- What are the GAC regeneration losses, and how can these be minimised?
- Which performance parameters should be used for the specification of GAC regeneration?
- When should a GAC cycle be terminated before the GAC is removed for regeneration? Should the water be continuously monitored, or should the remaining sorptive capacity of the GAC be measured periodically?

CHAPTER 2

LITERATURE STUDY - GAC

2.1 INTRODUCTION TO GRANULAR ACTIVATED CARBON

Activated carbon has long been recognised as one of the most versatile adsorbents for the effective removal of low concentrations of certain substances from solution. The use of charcoal, the forerunner of modern activated carbon, by ancient Egyptians for medical purposes and water purification dates back to 2000 BC (Faust & Aly, 1983). Activated carbon has the strongest physical adsorption forces or the highest volume of adsorbing porosity of any material known to mankind.

Granular activated carbon is used in different types of water treatment systems to remove chlorine, turbidity, dissolved organics, odour, taste, colour, and synthetic organic contaminants from water supplies. The high adsorptive capacity of activated carbon, the main reason for its widespread utilization, is attributed mainly to its highly porous structure, resulting in a relatively large surface area of up to 1500 m²/g (Faust & Aly, 1983; Kienle, & Baeder, 1980).

This renders activated carbon a suitable agent to support water purification processes for drinking water. Especially in South Africa, where water quality is deteriorating, activated carbon should find increasing application.

2.2 PRODUCTION AND ACTIVATION OF ACTIVATED CARBON

Activated carbon can be made from many substances containing a high carbon content such as bituminous coal, wood, nut shells, lignite, peat sawdust, bone and petroleum coke. As is true with any production process, the starting material influences the quality of the final product. In the past, activated carbons that were used for industrial applications were commonly produced from wood, peat, and other vegetable derivatives. Today, lignite, natural coal, and coke are the most frequently used sources of activated carbon due to their availability and attractive price.

The production of activated carbon involves a number of steps. Firstly, the raw material should be converted to a uniform particle size. By using techniques like high-pressure extrusion, pelletisation or agglomeration, one can influence the physical properties of the final product, such as granule size, particle size distribution, shape, roughness and hardness. Depending on whether the raw material contains carbohydrates or cellulose (e.g. wood), a second step, so-called carbonisation or pyrolysis, is introduced, whereby raw material is slowly heated in the absence of air to temperatures below 600°C to remove volatile pyrolysis products from the starting material. Finally the activation process takes place, during which the specific surface area of the carbon is increased by creating a microporous structure of tears, clefts and pores through a selective breakdown of the carbon.

The alternative to agglomeration is direct activation, which skips the initial steps and proceeds directly to crushing, sizing, baking and activation. Since the process must activate a relatively large granule completely from the outside, direct activation produces a granule with high surface activity on the outer shell and little surface area in the centre of the granule.

These two different activation processes produce GAC with different performance characteristics. The agglomerated process produces an activated carbon that is much denser and more resistant to abrasion. Also, the addition of the man-made pores and the well distributed activity of the agglomerated granule allow increased adsorption performance in many applications (Van Stone, Brooks, & Neulight, 1999).

One distinguishes between two different ways of activation. Firstly, chemical activation is used for non-charred (i.e. non-pyrolysed) raw material such as sawdust and peat. These materials are treated with dehydrating additives like zinc chloride or phosphoric acid at high temperatures in order to obtain a wide microporous system. Secondly, gas activation is used for charred raw materials like charcoal, peat coke and nutshell. By using either steam or CO₂ in a special furnace, like the most frequently used multiple hearth furnace at temperatures of about 800 to 1000°C, the oxidising agents selectively attack portions of the char and transform it to gaseous products. The

resulting hollow pores are systematically developed and enlarged (Zolf, Steenkamp, & Breet, 2000). The powder activated carbon is mainly produced by pulverization of the final product.

Along with the raw material, the activation process has a very large influence on the characteristics and performance of activated carbon (Chemviron Carbon, n.d).

2.3 THE STRUCTURE OF ACTIVATED CARBON

As a rule, the structure of the usual types of active carbon is tridisperse, i.e., they contain micropores, transitional (meso) pores, and macropores. According to Dubinin (1966) only a few of the micropores lead directly to the outer surface of the carbon particle. Most of the pore structures of the particles are arranged in the following pattern: the macropores open directly to the external surface of the particle; transitional pores branch off from macropores; and micropores, in turn, branch off from the transitional pores. The specific area of the micropores usually amounts to at least 90% of the total surface area (U.S. Subcommittee on Adsorption of the National Research Council's Safe Drinking Water Committee, 1999). The amount of each of these pores is very important to the type of particle being absorbed. For example, different size molecules will fill different size spaces in the structure. For the municipal water treatment industry, micropores are very important, as most of the particles removed from the water will be found there.

2.4 STANDARD CARBON SPECIFICATIONS

The selection of a suitable activated carbon is an integral part of the design of a carbon treatment plant. Although there are a fair number of manufacturers of granular activated carbon, many of their carbons are not necessarily suited for municipal water treatment. In addition, some carbons have an advantage over others in adsorption capacity, physical durability, operating characteristics, or cost. All candidates should be fairly tested by several criteria, since process cost depends upon much more than adsorbent cost. Product quality is, of course, a factor which may override cost considerations in some cases.

Firstly, carbons may be specified by their origin, for example:

ARCE Systems stocks the following

8 x 30 BC is size 8 x 30 bituminous coal based carbon

12 x 40 CS is size 12 x 40 coconut shell based carbon

Secondly, carbons may be specified by their adsorption capacities and physical properties.

Table 2.4.1 lists a number of standard carbon specifications of GAC, which relate to its adsorptive character and its use in operations. The data for these commercially available carbons was drawn from quotes from well-known GAC suppliers. The list of carbons is of course not all-inclusive and is merely intended to illustrate some physical properties and specifications (Van der Walt, 2001).



	UDEC		Chemimpo	Montan	Vivendi		Chemquest	Marlyn	BHT
	Aquasorb 1000	Aquasorb 2000	Norit 1240	Norinco	Filtrisorb 200	Filtrisorb 400	Diahope CQ 106	208 EA	PAU 2
Adsorptive capacity									
Iodine number (mg/g)	900	1020	1020	950	850	1050	1050	950	1100
Molasses number	n/a	n/a	230	n/a	177	243	280	250	n/a
Methylene blue number (mg/g)	220	260	200	230	200	260	190	250	n/a
Phenol value (kg/g)	45	55	20	n/a	61	68	56	n/a	n/a
Apparent density (kg/m³)	450	450	440	490	500	425	475	450	460
Particle size distribution	12 x 40	12 x 40	12 x 40	12 x 40 or 8 x 30	12 x 40	12 x 40	8 x 30	12 x 40	8 x 16
Moisture content	2%	2%	2%	5%	2%	2%	2%	5%	3%
Hardness	96%	95%	97%	90%	75%	75%	94%	95%	99%
Ash content	12%	12%	7%	14%	10%	10%	5%	15%	4%
Cost for 16m³ by Jan 2001*									
Cost per kg	R 7.82	R 8.72	R 14.58	R 8.72	R 12.76			R 11.30	R 12.93
Cost per m ³	R 3 519	R 3 575	R 6 417	R 4 273	R 6 380			R 5 137	R 5 952
Cost for 160m³ by 30/04/2001									
Cost per kg	R 7.82	R 8.72	R 13.68	R 8.95		R 13.86	R 12.57	R 11.30	R 13.68
Cost per m ³	R 3 519	R 3 575	R 6 022	R 4 386		R 6 009	R 5 973	R 5 137	R 6 293
Valid for time period	3 months	3 months		30 days	30 days	30 days	3 months	30 days	End Feb

*Including manufacturing, shipment cost, docking and all duty fees, rate of exchange forward cover, transport and handling cost and VAT.

Table 2.4.1: Specifications of several commercially available carbons

2.4.1 Adsorption

As stated before, activated carbon has a large volume of very small pores, which creates a large surface area. Adsorption is a process in which activated carbon removes an impurity from the liquid stream being treated, and refers to the accumulation of molecules or atoms on a surface, held there by chemical forces, electrostatic (physical forces - predominant or both). In the case of GAC, the adsorptive surface refers to the walls of the pores, which are formed inside the carbon particles during the activation process.

GAC adsorption is a time-related phenomenon that takes place in three steps. Initially, impurities in solution bump into the external surface of a carbon particle as the liquid passes through the GAC bed. Secondly, impurities, or adsorbates, diffuse into the pores of the carbon particle. The diffusion step in the process is the adsorption rate determining step. Finally, the impurity is attracted to the pore wall and held by electrostatic or chemical forces. The process is concentration driven and time dependent. Therefore, the highest loading of the impurity on the GAC, on a weight-percentage basis, will occur in the presence of high-contaminant concentrations and at times sufficient for the carbon to reach equilibrium.

The mass transfer zone (MTZ) refers to the area in a bed of activated carbon where adsorption occurs. It also is known as the adsorption wave zone, because it moves through the GAC bed as the carbon becomes spent. In an ideal single contaminant case, as long as the flow rate, impurity composition and concentration remain constant, the length of the MTZ remains fixed as it moves through the GAC bed. Breakthrough occurs when the leading edge of the MTZ, where impurity concentration is lowest, moves beyond the end of the GAC bed and vessel. (Naylor & Rester, 1995). But real world conditions are never that simple.

The characteristics of the carbon material (particle and pore size, surface area, surface chemistry, density, and hardness) influence the efficiency of adsorption. The characteristics of the chemical contaminant such as the tendency of the chemical to leave water are also important. Compounds that are less water soluble (hydrophobic) are more likely to be adsorbed to a solid. A second

characteristic is the attraction of the contaminant to the carbon surface. If several compounds are present in the water, strong adsorbers will attach to the carbon in greater quantity than those with weak adsorbing ability. These combined factors enable the activated carbon material to draw the molecule out of the water (Wagnet & Lemley, 1995).

2.4.1.1 Interference with the Adsorption Process

a. Total Organic Carbon

Total organic carbon (TOC) is the heterogeneous mixture of organic compounds including humic substances (humic acid and fulvic acid). These compounds are adsorbable and reduce the capacity of the carbon to adsorb the compounds of interest. However, some of the substances which comprise TOC are non-adsorbable, resulting in the immediate appearance of TOC in the effluent (i.e. breakthrough).

b. Iron and Manganese

Iron and manganese are known to cause fouling problems in filtration systems. Both may be oxidized by dissolved O_2 and precipitate within the GAC pores. Capacity loss is expected as pores become filled with oxidized minerals.

Accelerated degeneration of the carbon will also result if inorganic compounds are not removed from the carbon prior to regeneration. During successive GAC regeneration cycles, an increasing ash content may cause an accelerated degradation of the GAC structure, as indicated by decreasing iodine and molasses numbers. These changes may be attributed to the oxidation of the carbon structure, which may be catalysed by inorganic compounds such as Fe_2O_3 , CaO , and NaO .

c. Calcium Carbonate

Lime softened water or water supersaturated with calcium carbonate may result in the deposition of calcium carbonate on the GAC particle which could cement the filter grains together, cause an increase in grain size and a deterioration in water quality, or reduce the adsorptive efficiency of the GAC.

d. Biological Growth

Biological growth may occur within the filter, and, over time, may plug the filter resulting in increased operating pressures and requiring more frequent backwashing. However, microbial activity may extend the bed life for biodegradable compounds. Degradation of organic substances by microbial growth on carbon may contribute to improved removal of compounds including TOC and benzene.

e. Desorption

Adsorption is a dynamic and reversible process, and, as a result, desorption of contaminants may also occur. Desorption may result from:

1. Competition from more strongly adsorbing species.
2. Reduced influent concentrations, causing materials to be desorbed as a new equilibrium is established.
3. Destratification or mixing of the GAC, again causing carbon originally exposed to higher contaminant concentrations to establish a new equilibrium under a lower contaminant concentration.
4. Changes in water quality, such as pH.
5. Increases in temperature.

Desorption also has the effect of leaving additional capacity for periodic high concentrations of contaminants of incoming species (ARCE Systems Inc., 2000).

2.4.2 Measuring adsorptive capacity

2.4.2.1 Background

The surface areas available for adsorption in the porous structure of the activated carbon may be measured by several methods. The weights of different standard substances such as nitrogen gas, iodine, molasses, phenol, or methylene blue can be used to measure the surface availability in certain fractions of all the pores. Nitrogen adsorption by the Brunauer-Emmett-Teller (BET) method is a measure of the total surface area of a carbon granule. Used as a primary indicator of

the activity level, based on the principle that the greater the surface area, the higher the number of adsorptive sites available.

The other standard adsorbates are used to measure surface areas associated with pores of a given size. Iodine numbers are commonly used to measure regeneration efficiency since they are easier to run than BET tests. Iodine is adsorbed within relatively small pores and is thus a rough measure of total surface area. The iodine number coincidentally approximates the square metres per gram number from the BET test (Swindell-Dressler Company, 1971).

The International Union of Pure and Applied Chemistry (IUPAC) defines pore size distribution as:

Micropores $r < 1 \text{ nm}$

Mesopores $r = 1\text{-}25 \text{ nm}$

Macropores $r > 25 \text{ nm}$

The macropores are used as the entrance to the activated carbon, the mesopores for transportation and the micropores for adsorption.

2.4.2.2 Iodine number

Common Specifications:

Iodine Adsorption (mg/g), minimum:

500, 600, 800, 900 or 1000.

The iodine number provides an indication of the amount of micropores in carbon. It is defined as the milligrams of iodine (I_2) that are adsorbed per gram of carbon when the equilibrium concentration of the bulk saturation (C_{eq}) is 0.02 N. It is also correlated with the surface area in pores with diameters less than 10 Angstroms. Because iodine is a small molecule, it provides an indication of a particular carbon's capacity to adsorb smaller molecules. This gives a good indication of the condition of the carbon for water purification purposes.

This test was chosen to be the primary means to measure the adsorptive capacity of the carbon for during the investigation. The method was already being used by Rietvlei laboratories as well as the regeneration contractors.

2.4.2.3 Molasses number

Common Specifications:

Molasses number (mg/g), minimum:

170, 200, 220, 230, 250 or 280.

The molasses number represents the amount of larger pores in carbon. It is calculated from the ratio of the optical densities of the filtrate of a molasses solution treated with a standard activated carbon and one treated with the activated carbon in question. The molasses number can be correlated with the surface area in pores with diameters greater than 10 Angstroms. Because the colour pigments in molasses are large molecules, this information provides an indication of a particular carbon's capacity to adsorb larger molecules, particularly useful in the sugar industry.

2.4.2.4 Methylene blue

Common Specifications:

Methylene blue number (mg/g), minimum:

190, 200, 220, 230, 250 or 260.

Owing to molecular sieve effects, the accessibility of methylene blue (MW 394) is restricted to larger micropores and mesopores. Results appear to suggest that narrow micropores are more readily saturated by organic matter present in natural waters, while larger pores are still largely available even in field spent activated carbons regarded as being exhausted (San Miguel, Lambert & Graham, 2001). For this reason, this method was not used during the investigation except by the regeneration contractors.

2.4.2.5 Phenol value

Common Specifications:

Phenol value (mg/g), minimum:

110, 120, 150, 160 or 180.

For phenol number there are at least like three standard tests. The German standard DIN 19603 and there are two AWWA tests to cover powder and granular. But its been found to be a less sensitive test, and it will be effected by pH of the actual water used, i.e. at low pH phenol adsorption is much greater than at neutral or alkali pH.

2.4.3 Apparent density

Common Specifications:

Apparent density (kg/m³):

425, 450, 475, or 500.



The density of the carbon can be expressed in several different ways. The apparent density is the mass of carbon per unit volume, which can be packed into an empty column. This can also be given in terms of a wetted, backwashed and drained column. The real density is nothing more than the specific gravity of the carbon granule. The particle density is the mass of carbon per unit volume of granule, including pore volume.

Higher density GAC is preferred for several reasons. First, high density GAC products have more carbon structure. In addition, a denser product indicates that for each cubic metre of volume, more GAC can be installed. The denser material also provides a stronger material, which is better able to withstand frequent backwashing. With the limited space available in filters originally designed for sand filtration only, this becomes critical. Bituminous coal based GAC provides a much denser material as compared to lignite and sub-bituminous alternatives (Van Stone, Brooks, & Neulight, 1999).

There was a marked change in apparent density of the GAC during a regeneration cycle. For this reason, it was decided to keep on monitoring this closely during the investigation.

2.4.4 Particle size distribution

Particle size is expressed by several different parameters. In this instance the sieve specifications which characterise the carbons are U.S. Standard Sieve Series mesh numbers, e.g., 12 x 40, 8 x 30. The particle size distribution is measured by a sieve analysis in which a sample of GAC is passed through a succession of decreasing sieve sizes. The mass of carbon retained on each sieve is weighed and the cumulative mass passed by a given sieve is plotted against the mesh size of that sieve on a semilogarithmic plot. The designation denotes two sieve sizes, which describe the maximum and minimum size for the bulk of the material. For example, a 12 x 40 mesh GAC indicates that the bulk of the material would fall through a 12 mesh screen but be retained on a 40 mesh screen. Reading from such a plot, the sieve size which passes 10% of the total sample mass is the effective size. The 60% passing sieve size divided by the effective size gives the uniformity coefficient. The 50% passing sieve size is approximately the mean particle diameter, although this parameter can be obtained in other ways.

The uniformity coefficient is a dimensionless value that indicates the degree of uniformity of the GAC. A value of one (1) would indicate all particles are identical in size; greater values relate to a higher degree of variation. (Van Stone, Brooks & Neulight, 1999).

Initially, a 12 x 40 mesh GAC was the standard, as this size most closely approximated the effective size of sand. In an effort to retain the filtration properties but reduce head loss, the 8 x 30 product was introduced. This allowed for higher filtration rates and remains common in the municipal water treatment. This move to the larger mesh size prompted the development of even larger GAC products such as the 8x16 and 8x20 products. These have been effective in direct filtration plants, as they allow deeper beds and higher filtration rates with acceptable head loss.

The finer material has a higher rate of adsorption, but also a higher head loss per unit bed depth. Furthermore, since these beds have lower porosity, they have a greater tendency to foul by collecting colloidal materials from the water. Conversely, the 8 X 30 mesh has a lower adsorption rate, lower head loss per unit bed depth, and withstands regeneration with few losses (U.S. Army Corps of Engineers, 1986). It reduces losses during regeneration and greatly simplifies carbon column operation, at only slight loss in efficiency (Manangoly, 1994)

The GAC in a water filter is initially backwashed to segregate the granules. Following this backwash, the smallest granules will be at the top of the filter and the largest at the bottom. From a mechanical standpoint, the size of the GAC granules in the top part of the filter relates to the pressure drop and the filtration efficiency. The smaller the particle, the higher the pressure drop and the higher the filtration efficiency.

2.4.5 Moisture content

Common Specifications:

Moisture content (%), minimum:

2, 3 or 5% after regeneration, 50%+ before regeneration.

The percent by mass of water adsorbed on activated carbon. Some carbons may retain more water than others. This becomes important if the regeneration contract charges per kg wet carbon, instead of dry carbon.

2.4.6 Hardness

Common Specifications:

Hardness (%), minimum:

75, 85, 95 or even 99%.



The hardness number is the resistance of a granular carbon to the degradation action of steel balls in a Ro-Tap machine. It is calculated by using the mass of granular carbon retained on a particular sieve after the carbon has been in contact with steel balls.

Presently the best carbons for treatment of water appear to be those made from select grades of coal. These carbons are hard and dense and can be conveyed in water slurry with no appreciable deterioration. The physical strength of the carbon must be great enough to withstand the repeated handling required during regeneration (Manangoly, 1994)

2.4.7 Ash content

Common Specifications:

Ash content (%), maximum:

5, 10 or 15%

The mineral oxide constituents of activated carbon. It is normally defined as a weight percent basis after a given amount of sample is oxidised. Can be measured by the change in weight by burning a sample to constant weight at 800°C.

2.4.8 Abrasion number

Common Specifications:

≥ 78

Another physical parameter, which pertains to carbon performance in filter operation, is the abrasion number, which is a measure of hardness (see section 2.4.6). It is calculated by contacting a carbon sample with steel balls on a Ro-Tap machine and determining the percent ratio of the final mean particle diameter to the original mean particle diameter.

The abrasion number defines the GAC's resistance to abrasion and formation of fines, with a higher number indicating greater resistance. This parameter is important in municipal drinking water applications due to the rigors of routine backwashing that may rapidly degrade a softer GAC. When GAC is used for filtration, adsorption, and as a biological support media, this benefit is even more pronounced, as backwashing is required on a more frequent basis. Bituminous coal-based GAC offers the greatest resistance against abrasion as indicated by this measurement (Van Stone, Brooks, & Neulight, 1999).

2.5 BACKWASHING

The purpose of backwashing is to reduce the resistance to flow by disengaging solids that have been trapped in the bed. The rate and frequency of backwash is dependent upon the hydraulic loading, the nature and concentration of the suspended solids in the influent, the carbon particle size, and the method of contacting (upflow, downflow).

Backwash frequency may be determined by any of several criteria: buildup of headloss, deterioration of effluent turbidity, or at regular predetermined intervals of time (Swindell-Dressler Company, 1971).

At Rietvlei, the plant is controlled by an electronic supervisory_control_and_data_acquisition (SCADA) system. The system determines the backwash frequency by means of headloss, whereby valves keep downflow rate constant. When the valves are fully open, the system indicates the need to backwash.

Activated carbon filters do not differ from normal sand filters, as far as the valves, piping and appurtenances are concerned. However, the backwashing operation is different and special equipment is needed for the introduction and the removal of the GAC. For sand filters, a mixed air/water backwashing is used, but this treatment can cause floatation of the carbon particles and lead to high carbon loss. Consequently, water alone is normally used for backwashing.

The necessary backwashing velocity for most carbons is between 25 and 35 m/hr; however, this depends on the diameter and on the density of the carbon used. Accordingly, some flexibility for backwashing velocities are required because these properties can change during regeneration and they are known to vary with the GAC batch.

Another consequence of backwashing is that the stratification of the bed is destroyed. This influences the mass transfer zone within the filter and reduces the effectiveness of the carbon filter. Therefore, backwashing should not be done very often; although, some of the original integrity of the mass transfer zone can be maintained if a distribution of particle sizes is used. This is because once the bed is stratified after the first backwash, the stratification will remain as long as the backwashing velocity is decreased slowly, as the adsorption and biological growth do not effect carbon size or density.

If backwashing is performed carefully, it can be used to remove carbon fines, which are formed during reactivation. In addition, practical experience has shown that it is worthwhile to have a carbon trap for the backwash water, because this allows for the recovery of the carbon that could be lost because of too high backwashing velocity. Alternatively, large mesh screens on the wash water troughs have proven useful to prevent GAC loss during backwashing (Sontheimer, Crittenden & Summers, 1988).

It should be pointed out that as the temperature affects the viscosity of the water, the backwash rate must be adjusted to compensate for this temperature difference. For example, if the water temperature is 2 °C, a backwash rate of 24.5 m/hr would expand an 8 x 30 bed 22 %. If the water temperature increased to 24 °C, this backwash rate would expand the bed to only 10 %. In the summer months with the increased temperature of the water, the backwash rate typically needs to be increased to compensate for this viscosity effect (Van Stone, Brooks & Neulight, 1999).

Rietvlei experiences a temperature range of 9° - 23°C. The usual procedure is just a 10 minute backwash at approximately 20 m/hr, without an air scour. Also, to date, no stratification backwash is done, or a seasonal change of backwash rate.

2.6 REGENERATION FREQUENCY

At first glance, determining the regeneration frequency seems simple. For example: The GAC column or bed is exhausted when the effluent contaminant concentration equals or exceeds 95 % of the influent concentration (U.S. Army Corps of Engineers, 1986). But upon closer inspection, there are countless factors complicating this decision.

2.6.1 Breakthrough behaviour of activated carbon

The mass transfer zone (MTZ) refers to the part of the bed of activated carbon where adsorption occurs. It also is known as the adsorption wave zone, because it moves through the GAC bed as the carbon becomes spent. As long as the flow rate, impurity composition and concentration remain constant, the length of the MTZ remains fixed as it moves through the GAC bed.

Breakthrough occurs when the leading edge of the MTZ, where impurity concentration is lowest, moves beyond the end of the GAC bed and vessel (U.S. Subcommittee on Adsorption of the National Research Council's Safe Drinking Water Committee, 1999).

A typical breakthrough curve for DOC can be divided into five characteristic zones.

Generalisations can be made about each zone of removal, but there are often exceptions, which should be kept in mind before final conclusions are made. The results discussed here are similar to those reported by Roberts and Summers (1982), who quantified the breakthrough behaviour of nearly fifty data sets (Roberts, Summers & Regli, 1984).

Zone A: Immediate breakthrough

The value of the effluent concentration immediately after start-up is dependent on the concentration of the nonadsorbable organic substances and the process conditions. The EBCT, or bed depth and the diffusion kinetics of the weakly adsorbing compounds are variables that have an impact. Under normal operating conditions with (column) bed depths greater than 1.5 m and

filter velocities of 5 to 12 m/h, the immediate breakthrough will be comprised mainly of the nonadsorbing substances.

Zone B: High adsorption efficiency

After the immediate breakthrough, a time span of nearly constant effluent concentration can occur. The extent of this favorable filter behaviour depends mainly on the EBCT of the column and on the adsorbing capacity of the activated carbon for the weakly adsorbing substances in the water. For columns with short EBCTs or water with large percent weakly absorbable compounds, a rapid increase in effluent concentration will occur. After the immediate breakthrough, which is effected by the EBCT, an area of nearly constant effluent concentration is attained. The length of time of this high adsorption efficiency is a function of the EBCT, with longer EBCTs giving rise to longer times of high removal.

Zone C: Decreasing adsorption efficiency

This part of the breakthrough curve corresponds to the greatest change in the effluent concentration as the main part of the adsorption zone breaks through to the end of the column. The rate of decrease in the adsorption efficiency is affected by the adsorption equilibrium and mass transfer kinetics, as well as the EBCT.

The shape of the adsorption isotherm can determine the length of this zone, although for the adsorption of natural organic matter as measured by DOC, the influence of isotherm shape on the breakthrough is more difficult to interpret. In general, the transition from Zone B to this zone is determined by weakly adsorbing substances, while the length of this zone is a function of the more strongly adsorbing compounds.

Zone D: Low adsorption efficiency

During this part of the breakthrough curve, only a small part of the dissolved organics is removed by adsorption. The effluent concentration slowly increases with time, but this increase can be smaller than the fluctuations of the effluent concentration, which are due to the changes in the raw water quality and concentration. Several mechanisms have been proposed for the removal in this zone: a slow increase in biodegradation with time; slow adsorption into micropores; and the long term displacement of weakly adsorbing substances by strongly adsorbing substances. It is difficult to prove which mechanism is responsible for the removal and quite likely all three can contribute depending on circumstances. From a practical point, its not of critical importance, as the removal in this zone is normally quite small and column runs are often terminated before this zone is reached.

Zone E: Constant removal efficiency

The removal in this zone is attributed to biological degradation and adsorption is thought not to be directly contributing to the removal. Depending on the nature of the water and the pretreatment steps, this steady-state removal ranges between 10-35% (Roberts & Summers, 1982). Preozonation has been found to significantly improve this biodegradation.

The generalizations made in this qualitative survey on the typical zones of a breakthrough curve of a GAC column should not be taken too rigidly. The complexity and fluctuations of the influent raw water quality make such generalizations difficult. Helfferich (1962), a well-known researcher in the field of adsorption processes, came to the following conclusion:

The correct explanation of a breakthrough curve requires a lot of experience. Very often the conclusions are more typical for the theory used in the description of these curves than for the actual processes occurring

Qualitatively, the breakthrough of the precursors of trihalomethanes as measured by the total trihalomethanes formation potential (TTHMFP), is often similar to the breakthrough of dissolved organic carbon (DOC) and chemical oxygen demand (COD) (Sontheimer, Crittenden & Summers, 1988).

2.6.2 Displacement effects

Organics found in water supplies exhibit a wide spectrum of adsorption behaviour. Therefore, competition for adsorption sites should be expected. It is conceivable that the effluent concentrations of the more weakly adsorbed components could exceed the concentrations in the influent to the GAC bed if competitive adsorption occurred. Pilot plant studies have shown that effluent concentrations of chloroform and, possibly, 1,1-dichloroethane and trichloroethylene exceeded influent concentrations to the GAC bed; however, from existing data, it is not possible to distinguish a displacement effect due to competitive adsorption from that due to reequilibration with a changing influent concentration. Shifts in concentrations and composition of organics in the influent to the GAC bed, which then cause reequilibration, may be as important as competitive adsorption in determining effluent concentration. Because of the large number of organic components, mathematical predictions of treatment effectiveness for each component would be impractical, if not impossible.

Thus organic compounds in the water and their competitive interactions determine the frequency of GAC regeneration. The types and concentrations of organic compounds may vary widely among different locations and seasons of the year. Competitive interactions are complex and presently cannot be predicted without data from laboratory and/or pilot scale tests on the water to be treated (U.S. Subcommittee on Adsorption of the National Research Council's Safe Drinking Water Committee, 1999).

2.6.3 Removal of UV₂₅₄

The continuous determination of the organic content of a water by means of DOC analysis is time consuming and impractical on a plant where action needs to be taken quickly should circumstances warrant it. Due to this, a surrogate analysis for measuring of organic content in the water has been developed making use of ultra-violet spectrophotometry.

Many organic substances found in raw water exhibit the characteristic property of absorbing light in the ultraviolet (UV) and visible regions, wavelengths 10 to 400 nm and 400 to 800 nm, respectively. Most of the absorbance occurs in the near UV range of 200 to 400 nm. This UV-absorbance, due mainly to the stimulation of π -electrons, is characteristic for substances with carbon-carbon and carbon-oxygen double bonds. The UV-absorbance spectra of naturally occurring substances is featureless due to random interactions and the spectra monotonically decreases with increasing wavelength. Because of this featureless spectrum and for convenience, a single wavelength, often 254 nm, is preferred in UV-absorbance determinations of organic substances.

With the presently available spectrophotometers, the decadic spectral UV-absorbance $A(\lambda)$ is related to the ratio of the entering radiation flux to the exiting flux.

$$A(\lambda) = \log (\varphi_{\text{in}}/\varphi_{\text{ex}})$$

φ_{in} = entering flux of radiation

φ_{ex} = exiting flux of radiation

λ = wavelength (nm)



Including the path length of the cuvette d (m), the UV-absorbance yields the spectral absorption coefficient (SAC).

$$\text{SAC} = A(\lambda)/d$$

The SAC-values in this study are measured at a wave length of 254 nm with initially 5 cm and then later 1 cm cuvettes.

The percentage removal of organic content from influent to effluent measured at UV_{254} can be monitored.

2.6.4 Isotherms

The actual measurement (and prediction) of adsorption capacity is also complicated by the situation prevailing in filter operation. In batch operations, adsorption isotherms can give well-defined values for capacity. However, these values cannot be extrapolated to filter operations. For tertiary treatment applications, higher than predicted values of COD removal have been reported. The contribution of biological processes is responsible for these apparent high adsorption capacities. For this reason, the term 'removal capacity' is probably preferable to adsorption capacity (Swindell-Dressler Company, 1971). Isotherm tests on spent carbon are comparative, unreliable and time consuming (Kermeen, 2001).

2.6.5 Iodine number

As the carbon becomes saturated, the iodine adsorption capacity decreases, so the iodine number decreases. This may indicate the urgency to regenerate. Regeneration plants indicate that carbon iodine numbers should go no lower than 400 mg/l as it makes regeneration more difficult.



2.7. REACTIVATION AND REGENERATION OF ACTIVATED CARBON

2.7.1 Introduction

Once exhausted of their adsorption capacity, spent carbons can be landfilled, incinerated or thermally regenerated for reuse. Regeneration has become widely adopted in the last decade as it represents the most cost effective and environmentally sound option. However, the economics of this practice are highly dependent on the characteristics of the regenerated carbon and also to any mass losses during the process (Cannon et al., 1994; Roskill, 1994; Hutchins, 1973).

While the terms regeneration and reactivation are often synonymously used in the water treatment field, it is useful to distinguish between them based on their removal mechanism.

Regeneration occurs when the adsorbed molecules are removed from the carbon surface through desorption in their original or modified state without change in the carbon surface. During the reactivation process, the restoration of the adsorption capacity occurs through partial desorption and then the burn-off of carbonaceous residual on the carbon surface (Sontheimer, Crittenden & Summers, 1988).

The process of thermal regeneration involves a pyrolytic and an oxidative stage. The pyrolytic stage occurs when the spent carbon is exposed to temperatures up to 800°C under inert conditions. This results in the elimination of any volatile compounds adsorbed in the carbon porosity, including residual moisture, and the thermal decomposition of other less volatile compounds. A residue of char is formed from the adsorbed compounds, which occupies some of the carbon porosity. The oxidative stage involves the controlled gasification of the pyrolysed carbon at temperatures usually around 800°C in the presence of a mildly oxidising atmosphere, usually steam or carbon dioxide or a mixture of both. This results in the elimination of the charred residue and the exposure of the original carbon-pore structure.

The characteristics of the regenerated GAC are primarily determined by the conditions employed during the oxidation stage. The amount of char that is formed from the organic adsorbates determines the amount of material that needs to be oxidised. Process temperature and reaction time can be adjusted in order to control the extent of carbon gasification. The application of too mild conditions will not achieve the complete elimination of accumulated carbonised char and recovery of the carbon characteristics will not be maximised. However, the use of too severe conditions will result in damage to the original carbon structure and reduce yields (Juhola, 1970). Damage incurred during successive regeneration cycles has a cumulative effect on the carbon porosity and should therefore be minimised as much as possible.

The thermal regeneration of GAC exhausted with different organic species has been investigated by various researchers (Moreno-Castilla *et al.*, 1995; Ferrero-Garcia *et al.*, 1993; Waer *et al.*, 1992). Results reported by San Miguel, Lambert & Graham (2001) show that surface areas and adsorption characteristics could easily be restored, or even improved, when regeneration

conditions were optimised. Furthermore, under optimised conditions, the application of successive regeneration cycles did not appear to have any detrimental effect on the original porosity of the carbons.

2.7.2 Methods of regeneration

Methods to regenerate carbon include: passing low pressure steam through the carbon bed to evaporate and remove the adsorbed solvent; extraction of the adsorbate with a solvent; regeneration by thermal means; and exposure of the carbon to oxidizing gases. The most positive results of carbon regeneration are accomplished through thermal means.

The two most widely used reactivation methods use rotary kiln and multiple-hearth furnaces. In rotary kilns, carbon moves countercurrent to a mixture of combustion gases and superheated steam, with carbon recovery reportedly more than 90 to 95 %. Multiple hearth furnaces are heated to temperatures sufficient to burn off the carbon monoxide and hydrogen produced by the regeneration reaction. A shaft with rabble blades agitates the carbon to continuously bring fresh granules to the surface and move the carbon toward the hearth outlet opening. This process allows for carbon to be transferred from hearth to hearth.

System recoveries of 90 to 95 % are reported, with adsorptive capacity of the regenerated carbon similar to that of the new carbon. Closely controlled heating in a multiple hearth furnace is the most successful procedure for removal of adsorbed organics from activated carbon (Manangoly, 1994).

The carbon being investigated in this study was regenerated by means of the fluidised bed method and the continuous bed method:

2.7.2.1 Fluidised bed reactor

Fluidised bed reactors were used in the 1950's for carbon production and in the 1960's they were applied for the reactivation of spent carbon (Klein and Juntgen, 1984). By the late 1970 full-scale, fluidised bed reactors were used in West Germany to reactivate water treatment carbons using single-stage (Strack, 1976) and two stage (Poggenburg, 1978) reactors. The single stage reactor was used at the Benrath treatment plant in Wuppertal, West Germany and had a capacity of 200 kg/h. The residence time and bed height at constant carbon input was controlled by an effluent weir. The average residence time at 600°C was 45 minutes.

The two-stage reactor is used by the City of Düsseldorf, West Germany, to reactivate carbon at a capacity of 250 kg/h. The first stage is used for drying at 200 to 300°C and reactivation occurs in the second stage at 750 to 820°C for 20 minutes.

The advantage of fluidised bed reactors are: a) good mass transfer characteristics, which reduces energy costs; b) no moving parts, which contributes to low equipment and maintenance costs; and c) flexibility in terms of reaction conditions and carbon throughput. The major disadvantage of the continuously operated fluidised bed is back-mixing which causes a wide residence time distribution. This produces some particles that are underactivated and others that are overactivated, which yields losses in adsorption capacity and carbon mass, respectively. Multistage reactors help reduce this back-mixing, as does weir placement on the beds. For example, the two-stage reactor at Düsseldorf uses multiple weirs on the second stage. The carbon losses range from 3 to 12% depending on reactor configuration and the carbon quality (Sontheimer, Crittenden & Summers, 1988).

2.7.2.2 Continuous bed reactor

The temperature required for regeneration is generated within the carbon, by means of an electrical current passed through the carbon bed, rather than externally. This means that the transfer of energy to the carbon is virtually 100 per cent. The highest temperature prevails in the carbon, and not in the furnace structure, which leads to an increase in furnace life. The heating chamber can be made of insulating refractory materials, which are much better suited to the high

temperatures and corrosive environment within the furnace than the metal tubes used in other furnaces and kilns. Also, there are no heater elements that require frequent replacement.

The reactive process is based on electrical heating of the carbon in the presence of steam. The spent carbon enters via a feed hopper, passes through a furnace by means of gravity, and exits via a timed discharge device. An electrical current is passed through the carbon bed. This is controlled by means of thyristors (devices which control the current passing through the bed) to maintain the desired temperature profile in the bed. Steam enters the bed at the bottom to pass counter-current to the carbon flow. A distributor ensures even flow throughout the bed. Residual water vapour is driven off in a pre-heating step before the carbon enters the furnace. Volatiles and water gas (from the reactivation reaction) are driven off and combusted after leaving the furnace (Cactus Carbon, 2000).

2.7.3 Methods of quality control

2.7.3.1 Apparent density

The regeneration process may be monitored by reducing the apparent density of the carbon back to its virgin value. Larger apparent densities than the virgin value indicate an incomplete regeneration of the carbon and smaller densities are indicative of burning of the carbon (Swindell-Dressler Company, 1971).

2.7.3.2 Iodine number

Laboratory analyses can confirm the regeneration of the adsorptive capacity of the carbon by measuring the effective surface area of the carbon. Two measurements that may be correlated with the surface area are the iodine and molasses adsorption tests. (Swindell-Dressler Company, 1971).



2.7.3.3 Volatile content

The volatile content indicates the amount of organic matter being burnt off.

2.7.4 Reactivity and mass loss during thermal reactivation

According to San Miguel *et al.*(2000) experimental work showed that field spent carbons lost between 12 and 22 % of their mass when heated to 800°C under inert conditions (denoted as zero regeneration time). This was due mainly to the elimination of residual moisture but also the pyrolysis and volatilisation of organic compounds accumulated in the carbon porosity. This pyrolytic process also resulted in a significant reduction of the apparent densities of the spent carbons. Carbon gasification rates at 800°C were calculated at between 59.8 and 76.2 mg/min. The extent of carbon gasification (carbon burn-off) is the key parameter in the process of thermal regeneration. Assuming constant atmospheric conditions, the extent of gasification for a particular carbon is primarily dictated by furnace temperature and reaction time.

San Miguel *et al.* (2000) also found that as gasification proceeded to values in excess of 15 % burn-off, most spent carbons experience a progressive loss of microporosity and a rapid development of their external surface area which usually exceeded the levels in the virgin carbon. These effects have been associated with the conversion of micropores into mesopores due to the progressive burn out of pore walls. As a result, regenerated carbons experienced a reduction in their adsorption capacities for small molecular size compounds (such as phenol), but a gradual increase in their capacity to remove larger molecular-sized compounds (such as methylene blue) from solution.

2.7.5 Adsorptive capacity

Activated carbon contains chemically bonded elements such as oxygen and hydrogen. These elements can be contained in the starting material and remain as a result of imperfect carbonisation, or they can become chemically bonded to the surface during activation. In

addition, the activated carbon contains ash, which is not an organic part of the product. The ash content and its composition vary widely with the kind of activated carbon (Anderson and Emmett, 1947; Kipling, 1965). The adsorption by activated from solution is significantly influenced even by small amounts of ash (Blackburn and Kipling, 1955).

Carbon may adsorb significant quantities of various metals that can become incorporated in the carbon structure during regeneration procedures. Thus, the recycling and regeneration of carbon can result in a material significantly different from the virgin activated carbon.

Combustion of the adsorbed organics is never really complete. The nett losses have been measured by English *et al*, (1970), for the Pomona pilot plant in a tertiary treatment application. In a four-stage system, the percent removal of dissolved COD in the lead contactor declined from 89 to 71% in two complete regeneration cycles, but thereafter remained virtually constant at 70%. This included the effect of make-up carbon. In a single stage system, the corresponding loss was from 53% to 47% (Swindell-Dressler Company, 1971).

2.7.6 Losses during regeneration

2.7.6.1 Regeneration of the carbon

The regeneration actually burns some of the carbon away and there will be a mass loss. Over successive reactivation this will result in more fragile carbon which will break into smaller particles, resulting in a loss of carbon volume and a higher loss during backwashing (Pryor, 2001).

2.7.6.2 Typically reported losses

- The Wastewater Technology Fact Sheet, Granular Activated Carbon Adsorption and Regeneration, EPA 832-F-00-017, September 2000, reported: Approximately 5 to 10 % of the carbon is destroyed in the regeneration process or lost during transport and must be replaced with virgin carbon.



- The Process Design Manual for Carbon Adsorption for the EPA, Swindell-Dressler Company, October 1971 indicated if a 5 % loss of carbon per regeneration cycle is assumed, then most of the carbon originally in use will have been replaced after 20 cycles.
- DeMarco et al. (1983) reported total losses (transport plus loss in the furnace) of 16 to 19 % in an experimental system in Cincinnati, while Koffskey and Lykins (1987) observed a 9 % loss (7 % in the furnace and 2 % during transport).

2.8 CARBON TRANSPORT

In early plants, transport of carbon was by mechanical means such as conveyors. However, recent installations have successfully utilized hydraulic systems to pump the GAC in a water medium since movement of liquids in pipe lines is inherently easier than transport of solids by mechanical means. The hydraulic transport of carbon is accomplished by pumping the mixture at a high enough velocity to create sufficient turbulence in the pipeline to prevent the particles from settling and collecting along the bottom of the pipe.

The maximum concentration for such a transport in water is about in the range of 280 kg/m³, but a somewhat lower density is recommended to prevent clogging. Waterworks use about 3 m³ of water/m³ of carbon and this gives GAC slurry densities of about 120 to 180 kg of GAC/m³ (Poggenburg, 1978; EPA Manual, 1973). The transport velocity for the suspension should not be lower than 1.2 m/s and not be higher than 3 m/s. Lower velocities lead to sedimentation and clogging and higher velocities may lead to abrasion and to erosion corrosion, especially at the curves of the pipes (Sontheimer, Crittenden & Summers, 1988).

Pilot plant tests (Harris, 1966) indicate that after an initial higher rate, the rate of attrition for activated carbon in moving water slurries is approximately constant for any given velocity, reaching an approximate value of 0.12% fines generated per exhaustion-regeneration cycle. This continual deterioration of the carbon with cyclic operation has been reported to be independent

of the velocity of the slurry (within the range recommended previously). Losses of carbon by attrition in hydraulic handling are not related to the type of pump (diaphragm or centrifugal) used.

In most installations, the spent carbon is transported in excess water, and as much of this water as possible must be removed prior to feeding this material to the regeneration equipment. Tests have indicated that dewatering of the spent carbon slurry can be successfully accomplished mechanically (screens, classifiers, forced air) or by gravity. In commercial installations, slurries have been dewatered to 45-55% moisture content by gravity drainage in a tank if sufficient area and time are allowed. Normally 1 hour is sufficient to provide an economically justifiable reduction of the moisture content (EPA Manual, 1973).



CHAPTER 3

LITERATURE STUDY - RIETVLEI

3.1 RIETVLEI DAM

3.1.1. Location, catchment area and hydrology

Rietvlei Dam is situated on the Hennops River, 25.87°S and 28.26°E, approximately 15 km southeast of Pretoria. Its catchment, covering an area of 481 km², extends predominantly southeast to include Kempton Park's northeastern peri-urban area (See figure 3.1). The Johannesburg International airport forms the catchment's eastern boundary (Van der Walt *et al*, 2000). The average evaporation of the area is 968 mm per year and the average rainfall is 675 mm per year. The mean annual runoff (MAR) is 10.5 million m³.

Rietvlei Dam was completed in November 1933 and has a working capacity of 12.2 million m³. The average depth of the dam is 6.1m and the total area is 187 ha. The siltation rate is relatively low; only 5.2% of the capacity was lost after 44 years of operation.

The Hennops River is the major drainage channel in the catchment area, but other smaller non-perennial streams connect to the river. The river flows into the marshy area a few kilometres east of Kempton Park and passes through a wetland before it receives the outflow of the Kempton Park sewage works. After this it flows through a stretched out marshy area and the Marais Dam in the Rietvlei Nature Reserve, before it flows into the Rietvlei Dam (Van Staden, 1996 & Van der Walt, 2000).

An additional supply of water comes from four springs within the Reserve, from one spring on the adjoining private property, and from five boreholes in the Reserve. Today Rietvlei Dam and its environs provide 26% of Pretoria's water requirements.

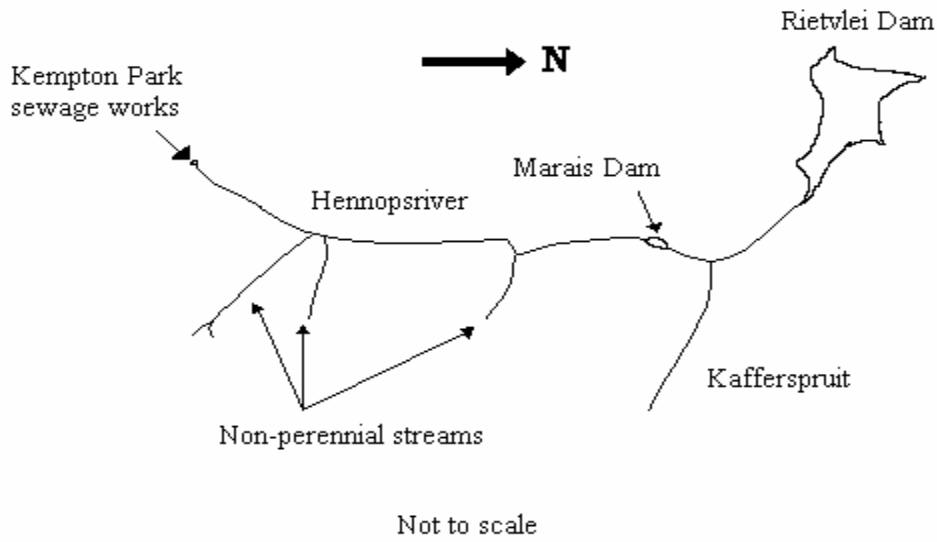


Figure 3.1 Catchment area of Rietvlei Dam



3.2 NECESSITY FOR FURTHER UPGRADING

The City Council of Pretoria started using the Rietvlei Dam as drinking water source in 1934. The original treatment plant process configuration consisted of; aluminium sulphate dosing, lime stabilisation, baffled channel flocculation, sedimentation in rectangular tanks, rapid sand filtration and disinfection. This process worked well for approximately 50 years until it was upgraded in 1988. The process was then augmented with dissolved air flotation in 1988 (DAFF added, settling omitted).

During 1994, the Pretoria Metropolitan Substructure launched a comprehensive study of Rietvlei Dam to consider the available management options to ensure the long-term viability of the Rietvlei system as a source of economical, high quality drinking water to the citizens of Pretoria.

This study was completed in 1996 and the conclusion was that the quality of the water in Rietvlei Dam has deteriorated considerably over the last 20 years. This was attributed to increased effluent discharges into the catchment, poorer sewage effluent quality and the reduction in natural runoff, which dilutes and flushes out pollutants.

The following problems were found in the 1994 study:

- The algae growth potential increased dramatically during the previous five years as measured by phosphate and ammonia. The ratio of phosphate and ammonia had developed to the point where the conditions favoured the growth of bluegreen algae (which can lead to odours, tastes and toxins).
- Work done in the seventies showed that the valley area further up in the stream worked as 'nitrogen filter', which eliminated most of the ammonia. This caused Rietvlei Dam to be nitrogen limited, which differs from most South African dams which are phosphate limited.

- Data from 1988 – 1993 showed that extensive amounts of nitrogen was being pumped into Rietvlei Dam and it seemed as though the wetlands areas had somewhat lost their potential to remove the nitrogen.
- The high concentration of ammonia reached by the plant caused the chlorine dosing to be insufficient to deliver at full capacity when the ammonia levels reached their peaks.
- The taste and odour problems are greatly due to the blue-green algae, which had replaced the previously dominating green algae. (Van Staden, 1996).

The presence of nuisance compounds like geosmin and 2-Methylisoborneol (MIB) in drinking water often leads to consumer complaints. Unfortunately, toxic compounds like microcystin may go by unnoticed. Very few water treatment plants in South Africa are equipped to remove such troublesome compounds as unit treatment processes for the removal of taste and odour compounds and other algal metabolites are usually not installed. This is because the problems normally occur sporadically or seasonally. There is seldom any associated health risk and treatment costs are high.

People are also increasingly concerned about contaminants in their drinking water that cannot be removed by water softeners or physical filtration. Solvents, pesticides, industrial wastes, and leaking underground storage tanks are some sources of this contamination. The reaction of chlorine with organic matter during the chlorination of drinking water can produce other compounds such as trihalomethanes as by-products, which may increase the risk of certain cancers (Wagnet & Lemley, 1995).

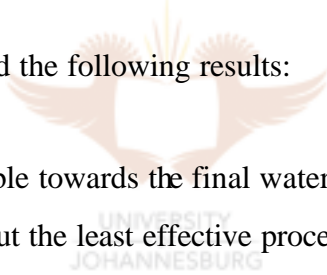
3.3 PILOT PLANT STUDY (VAN STADEN, 1996)

The pilot plant study consisted of three columns operated in series and in downflow mode, each with an empty bed contact time (EBCT) of 3 minutes. Samples were collected after each column and analysed for indicators such as DOC, COD, UV adsorption, chlorine demand and turbidity.

The study had the following objectives:

- To measure the improvement in treatment efficiency by granular activated carbon filtration, by operating a battery of pilot plant filters for six months;
- To measure the improvement in treatment efficiency by pre-ozonation, by conducting periodic batch tests;
- To project the improvement in treatment efficiency by ozone in conjunction with granular activated carbon filtration, by literature review of work done elsewhere;
- To propose, from above findings, practical design parameters for the improvement of the Rietvlei Water Treatment Plant; and
- To prepare preliminary design and cost estimates for recommended improvements (Van der Walt, 2000).

The pilot plant investigation showed the following results:

- 
- All these processes are favourable towards the final water quality
 - Pre-ozonation is the cheapest, but the least effective process for the improvement of the final water.
 - A combination of ozone and granular activated carbon is the most expensive but will deliver the best improvement in water quality.
 - Activated carbon is the optimum process if both cost and water quality are considered.
 - The final proposal is the implementation of activated carbon with an empty bed contact time of 10 minutes (Van Staden, 1996).

In parallel with this fundamental research, an extended study tour was undertaken to Europe to investigate the different possibilities of carbon handling and regeneration, and how to adapt these technologies to local conditions (De Kloe, 2000).

3.4 BACKGROUND OF ACTIVATED CARBON USE AT RIETVLEI

The treatment plant had the capability to dose powder activated carbon (PAC) in emergencies, but was still not able to cope with lengthened intensive incidents of taste and odour. The question arose whether to continue dosing with PAC or build an auxiliary facility like a granular activated carbon (GAC) plant.

In terms of capital cost, the PAC is preferable as current flocculation processes could be used for contact time (which would be greater than the 10-20 minutes GAC contact time), where as with GAC the capital costs could be extensive, as building of tanks, pipe work etc would be required.

In terms of operating cost, GAC is preferable as it could effectively be regenerated and reused. The adsorption property of the carbon could also be used to its fullest, where as this would not be the case with the PAC because it is only placed through the system once (De Kloe, 2000).

3.5 DESIGN CONSIDERATIONS

3.5.1 Site restrictions

As the GAC filtration module is an add-on process to the existing water treatment plant, cognisance had to be taken of the site restrictions and required hydraulic considerations. The plant before upgrading had inlet works, the flocculation step and then the dissolved air flotation and sand filtration process. After filtration, the water gravitated to a reservoir where chlorination took place.

For incorporation of the new GAC filter block, it was therefore required to add additional height to the system. A screw pump was thus installed between the old sand filters and the new GAC filters and a bypass line to the existing clear water reservoir constructed.



3.5.2 Mode of operation / filtration

GAC contacting is normally carried out in a system with one or more adsorbers / filters. These filters can be columns or open gravity concrete filters and can be operated in a number of configurations such as countercurrent moving bed, expanded bed upflow and fixed bed downflow. The choice fell on a parallel system using the downflow fixed bed mode of operation.

As with the choice of adsorber type, bed depth design criteria vary and bed depths can be 3 – 5m. These depths are however more applicable to columns and pressure filtration. For open beds, bed depths should not be less than 1m to minimise short-circuiting and dead spots in the beds. A filter bed of 1.4m was chosen, with an EBCT of at least 10 minutes. The maximum filtration rate, achieved when 18 out of the 20 filters are in operation is 9m/h.

3.5.3 Type of activated carbon

There are numerous activated carbons available for GAC applications – each carbon with properties making it more suitable for certain applications than others. It was therefore important to establish the most cost-effective carbon for use taking into account the initial cost, hardness of the carbon and its adsorptive properties. A tender for the supply of GAC was called for with the prospective tenderers required to indicate key parameters of the GAC such as iodine number, hardness, ash content and density. A 12 x 40 coal based carbon, 208EA from Sutcliffe Speakman was chosen to be the most cost effective carbon and loaded into the filters.

3.5.4 Contact time and usage rate

The EBCT was selected on the basis of the pilot plant performance. Another important element is also the carbon usage rate (CUR), i.e. how often will regeneration be required. The pilot plant study indicated no signs of carbon exhaustion after 200 days. This was confirmed by performing isotherm tests, indicating that the carbon should be regenerated after approximately 16 months.

3.6 OPERATIONAL CONTROL

3.6.1 Transfer system

As activated carbon filtration is a physical process using available space inside the carbon, the carbon will become exhausted over a period of time. In order to make GAC economically feasible, the exhausted carbon must be regenerated and reused. A removal system was therefore provided as well as enough storage space for the storage of GAC for a short period on site before the carbon is taken to a suitable regeneration facility.

The placing system consists of a slurry bin in the GAC handling facility where the carbon is discharged to. At the bottom of the bin, the motive water pumps create a venturi where after the GAC slurry is conveyed to the applicable filter by means of a piping system. It takes approximately 5 hours to transfer 7.5 tons of GAC from the loading facility to a filter. The general practice in European countries for extraction is using vacuum tank trucks and pumping the GAC slurry directly into these for transport to the regeneration facility. In South Africa these facilities are not available. A new transport system had to be developed. For the extraction of the carbon from the filters, use is made of a slurry pump for suction of the GAC from the bed. The suction end is a manifold, designed such that only a slurry concentration of about 15% is allowed in the piping system. The GAC slurry ends up in a storage bin where the slurry is dewatered and the GAC transferred into 1m³ bags for transport to the GAC regeneration facility (Van der Walt et al, 2000).

3.6.2 Monitoring of the system

Upon commissioning, a year of close monitoring by De Kloe (2000) followed to measure the GAC performance at full-scale. The average GAC colour-, turbidity- and UV removal (as a percentage of the DAFF water) was calculated and compared with the percentages obtained from the pilot plant study.

For the time ranging between January to September 2000, the average colour removal of the actual plant was 13% less than the pilot plant study, the average turbidity removal of the actual plant was 68% greater than the pilot plant study and the UV removal of the actual plant was 61% less than the pilot plant study (De Kloe, 2000).



	Raw water		DAFF water		GAC water	
	Never greater than	Never less than for 50% of the time	Never greater than	Never less than for 50% of the time	Never greater than	Never less than for 50% of the time
Colour	70 Hazen	22 Hazen	20 Hazen	11 Hazen	18 Hazen	8 Hazen
pH	9	8.2	8.3	7.5	8.3	7.5
Conductivity	0.56 mS/m	0.33 mS/m	0.43 mS/m	0.33 mS/m	0.4 mS/m	0.28 mS/m
Temperature	23 degrees C	16 degrees C				
Turbidity	17 NTU	1.8 NTU	2.5 NTU	0.38 NTU	1.13 NTU	0.18 NTU
UV Adsorption	2.21 adsorption/cm	1.15 adsorption/cm	1.20 adsorption/cm	0.80 adsorption/cm	1.00 adsorption/cm	0.65 adsorption/cm

% removal between % removal between
 DAFF and GAC water Raw and DAFF water

	Less than for 50% of the time	Less than for 50% of the time	Average removal Pilot plant	Average removal Actual plant
Colour	52%	46%	53%	46%
Turbidity	79%	57%	34%	57%
UV Adsorption	31%	20%	51%	20%

(De Kloe, 2000)

Table 3.6.1 Water quality data – year of monitoring

3.7 COST AND PROGRAM

The cost for implementing activated carbon filtration as part of the treatment train for the production of potable water from the Rietvlei Dam was R20.4 m. It was estimated that the operating cost for the GAC filters would be 23c/m³ of water treated.

Construction of the activated carbon filtration block commenced in August 1997 and commissioning of the filters was done towards the middle of 1999 (Van der Walt, 2000).

3.8 DETERMINATION OF THE MOST COST EFFECTIVE GAC FOR THE RIETVLEI WATER TREATMENT PLANT

Since the GAC plant at Rietvlei, Pretoria was put into operation in August 1999, a number of the filters have been regenerated. During the regeneration phase and also during the removal of the carbon and the operations of the filters, losses of carbon have been experienced and preliminary indications are that these losses could be as high as 30% during one regeneration cycle. As part of the contract for the supply and delivery of GAC in 1999, additional carbon was supplied to counter the losses of the GAC during the regeneration. This additional carbon had been exhausted by January 2001 and it was required to ask for new quotations for the supply and delivery of new GAC. A number of well-known GAC suppliers were consequently contacted to provide the Municipality of Pretoria with these quotations.

All the suppliers were asked to present a sample of the proposed carbon with their quotations for laboratory tests to be performed on them. These tests were required in order to determine the suitability of the carbon for the removal of the target compounds. The parameters measured for removal were UV254, colour and dissolved organic carbon (DOC). A series of isotherm tests were conducted on the carbons in the laboratory in order to determine the ability of a specific carbon to remove targeted compounds.

From the results obtained it was recommended that:

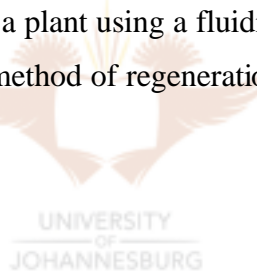
Two carbons, the Jacobi Aquasorb 2000 and the Montan Norinco be purchased. It was furthermore foreseen that another batch of carbon would be required by around April 2001. As the Jacobi carbon had a shorter delivery period than Montan carbon, it was recommended that this carbon be purchased first.

Due to the losses experienced by the current 12 x 40 carbon, a 8 x 30 size carbon was purchased as the regeneration plant had experienced less losses with the bigger size carbon..

A monitoring program be implemented on three filters, namely one filter with the virgin Jacobi carbon in it, one filter with Montan carbon in it and one filter with regenerated carbon (Van der Walt, 2001).

3.9 CHANGE OF REGENERATION METHOD

Previously, the GAC was regenerated at a plant using a fluidised bed reactor. At the end of July 2001, a plant using the continuous bed method of regeneration won the tender for regeneration. Both these methods are explained later.



CHAPTER 4

MATERIALS AND METHODS

The following table gives a clear account what tests were conducted and by who they were conducted:

TESTS ON GAC

	Porosity	Density	Iodine nr	Apparent density	Sieve analyses	Volume	Bed expansion
Own measurements	yes	yes	no	yes	yes	no	yes
Rietvlei operational staff	no	no	yes	no	no	yes	no
Regeneration contractor	no	no	yes	yes	no	yes	no

TESTS ON WATER

	UV	Colour	Rate of rise
Own measurements	no	yes	yes
Rietvlei operational staff	yes	yes	no
Regeneration contractor	no	no	no

Table 4.1.1 Test conducted on the carbon and the water by the researcher, Rietvlei laboratories, and the regeneration contractor

All operational data, including backwashing and regeneration logs, kept by the plant were gathered and investigated.

4.1 LOSSES MEASUREMENTS

A sieve was placed in front of the outlet of the backwash water during the backwash and the channel in front of the outlet was cleaned before and after backwash. In this way the GAC lost during backwash was measured. This was done once for both the 12 x 40 (filter 1) and 8 x 30 (filter 2) size carbons (Extremely labour intensive with disruption to normal operations).

The volume of GAC lost every time GAC is removed from a filter to be regenerated was checked by one spot measurement. A sieve was introduced in the sump overflow line, which effectively changed the trap efficiency to 100%. The sump was then cleaned, and the GAC of one filter was removed. The sump was cleaned directly after this again, thus directly measuring the GAC lost.

To evaluate the performance backwash procedure the following tests were done:



4.2 EVALUATION OF BACKWASH DISTRIBUTION AND MEASUREMENT OF MEDIA EXPANSION

4.2.1 Introduction

This method contains procedures for determining the magnitude of filter bed expansion during backwash. It also involves procedures for the visual evaluation of the bed during backwash.

4.2.2 Theory

To calculate the percent expansion:

$$\% \text{ expansion} = \frac{\text{level of rise}}{\text{total media depth}} \times 100\% \dots\dots\dots(1)$$

where the total media depth excludes the gravel layer.

4.2.3 Apparatus and reagents

- Bed expansion tool (panpipe)
- 3m of 20 mm galvanised pipe (to support the expansion tool)
- One pipe or rod (long enough to stir the media during backwash, \pm 3-4 m)

4.2.4 Analytical procedure

This method was taken from WRG (2000).

- The filter needs to be completely drained.
- Place the media expansion tool on the surface of the media, at a location where it can be firmly secured to the supports.
- Backwash the filter.
- Observe the distribution of the backwash turbulence over the entire filter bed during the entire cycle. Report any boils or dead spots and the approximate location thereof on a sketch.
- Poke and stir the boils and dead spots. Avoid doing this in the vicinity of the expansion tool. Be careful not to damage the filter drainage system. Report whether this influences the distribution of the turbulence.
- After the backwash is completed, drain the filter.

- Remove the tool and determine the level to which the medium rose during backwash. This is determined by the length of the tallest tube completely filled with media. Record the value in mm.

- If any boils or dead spots could not be remedied during the test, further investigation is required to establish the causes thereof.
- Record the total depth (D) of the media bed, excluding the gravel layer.

4.3 MEASUREMENT OF BACKWASH RATE AND SEQUENCE

4.3.1 Introduction

This method contains procedures for the measurement of backwash rate and sequence.

4.3.2 Theory

- To calculate the difference in level of water (in meters) in the supply and drain tanks:

$$h_{\text{supply}} = h_{\text{before}} - h_{\text{after}} \dots\dots\dots (1)$$

$$h_{\text{drain}} = h_{\text{after}} - h_{\text{before}} \dots\dots\dots (2)$$

To calculate the volume of water (in m³) used for backwash from the rise in levels:

$$V_{\text{supply}} = h_{\text{supply}} \times \text{Area}_{\text{supply}} \dots\dots\dots (3a)$$

or

$$V_{\text{drain}} = h_{\text{drain}} \times \text{Area}_{\text{drain}} \dots\dots\dots (3b)$$

- To calculate the volume of water (in m³) used in a typical backwash, as measured by an online flow meter:

$$V_{\text{flowmeter}} = \text{reading}_{\text{after}} - \text{reading}_{\text{before}} \dots\dots\dots(4)$$

- To calculate the backwash rate (in m/hr) using the volumes calculated above:

$$Q_{\text{backwash}} = \frac{V}{A_{\text{filter}} \times t_{\text{water}}} \dots\dots\dots(5)$$

where

V = volume of water used (m³)

t_{water} = total time during which water was used (hours)

A_{filter} = area of filter bed (m²)

- To calculate the rise rate (in m/hr) of backwash water using the observations from the rate-of-rise tool:

$$Q_{\text{rise}} = \frac{\Delta h_{\text{rise}}}{\Delta t_{\text{rise}}} \dots\dots\dots(6)$$

4.3.3 Interferences and sources of error

- The rate of rise tool will be observed from the walkways during backwash. In order to effectively read off the level of the water as the operation progresses, it is important that the graduations on the tool be clearly marked.
- Foam on the surface of the backwash water makes the time measurement difficult.

4.3.4 Apparatus and reagents

- Rate of rise measuring tool (a yard stick that can be securely attached during backwash)
- Stop watch

4.3.5 Analytical procedure

- The filter must be completely drained to allow access to a suitable point on the surface of the bed from which the rate of rise tool can be positioned and attached.
- Record the wash water meter reading (in m^3), the wash water supply tank level (in m) and the wash water drain tank level (in m), if possible and applicable.
- Start the backwash and be ready to start timing the respective stages in the cycle.
- Time the duration t (in sec) of each agent (water, air) during each stage.
- Observe the rise (h_{rise}) of the water on the tool at 30-second intervals during any stage.
- At the end of the backwash, record the wash water meters' readings, the wash water supply tank level and the wash water drain tank level, if possible and applicable.
- Record the area (m^2) of the filter bed, supply and drain tanks.

4.3.6 Calculation of results

To check the accuracy of the backwash water flow meters:

- Calculate the difference in level (Δh) of each tank using the Equations 1 and 2.

- Calculate the volume of water (V) used in total, using Equations 3a, 3b and 4. Compare the results. The three volumes should be the same.
- Add the times during which water was used for backwash (t_{water}) and express in “hours”.
- Using Equation 5, calculate the backwash rate (Q_{backwash}) using the three volumes calculated in 7.2. Compare the results. The results should be the same.
- From the time-rise data obtained, calculate Δt_{rise} (convert to hours) and Δh_{rise} (convert to m) between any two pairs of data recorded.
- Now using Equation 6, calculate the rise rate (Q_{rise}) as measured by the tool. Compare with the results from 7.4.

4.4 MEDIA FLUIDISATION AND EXPANSION

4.4.1 Introduction

This method outlines the determination of the relationship between filter bed expansion and backwash flow rate using a test column.

4.4.2 Theory

The determination is carried out on the same column used for the previous method.

Equation 1 below is useful in calculating the percentage expansion of the bed during backwash at a given flow rate.

$$\% \text{ bed expansion} = \frac{L - L_o}{L_o} \times 100 \dots\dots\dots (1)$$

where L = the expanded bed depth
 L_o = the bed depth at rest

There exists a relationship between bed expansion and porosity. This relationship is described by Equation 2 below.

$$\frac{L}{L_o} = \frac{1 - \epsilon_o}{1 - \epsilon} \dots\dots\dots (2)$$

where L = the expanded bed depth
 L_o = the bed depth at rest
 ϵ = the porosity of the expanded bed L
 ϵ_o = the fixed bed porosity

There also exists a relationship between head loss and backwash velocity. Thus by measuring the head loss through the bed using manometer tappings, a graph can be plotted relating the head loss to the backwash flow velocity.

4.4.3 Apparatus and reagents

- A test column similar to that used in the previous method.
- Backwash water supply (with flow control valve and flow measurement device).

4.4.4 Analytical procedure

- Close the valve on the inlet to the column.
- Record the bed depth at rest (L_o) of the media at rest in the column.
- Gently open the valve on the backwash line, allowing water to enter the column.
- The flow needs to be gradually increased in increments throughout this determination. Take note of the following measurements and observations throughout this process.
 - Record the flow rates (V) in l/hr as increased incrementally and the corresponding differential headloss in 'mm' through the bed as read of by the manometer.
 - Record the expanded bed depth (L) in 'mm' corresponding to each incremental increase in flow rate. If there is no increase at the start of the process, note the bed depth as equal to the initial bed depth.
 - As the flow rate is increased, observe the media in the column for the start of fluidisation.
 - Record the flow rate (V_{mf}) at which fluidisation starts, referred to as the point of minimum fluidisation.
- Continue in this manner until the media in the column occupies about 75% of the total column depth.
- Gradually decrease the backwash flow until the valve is completely closed.

4.4.5 Calculation of results

Use the equation given earlier to calculate the % bed expansion at each corresponding flow rate.

Sample calculation

INITIAL BED DEPTH, L_o (mm)	450
EXPANDED BED DEPTH, L (mm)	FLOW RATE, V (l/hr)
450	50
460	60
475	80

$$\begin{aligned}
 \% \text{ bed expansion at } 60 \text{ l/hr} &= \frac{L - L_o}{L_o} \times 100 \\
 &= \frac{460 - 450}{450} \times 100 \dots\dots\dots (3) \\
 &= 2.22\%
 \end{aligned}$$

Plot a graph of % expansion versus backwash flow rate.

Calculate the porosity (ϵ) associated with each expanded bed depth (L) using Equation 2. For the fixed bed porosity (ϵ_o), use the value obtained from the column test.



Sample calculation

INITIAL BED DEPTH, L_o (mm)	450
FIXED BED POROSITY, e_o	0.49
EXPANDED BED DEPTH, L (mm)	FLOW RATE, V (l/hr)
450	50
460	60
475	80

For 80 l/hr, making ϵ the subject of the formula in Equation 2 yields the following:

$$\begin{aligned}
 \varepsilon &= 1 - \frac{L_o}{L}(1 - \varepsilon_o) \\
 &= 1 - \frac{450}{475}(1 - 0.49) \dots\dots\dots (3) \\
 &= 0.52
 \end{aligned}$$

Plot a graph of expanded bed porosity versus backwash flow rate.

Plot a graph of differential headloss versus backwash flow rate. The differential headloss is the headloss calculated between any two consecutive tappings. Thus for L in this calculation, use the distance between the tappings chosen.

To be able to calculate the theoretical predicted bed expansion versus backwash rate the following test was done:

4.5 DENSITY AND POROSITY DETERMINATION

4.5.1 Introduction

This method determines the density and porosity of filtration media using a measuring cylinder.

4.5.2 Theory

4.4.2.1 Density

Density is defined as the mass per unit volume of a substance. It can be expressed as either the absolute density or as specific gravity.

$$\text{Density } (\rho) = \frac{\text{mass of substance}}{\text{volume of substance}} \dots\dots\dots (1)$$

Using conventional laboratory balances, the mass can be determined with relative accuracy. The volume of a given mass of solid is inferred from the volume of water that the particular mass will displace. With regular single solids this displacement is rather elementary. However with granular solids, as is the case with sand, air trapped between the grains contributes to the displacement volume. Thus it is crucial to the accuracy of the analysis that trapped air be expelled from the sample to give a more accurate measure of the volume.

During filter operation, certain inorganic substances become deposited on the grains, thereby influencing the density. These deposits include calcium carbonate (calcite), manganese and ferric chloride. The table below lists typical values for these substances (Perry, 1984).

SUBSTANCE	SPECIFIC GRAVITY
Calcite	2.711 (at 25°C referred to water at 4°C)
Ferric chloride (molysite)	2.804 (at 11°C)
Manganese	7.2 (at 20°C)
Silica dioxide (quartz)	2.650 (at 20°C)

Table 4.5.1. Specific gravities of substances

As can be seen from the table, the deposits can increase the density of silica sand thus influencing the backwash requirements.

In conducting a density analysis, it is the aim to determine the density of the medium as it exists in the filter. The use of chemicals to treat the sample before analysis is not recommended as this would interfere with the properties of the existent medium, and result in an erroneous measurement.

4.5.2.2 Porosity

Porosity is defined as a dimensionless ratio between the volume of voids in a bed of media to the total volume of the bed (media and voids).

$$\text{Porosity } (\varepsilon) = \frac{\text{void volume}}{\text{total bed volume}} \dots\dots\dots (2)$$

- Determination using a measuring cylinder

Once again, using a given mass of sample, the volumes can be inferred from the displacement in volume of water brought about by the addition of the solid to the water. It is important to note that the porosity is influenced by the extent to which the bed is compacted (Ceronio, 1994). Thus, in determining the porosity, avoid artificial means of bed compaction, for example, by tapping the test cylinder containing the sample on a workbench in an attempt to expel air.

The results produced by the test procedure detailed below are reproducible. To reduce the effects of experimental error, conduct the tests in triplicate.

- Determination in a column

According to Ceronio (1994), the loosest possible configuration of a filter bed is called the porosity of minimum fluidisation. This porosity can be determined by fluidising the filter bed and then allowing the media to settle gradually by slowly yet steadily terminating the backwash operation. Thus the influence of the backwash on porosity is crucial and needs to be taken into account when measuring this variable accurately. To achieve this, it is preferable to conduct the

porosity test in a column that is representative of the filter and in which the backwash operation can be simulated.

Description of the test column

The unit consists of a Perspex tube (600 mm in length, 44 mm in diameter), with pressure tappings, a static pressure tank, a manometer board, a convergence zone, which contains a nozzle, and a stabilising zone.

The static pressure tank is flanged to the top of the column. It contains an overflow pipe that leads to the drain. The convergence zone is flanged to the column such that the base of the column rests on the top of this zone. Wire mesh is placed at the flange to retain the media in the column. The convergence zone is flanged at the bottom to the stabilising zone. The backwash water and compressed air supply enters the unit from the stabilising zone. An outlet to the drain is situated in this zone.



4.5.3 Interferences and sources of error

- Deposits adhering to the grains of the media contribute to the density resulting in an inaccurate determination. It is thus suggested that the media be thoroughly washed using tap water before analytical determination of the density. Use of chemicals to treat the media is not recommended.
- Inadequate drying of the washed sample will also influence the density since the initial sand mass recorded will not be reflective of only sand but also of moisture between the grains.
- Compacting of the media bed influences the porosity. It is thus advised that the grains should be allowed to settle freely without artificially compacting

them. Avoid tapping the cylinder on the workbench as this contributes to compaction.

- The finer particulate matter contained in the sample influences the porosity. It is thus advised that loss of such particles needs to be guarded against whilst washing the media. Avoid using very high flow rates during washing in order to reduce media losses.

4.5.4 Apparatus and reagents

- Three 1000 ml graduated measuring cylinders
- Top loading balance
- Glass beaker
- Drying oven
- Dessicator



4.5.5 Analytical procedure

4.5.5.1 Density and porosity determination using the measuring cylinder

This method has been taken from Haarhoff (1982).

- Determine the mass (m_{cyl}) of a 1000 ml measuring cylinder on the top loading balance. Record this mass.
- Transfer the cool media to the measuring cylinder to about the halfway mark. Record the mass of sand (a).
- Now add water to the cylinder containing the sand to a level of about 30 mm above the sand. Ensure that the water percolates the entire bed such that the sand is now covered and also lies in water.

- By placing your hand over the mouth of the cylinder, gently yet quickly invert the cylinder three times in an attempt to dislodge trapped air bubbles between the grains.
- Now add more water to the cylinder filling it up to the 1000 ml mark. Record the mass (b) of sand + water and the level (h) at which the sand had settled.
- Empty the contents of the cylinder and fill it up with water to the level were the sand had previously settled. Record the mass of water (c).
- Now add more water to the cylinder, filling it up to the 1000 ml mark. Record the mass of water (d).
- Repeat all the above steps two more times.

4.5.5.2 Porosity determination using the column

This method has been taken from Ceronio (1994).

- Place a known mass (m) of clean, cooled, dry media in the column and record this mass.
- Initiate a backwash flow of water through the column. The flow should be sufficient to cause the bed to fluidise minimally.
- Allow the backwash to run for a few minutes and then gently yet steadily stop the backwash. This can be achieved by closing the valve regulating the flow to completely closed in 15 seconds. Avoid agitating the column at this point as it can cause the bed to compact.
- Measure the depth (L_x), in mm, of the settled media in the column and record it, where the subscript 'x' represents the number of the respective test.
- Record the inside diameter (\emptyset) of the column in units of 'mm'.
- Repeat steps 2 to 4 six times.

4.5.6 Calculation of results

4.5.6.1 Density

You might need to subtract the cylinder mass from the recorded values in order to get a, b, c and d, unless the balance was zeroed with this mass. 1g of water occupy a volume of 1 ml. To determine the density of the sand in g/ml, substitute the recorded values into equation 3:

$$\begin{aligned} \text{Density } (\rho) &= \frac{\text{mass of sand}}{\text{volume of sand}} \dots\dots\dots (3) \\ &= \frac{a}{a + d - b} \end{aligned}$$

Repeat the above calculation for all three sets of results recorded. Compute the average density.

4.5.6.2 Porosity

- From cylinder test

To determine the porosity, substitute the recorded values into Equation 4:

$$\begin{aligned} \text{Porosity } (\epsilon) &= \frac{\text{void volume}}{\text{total bed volume}} \dots\dots\dots (4) \\ &= \frac{b + c - a - d}{c} \end{aligned}$$

Repeat the above calculation for all three sets of results recorded. Compute the average porosity obtained by the cylinder test.

- From column test

To calculate the volume (cm³) of sand (v_{sand}) placed in the column, divide the mass 'm' by the density obtained in 7.1 above. Compute the average depth (L) of the media after fluidisation. To obtain the average bed volume of the media (in cm³), substitute the respective values in the following equation.

$$\text{bed volume, } v_{\text{bed}} = \pi \frac{\varnothing^2}{4} L \dots\dots\dots (5)$$

where \varnothing = diameter of the column in cm (see above)
 L = the average depth (cm) of the media after fluidisation (see above)

To obtain the void volume (v_{void}) of the bed, subtract the sand volume (v_{sand}) from the bed volume (v_{bed}). Express the porosity as the ratio of the void volume to the total bed volume.



Samples of the water are taken every working day as the raw water comes in the plant and at the outlet of the DAFF filters and each GAC filters as well as a communal outlet from the GAC filters.

4.6 BACKWASHING ABRASION

To obtain a direct measure of the abrasion losses, laboratory tests were conducted whereby both the 8 x 30 and 12 x 40 GAC's were backwashed in a filter column for 50 hours (which is equivalent to the total backwashing time a carbon would receive over approximately 18 months of service at a typical water treatment plant). Sieve analyses were done on the carbon before and after the test.

4.7 ANALYSES OF THE ON-SITE PATHWAY

To establish the stratification of the filter bed, core samples were taken from filter 1. These once-off core samples were then tested for apparent density and a sieve analyses was done. In this manner, different layers in the filter bed could be analysed. To establish the properties of the GAC in the rest of the washout sequence (see section 5.3.1) it was necessary to sample the GAC in the backwash channel and the sump. During a test to establish how much GAC is lost during backwashing, a sieve was placed in front of the outlet of the filter and the channel next to the weir was cleaned before and after backwashing. The GAC collected from the channel after backwashing was once again tested for apparent density and a sieve analyses was done. During the second excavation of the sump, samples were taken of the GAC washed out into it and tested as above.

4.8 ANALYSES OF THE OFF-SITE PATHWAY

Several samples of GAC were taken from different stages of the regeneration cycle: in the filter at the water plant, before the GAC is pumped out, in the drainage tank where the volume of GAC is measured, in the bags used to transport the GAC to the regeneration plant. Then samples were taken in the bin at the regeneration plant where the volume of the GAC is measured, right after regeneration, in the bins where the GAC is left to cool down, after screening in the bags again. Samples of GAC were then periodically taken in the filter at the water plant before backwashing and lastly after backwashing. Samples of the raw water, DAFF effluent, the total GAC effluent and the effluent of each of the 20 GAC filters were taken every working day.

The carbon used in the two regeneration cycles came from Filter 3 and 6 at Rietvlei, which was a size 12 x 40 carbon, bituminous-based 208 EA. Both filters had been previously commercially regenerated once. Two different companies regenerated the two filters during the two regeneration cycles. The samples were oven-dried at 110°C until constant mass. The following tests were performed on the samples: Sieve analysis, iodine nr analysis, and apparent density analysis.

The sieve analysis and particle size distribution was done according to AWWA standard for granular activated carbon, in accordance with Sec. 5.2.5.

The iodine number analysis was done according to the test method of ASTM D4607.

The apparent density analysis was done according to AWWA standard for granular activated carbon, in accordance with Sec. 5.2.4.

4.9 IN-SITU IODINE NUMBER BEHAVIOUR

Every GAC filter was sampled across the bed by means of extracting carbon from the middle of the bed with an injection-type sampler on 19 October 2001. The samples were mixed and its remaining adsorption capacity was measured by the laboratory staff of the Rietvlei water treatment plant (the uniformity of the adsorption capacity vertically through the bed has been tested). The adsorption capacity (measured in mg/g) was then compared with the amount of days the filter had been in operation. The iodine number analysis was done according to the test method of ASTM D4607.



4.10 IODINE NUMBER AND METHYLENE BLUE NUMBER DURING REGENERATION

Fluidised bed method : The iodine number analysis was done according to the test method of ASTM D4607, the methylene blue number analysis was done according to the test method used by Chemviron.

Continuous bed method : The iodine number analysis was done according to the test method of ASTM D4607, the methylene blue number analysis was done according to an adaptation from the Chemviron test method.

4.11 TOC

The TOC is determined by an external laboratory with the AQUADOC TOC analyzer.

4.12 UV₂₅₄

The UV₂₅₄ was measured every working day by staff from Rietvlei water treatment plant. From the commissioning the Pharmacia LKB – Ultrospec II spectrophotometer was used to measure the UV adsorbance at a wavelength of 254 nm. An Microsoft Excel spreadsheet was generated containing this data from 9/11/99 to 03/09/01. The UV adsorbance was plotted versus time. For the frequency curves, the data points are arranged from minimum to maximum, and the curves are plotted with the parameters on the x-axis and the percentage of time smaller than on the y-axis. Then the seven day moving average from 01/01/01 to 03/09/01 for the ratio of inlet versus outlet for raw to GAC was calculated and plotted to better illustrate loose points.

4.13 COLOUR REMOVAL

The colour is measured with the DT 2000 Spectrophotometer by HACH Instruments, at the laboratory at the water treatment plant.

CHAPTER 5

RESULTS & DISCUSSION

5.1 GAC LOSSES AND PATHWAYS

The following questions arise in this section:

- What are the in-plant losses due to washout, and how can the backwash cycle be modified should these losses be excessive?
- What are the GAC handling losses, and how can these losses be minimised?

To examine the losses, a model of the system has to be constructed.

5.1.1 A model of the GAC management system

5.1.1.1 The physical system

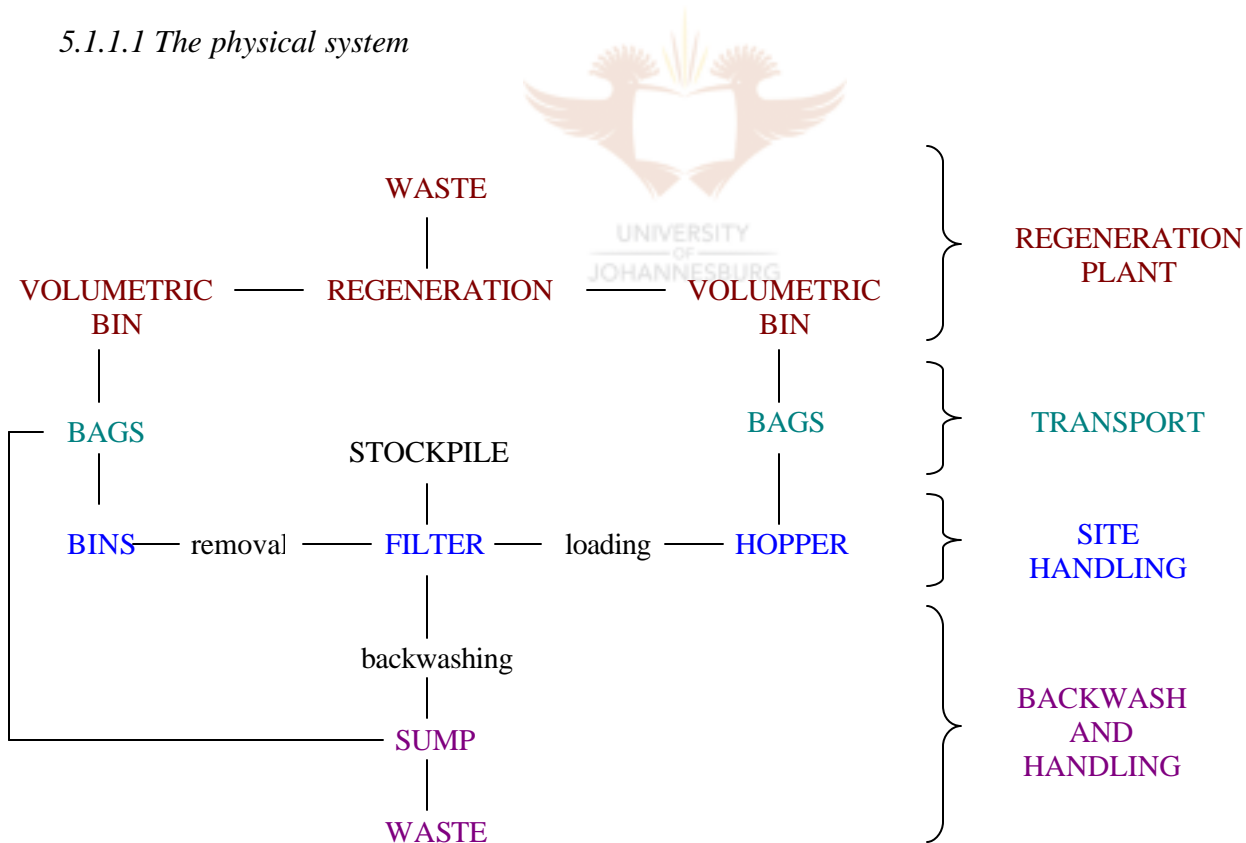


Figure 5.1.1 Schematic diagram of the GAC management system at the Rietvlei water treatment

The Rietvlei GAC management system is best modelled as two parallel circuits. The first off-site circuit removes GAC from the filters, transports it in bags by truck to a commercial regeneration plant where a fraction of GAC is lost due to the regeneration process. The remaining regenerated GAC is brought back onto site and loaded into the filters. The second on-site circuit collects GAC from the filters in a sump, which retains a fraction of the GAC whilst the rest of the GAC is washed into a river with the supernatant from the sump. The sump is periodically excavated, the GAC placed in bags, sent to the off-site regeneration plant and returned to the filters after regeneration. After a filter is filled with regenerated GAC, it is topped up to its original level from a stockpile of new GAC kept in reserve.

During normal operation, the only GAC lost from the filters, is the GAC swept out with the backwash water to the sump. When the GAC is removed from the filter for regeneration, the GAC is kept in suspension by the backwash system while the GAC is sucked out as slurry with a venturi system. During this process, a further volume of GAC is washed out to the sump. It should be further noted that a small volume of GAC remains in the filter after removal to act as a protective layer above the filter nozzles.

. The losses can therefore be presented as follows:

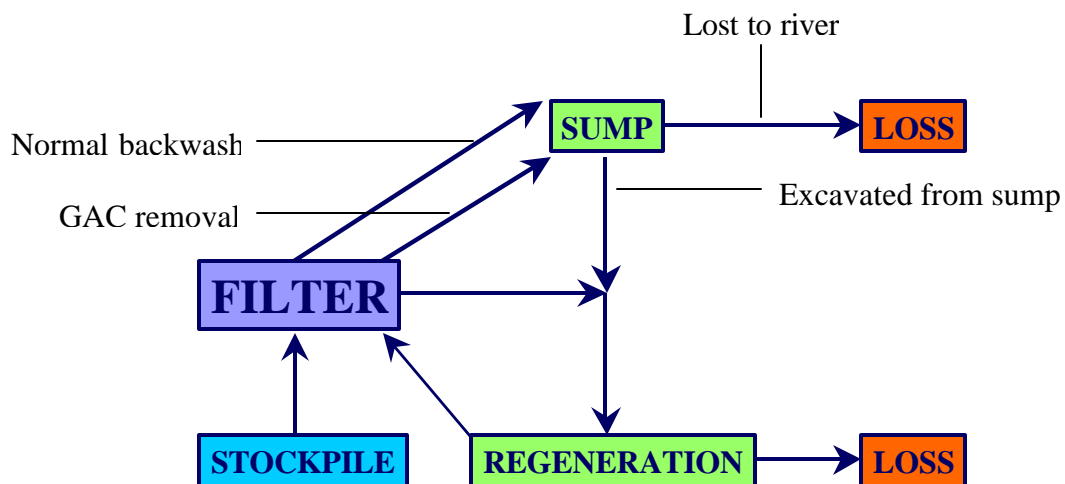


Figure 5.1.2 Representation of the losses in the system

There are a number of measuring points in the system. The level in each filter is carefully measured whenever GAC is placed in the filter, and again before the GAC is removed for regeneration. As the GAC is transferred to the bags on site, the number of transfer bins (with a known volume) is noted. As the GAC arrives at the regeneration plant, the volume is again measured by counting the number of volumetric bins filled. After regeneration, the GAC is again volumetrically measured in the same manner as before. This data is available in Appendix 8.1. On site, the volume of excavated GAC from the sump is also determined from the number of bags filled.

5.1.1.2 Mathematical representation of the system

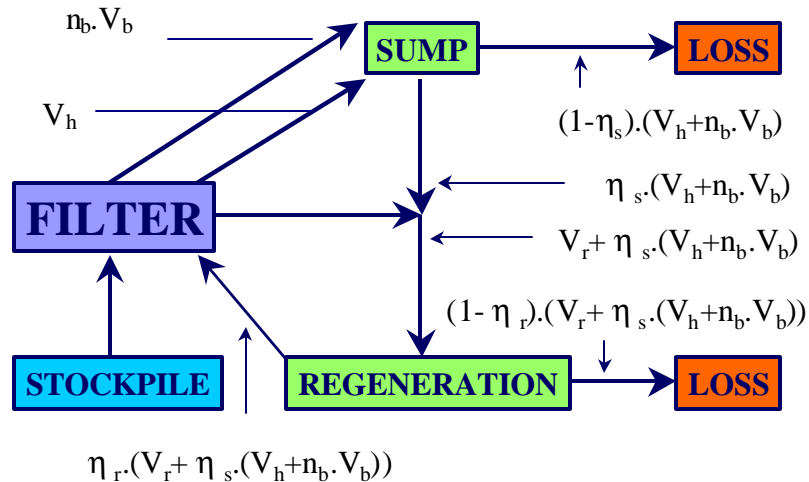


Figure 5.1.3 Mathematical representation of the system

The physical system can be skeletonised and mathematically represented as shown in Figure 5.1.3. The basis of the mathematical model is to consider the GAC flow for a single filter during a full regeneration cycle, i.e. from the point where the filter is filled with new or regenerated GAC, back to where it is again returned to the same condition after GAC was exhausted, regenerated and topped up again. The symbols and units, therefore, are:

V_s	=	top-up required for each filter (m^3/cycle)
V_b	=	backwash loss ($\text{m}^3/\text{backwash}$)
n_b	=	number of backwashes / regeneration cycle
V_h	=	handling loss (m^3/cycle)
η_s	=	trap efficiency of the on-site sump (-)
η_r	=	volumetric efficiency of the regeneration plant (-)
V_r	=	volume removed to the regeneration plant (m^3/cycle)

5.1.2 Calibrating the model

The above model contains seven unknowns. Once these unknowns are quantified, the flow of GAC through the system can be quantitatively described. The rest of this section describes the direct and indirect measures used to calibrate the model based on the first 23 months of operational experience.



5.1.2.1 Number of backwashes/cycle n_b

The events between the first and the second excavation of GAC from the sump were carefully reconstructed from the plant records. During this time, 1024 filter backwashes were recorded and the GAC of 5 filters had been removed. The number of backwashes/cycle is thus $n_b = 1024/5 = 205$.

5.1.2.2 Backwash loss V_b

The volume of GAC washed out from a filter during a single typical backwash was directly measured by inserting a sieve in the backwash channel immediately downstream of the filter. In this way, the backwashing loss rate was found to be $V_b = 0.00025 \text{ m}^3/\text{wash}$.

5.1.2.3 Top-up for each filter V_s

The total GAC volume, when all 20 filters are topped up to their maximum level, is 308 m³ or 15.4 m³/filter. When the plant was commissioned, a reserve volume of GAC was stored on site to be used to top up each filter after its regenerated GAC was returned to the filter. After 25 GAC batches had been regenerated, a total volume of 81m³ had been used for top-up to replace GAC lost due to handling and regeneration. Thus the top-up volume required was $V_s = 81/25 = 3.24$ m³/cycle.

5.1.2.4 Volume removed V_r

There are two methods available to estimate the total volume of GAC removed. In the first the level of GAC in the filter is measured before and after the GAC is removed from the filter for regeneration. The total volume removed is then estimated. The average volume thus calculated for the first 25 filters regenerated, indicated that an average volume of 12.68 m³ of GAC was removed from each filter.

In the second method, when the GAC arrives at the regeneration plant, it is again volumetrically measured by counting the number of 1 m³ bins filled. This was done for 19 filters, and the average volume of GAC removed per filter was 12.03 m³. These two independent estimates are remarkably close, with an average of $V_r = 12.36$ m³ /cycle.

5.1.2.5 Regeneration efficiency η_r

The GAC is volumetrically measured upon arrival at the regeneration plant, and again after regeneration. The same regeneration contractor was used for estimation purposes. The volume obtained from the first 19 filters indicated an average loss of 21.3% with a standard deviation of 4.8%. The regeneration efficiency is thus $\eta_r = 0.787$.

5.1.2.6 Solution of h_r and V_h

To estimate the remaining two unknowns V_h and η_r two equations are required. The first equation is provided by a volume balance across a filter for each regeneration cycle (refer to Figure 5.1.2):

$$V_{bn_b} + V_r + V_h = V_s + V_r\eta_r + \eta_r\eta_s(V_{bn_b} + V_h) \quad (\text{Eq. 5.1})$$

The second equation comes from the measured volume of GAC excavated during the second sump cleaning. During this excavation, a total volume of 5.93m^3 was recovered, which reflects the cumulative GAC trapped after 1024 filter backwashes and 5 filter regeneration cycles. This provides an estimate of $1.19\text{m}^3/\text{cycle}$ trapped in the sump. Mathematically:

$$(V_{bn_b} + V_h)\eta_s = 1.19 \quad (\text{Eq. 5.2})$$

Simultaneous solution of Equations (5.1) and (5.2) yields:

$$\eta_s = 0.77$$

$$V_h = 1.50\text{m}^3/\text{cycle}$$



5.1.2.7 Experimental verification of V_h

These results were checked by one spot measurement. A sieve was introduced in the sump overflow line, which effectively changed the trap efficiency to 100%. The sump was then cleaned, and the GAC of one filter was removed. The sump was cleaned directly after this again, thus directly measuring V_h . This gave a value of $1.52\text{m}^3/\text{regeneration cycle}$, which approximates the value obtained by the model. The model as calibrated can therefore be accepted as a reliable description of the GAC flow.

5.1.2.8 Residual GAC in filter after removal

The mathematical model provides an interesting additional piece of information. The calibrated model indicates that a total of 13.9 m³ is removed from the filter, and placed back after regeneration and top-up. The filter capacity is 15.4 m³. This means that the difference of 1.5 m³ remains in the filter after removal, representing a depth of 140 mm of GAC, which approximates that observed in practice. This adds credibility to the mathematical model.

5.1.2.9 Schematic GAC flow diagram

The model can finally be used to calculate the average flow of GAC at each point during a typical regeneration cycle, the volumes are expressed as percentages of the total volume of GAC of a fully filled filter. This is depicted in Figure 5.1.4.

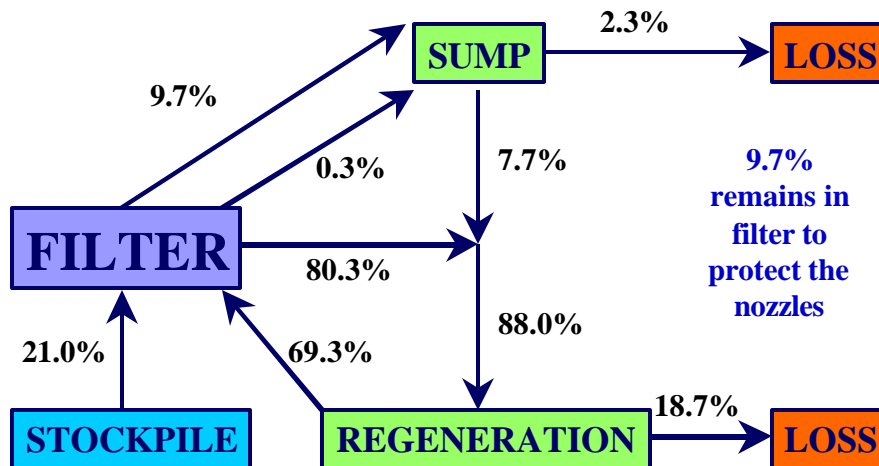


Figure 5.1.4 Summary of GAC flow during the first 23 months of operation at the Rietvlei water treatment plant.

5.1.2.10 Cost analyses

With the current loss situation the running cost of the GAC is as follows:

GAC FLOW	Volume (m³)	Mass (kg)	Unit rate (R)	Cost	% cost	% volume
In filter after top-up	15.40	12320			0.00	100
Backwash losses	0.05	41			0.00	0.33
In filter before removal	15.35	12279			0.00	99.67
In filter after removal	1.49	1192			0.00	9.68
Washed into sump during removal	1.50	1200			0.00	9.74
Transported to regeneration plant	12.36	1.00	800	800	1.77	80.25
Regeneration losses	2.63	2106			0.00	17.09
Transported back to plant	9.73	1	800	800	1.77	63.16
Deposited in sump	1.19	956			0.00	7.76
Washed to river	0.36	285			0.00	2.32
Transported to regeneration plant	1.19	956			0.00	7.76
Regeneration losses	0.25	204			0.00	1.65
Transported back to plant	0.94	752	2.71	2038.01	4.51	6.10
Top-up required	3.24	2595	16	41518.36	91.94	21.06
TOTAL				R 45156.37		
Days in operation	600					
Production (m ³) /cycle	1263158					
GAC running cost per m ³ (cents)	3.57					

Table 5.1.1 Cost analyses with sump trap efficiency = 0.77

The top-up of the carbon is obviously the most substantial cost. How can the top-up then be minimised? By minimising the losses that need to be topped up. It has already been established that these losses consist of the loss to the river and the loss during the regeneration of the GAC.

What effect will placing a sieve in front of the outlet of the sump have on the operational cost of the GAC? By changing the sump trap efficiency to 1.00, the change in cost can be analysed:



GAC FLOW	Volume (m³)	Mass (kg)	Unit rate (R)	Cost	% cost	% volume
In filter after top-up	15.40	12320			0.00	100.00
Backwash losses	0.05	41			0.00	0.33
In filter before removal	15.35	12279			0.00	99.67
In filter after removal	1.49	1192			0.00	9.68
Washed into sump during removal	1.50	1200			0.00	9.74
Transported to regeneration plant	12.36	1	800	800	1.90	80.25
Regeneration losses	2.63	2106			0.00	17.09
Transported back to plant	9.73	1	800	800	1.90	63.16
Deposited in sump	1.55	1241			0.00	10.07
Washed to river	0.00	0			0.00	0.00
Transported to regeneration plant	1.55	1241			0.00	10.07
Regeneration losses	0.33	264			0.00	2.15
Transported back to plant	1.22	977	2.71	2646.76	6.28	7.93
Top-up required	2.96	2370	16	37924.22	89.93	19.24
TOTAL				R 42170.99		
Days in operation	600					
Production (m ³) /cycle	1263158					
GAC running cost per m ³ (cents)	3.34					

Table 5.1.2 Cost analyses with sump trap efficiency = 1.00

So by just inserting a sieve there is already a saving of approximately R3000 (7% of running costs) per regeneration cycle. The only other way to minimise losses is to investigate the regeneration method. But this is the domain of the regeneration contractor. If we can convince the contractor to just bring down the regeneration losses to a modest 15%, there will be a further saving of R11 000 (25% of running costs), and the total cost per cycle will come down to R31 000.

5.1.2.11 Current regeneration contracts

The current regeneration contract stipulates that the losses that occur during regeneration are to be carried by the water treatment plant and that the regeneration contractor is only to transport the GAC from the treatment plant to the regeneration plant, regenerate the GAC, and then to return it to the treatment plant.

5.2 IN-SITU GAC BEHAVIOUR

The following questions arise in this section:

- How much of the GAC is lost due to abrasion?
- Can the direct washout of GAC be avoided or reduced by reduced backwash rates or increased freeboard?
- Is the current backwash still cleaning the bed sufficiently?

5.2.1 GAC abrasion

How much of the GAC is lost due to abrasion? During operation, GAC filters operate similarly to sand filters. The backwashing, however, is done slightly differently. To curb abrasion of the softer GAC grains, the use of air is omitted and water alone is used. At Rietvlei, allowance was made for both water and air, but the use of air is restricted as far as possible and only used when necessitated by an insufficiently cleaned GAC bed used at Rietvlei. The usual procedure is a 10 minute backwash, without air scour. To obtain a direct measure of the abrasion losses, laboratory tests were conducted whereby both the 8 x 30 and 12 x 40 GAC's were backwashed in a filter column for 50 hours (which is equivalent to the total backwashing time a carbon would receive over approximately 18 months of service at a typical water treatment plant). Sieve analyses were done on the carbon before and after the test and results showed no measurable effects on the GAC grain size distribution. Figure 5.2.1 indicates insignificant change in particle size analyses for the size 12 x 40 carbon and the results obtained from the 8 x 30 carbon showed even less change. The GAC losses due to attrition during backwash can therefore be eliminated as a measurable loss.

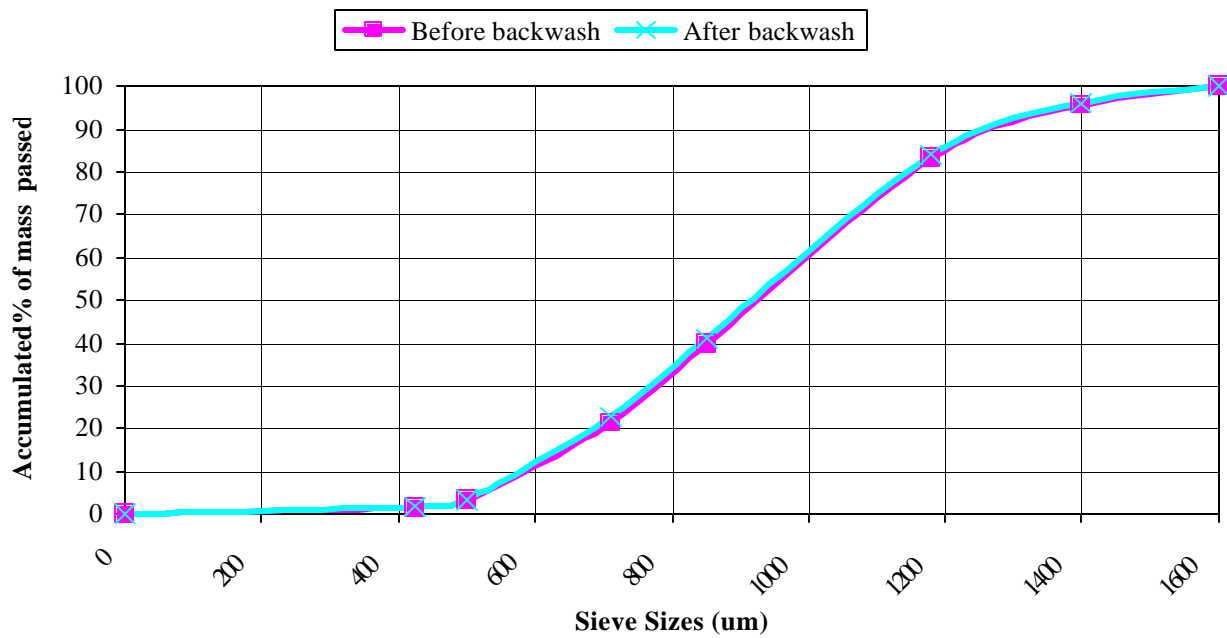


Figure 5.2.1 GAC sieve analyses of the 12 x 40 carbon before and after 50 hours of continuous backwashing in the laboratory.

5.2.2 GAC Sphericity

Bed expansion tests with actual Rietvlei GAC (both 12 x 40 and 8 x 30 sizes) were conducted in the laboratory and used to calibrate a theoretical bed expansion model. The GAC was placed in a laboratory column filter and the filter was backwashed at different flow rates and the bed expansion was measured.

To calculate the theoretical bed expansion, it is first necessary to calculate the porosity of the carbon. The porosity, however, varies through the bed and due to carbon size. Using the grading analyses for the GAC used in the laboratory test, seven layers of GAC sizes were analysed.

The porosity is calculated by using the Dharmarajah model. Dharmarajah (1986) developed a predictive model using a dimensional analytical approach. This seems to be the most comprehensive model to date. The model is reproduced in Equation 5.3.

$$\log(A1) = 0.56543 + 1.09348(\log \text{Re}_B) + 0.17979(\log \text{Re}_B)^2 - 0.00392(\log \text{Re}_B)^4 - 1.5(\log y)^2 \quad (\text{Eq. 5.3})$$

$$A1 = \frac{e^3}{(1-e)^2} \frac{r(r-r_s)g}{S_v^3 m^2}$$

$$\text{Re}_B = \frac{rV}{S_v m(1-e)}$$

$$S_v = \frac{6}{y d_{eq}} \text{ or } \frac{6}{y d_g}$$

ψ = sphericity of media grains

ϵ = predicted porosity

μ = dynamic viscosity of water

ρ = density of water

d_{eq} = equivalent diameter

d_g = geometric diameter

l = media depth



An example of one such calculation is given in Appendix 8.2. Different porosity's were chosen until Equation 5.3 was satisfied.

The theoretical bed expansion was then determined by using the following relationship. Here the subscript e denotes the expanded value and the subscript o denotes the value of the given variable for the bed before it is expanded.

$$\frac{l_e}{l_o} = \frac{1-e_o}{1-e_e} \quad (\text{Eq. 5.4})$$

The subsequent bed expansion for each porosity layer was calculated at 20°C to reproduce the conditions during the laboratory experiment. The theoretical bed expansion of a number of possible sphericities were checked and compared with the expansion achieved in the laboratory test. The difference between the theoretical and actual bed expansion was calculated, squared

and summed. The sphericity represented by the least sum of squares indicates the sphericity that approximates the GAC used in the laboratory the best. This data is available in Appendix 8.3.

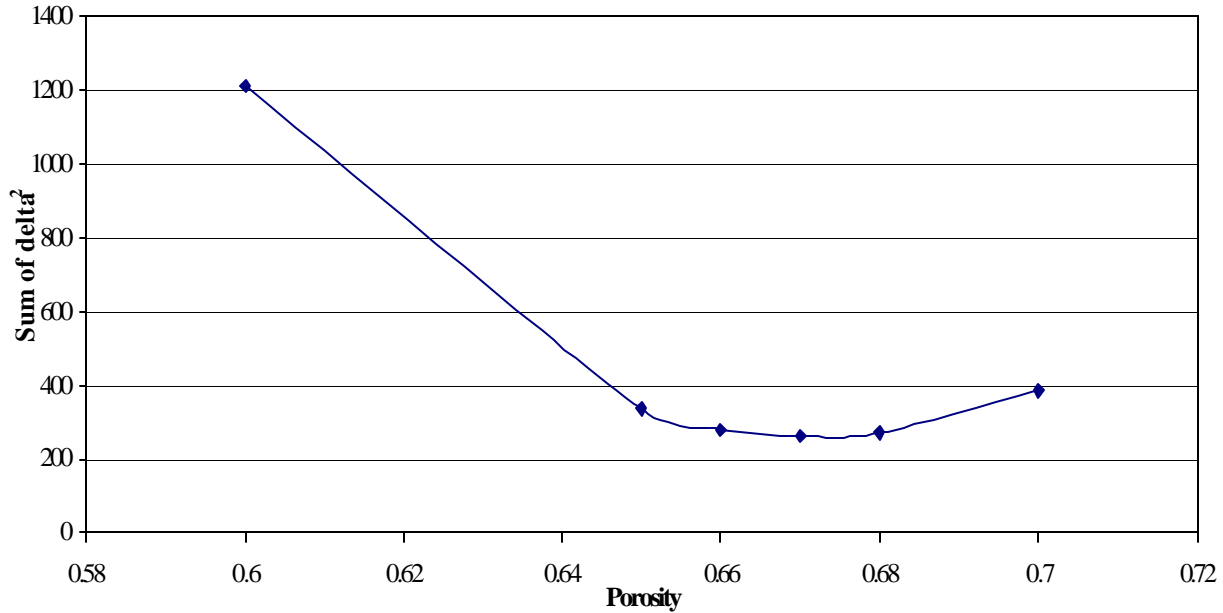


Figure 5.2.2 Least squares chart – 12 x 40

The calibration indicated media sphericity of 0.67 for the 12 x 40 size carbon.

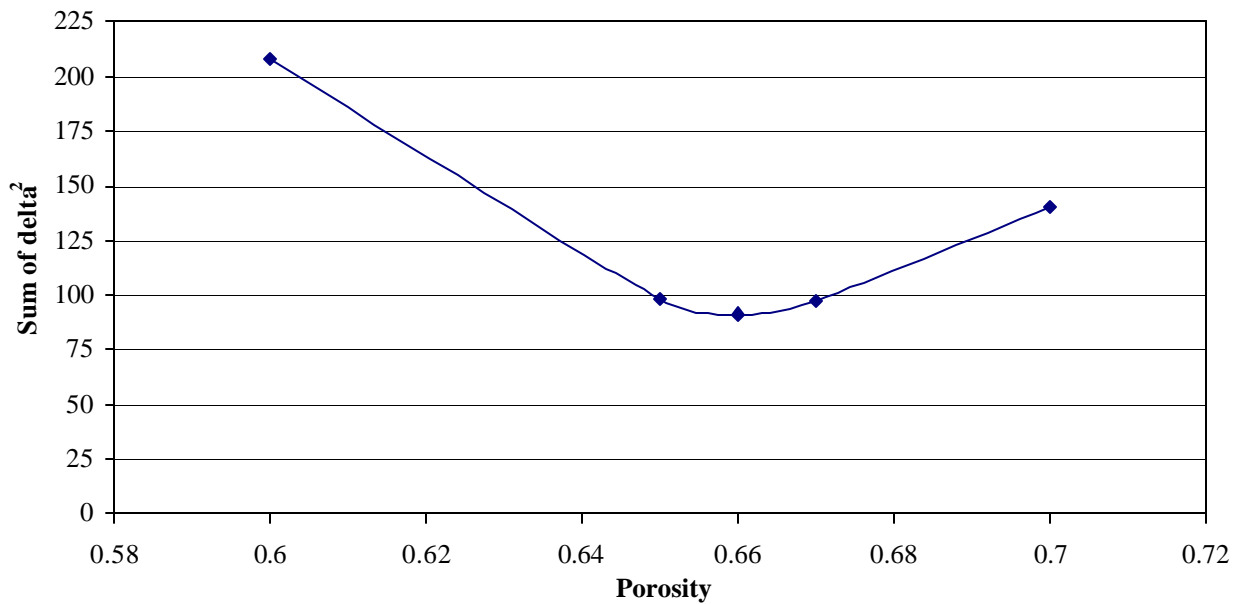


Figure 5.2.3 Least squares chart – 8 x 30

The calibration indicated media sphericity of 0.66 for the 8 x 30 size carbon.

To see how the calibration fits, the measured bed expansion and theoretical model for both size carbons are compared:

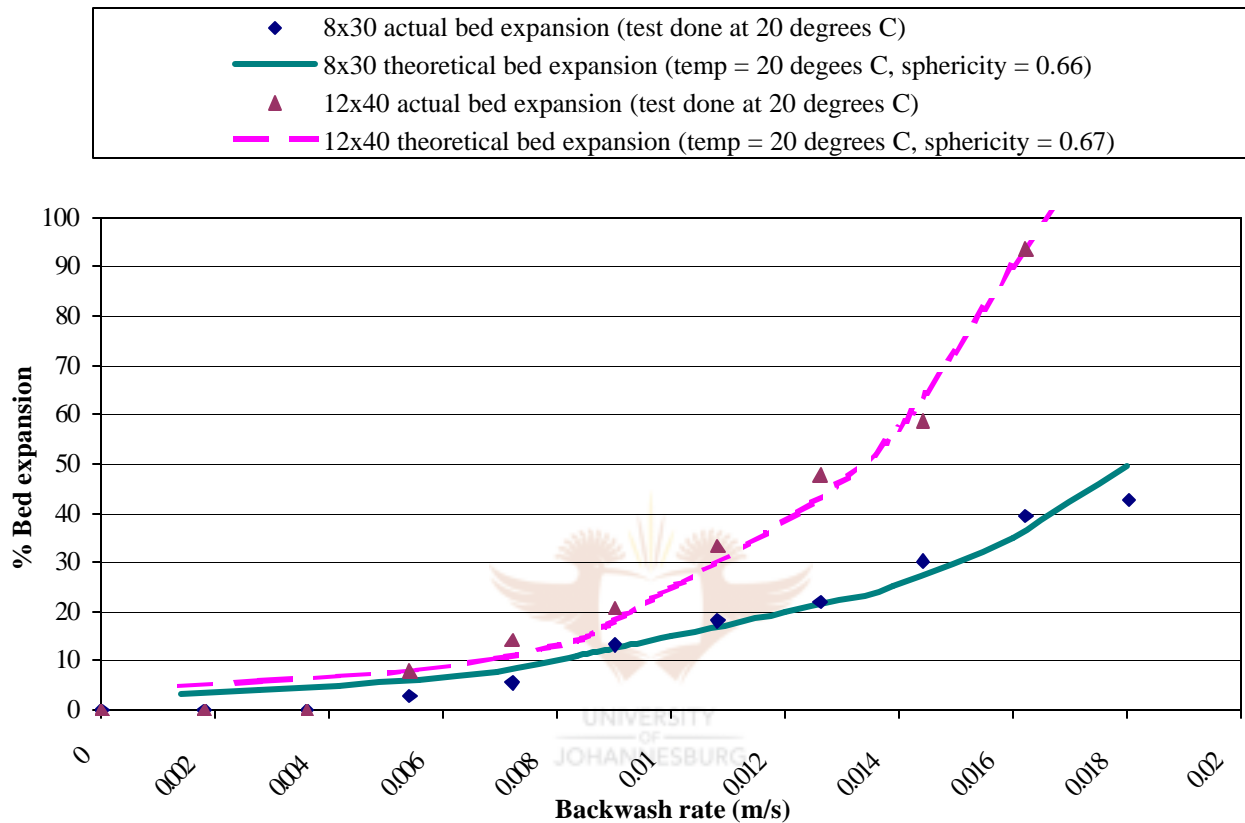


Figure 5.2.4 Theoretical and actual % bed expansion vs. backwash rate (12x40 & 8x30)

It is clear that the theoretical model fits quite well with the actual bed expansion measured in the laboratory. This model can now be used to predict bed expansion at extreme temperatures.

5.2.3 Expansion at extreme temperatures

Can the direct washout of GAC be avoided or reduced by reduced backwash rates or increased freeboard? The predicted expansion for the two Rietvlei GAC's was calculated as in the previous section at the extreme temperatures of 9°C and 20°C, and is shown in Figure 5.2.5.

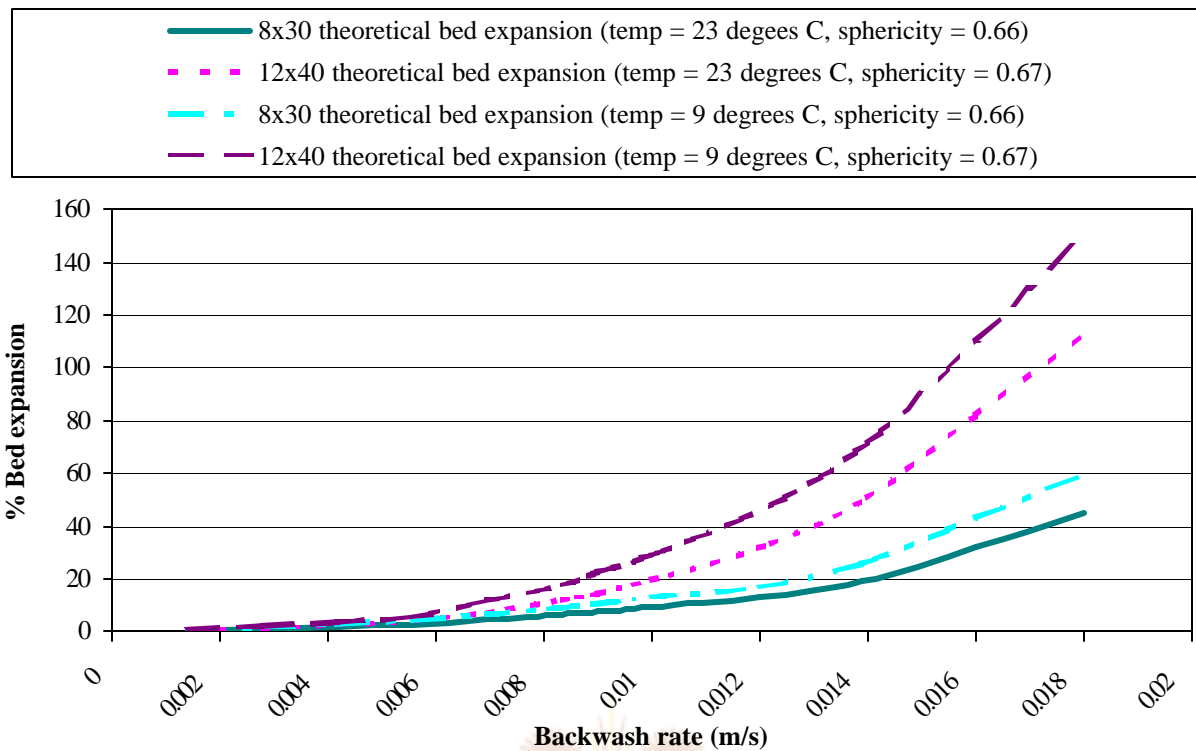


Figure 5.2.5 Actual and theoretical bed expansion vs. backwash rate for both the 12 x 40 and 8 x 30 size carbons.

The design backwash rate originally estimated during the design process is 20m/h for the 12 x 40 size carbon and 24m/h for the 8 x 30 size carbon. Site measurements of the rate of rise (as described in the materials and methods) indicated an actual rise rate of 18m/h. Can an actual rise rate of 18 m/h (0.005m/s) wash out the GAC? Given an average bed depth of 1400 mm, every percent of expansion is equivalent to 14 mm. The predicted bed expansion ranges from 3% to 5%, which translates into 42 mm to 70 mm. At the design backwash rates of 20 to 24m/h (0.006 to 0.007m/s) the expected bed expansion should range from 5 to 15%, or 70 mm to 210 mm. The average freeboard available is 650 mm for the 12 x 40 and 430 mm for the 8 x 30 carbon, indicating that the GAC should comfortably be contained within the filter beds during backwash.

The design freeboard is 700 mm. It was, surprisingly, found that the carbon bed expands upon initial placement. Van der Aa (2001) explains this by the fact that the bed stratifies: the largest grains settle down first and the smaller grains settle down later. In the stratified bed the large

grains are at the top and smaller grains at the bottom. Since the large and small grains are not mixed anymore, the porosity will be relatively high. He experienced approximately 10% expansion of the GAC bed after a stratification backwash, which would translate to 140 mm at Rietvlei and therefore reduce the freeboard to 560 mm. The GAC will still be comfortably contained in the filter bay.

An attempt was also made to measure the actual in-situ GAC expansion during backwash. These measurements indicated much higher values – 364 mm (26%) for the 12 x 40 carbon and 280 mm (20%) for the 8 x 30 carbon. If these measurements were to be reliable, the actual expansion does indeed come dangerously close to using all the available freeboard. Work is ongoing to improve on the in-situ measurement and to resolve the seemingly large difference between the expansion measured on site and in the laboratory.

5.2.4 Minimum fluidisation

What influence does the current or change in backwash rate have on the performance of the backwash, or more simply stated, is the current backwash still cleaning the bed sufficiently? To estimate this the minimum fluidisation versus grain size for both size carbons were estimated.

Velocity of minimum fluidisation was determined with a spreadsheet set up by Dr. T Ceronio for the Sand Filtration Course 2001 (RAU Water Research Group, 2001). An example follows:

Equations

$$\text{Re}_{mf} = \sqrt{33,7^2 + 0,0408 \cdot Ga} - 33,7$$

$$\text{Re}_{mf} = \frac{d_{eq} \cdot v_{mf} \cdot r}{m}$$

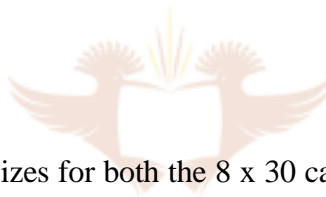
$$Ga = \frac{d_{eq}^3 \cdot r(r_s - r)g}{m^2}$$

Known values

d_{eq}	grain size	$d_{90} = 2180 \mu\text{m} = 0.00218\text{m}$
g	gravitational acceleration	9.81 m/s^2
μ	dynamic viscosity (N.s/m ²)	$0.00113 @ 20 \text{ deg C}$
ρ	water density (kg/m ³)	$999.099 @ 20 \text{ deg C}$
ρ_s	media density (kg/m ³)	1544

Calculation

$$\begin{aligned} \text{Ga} &= 43332 \\ \text{Re}_{mf} &= 20.2 \\ \mathbf{v_{mf}} &= \mathbf{10.5 \text{ mm/s}} \end{aligned}$$



This was repeated for all the grain sizes for both the 8 x 30 carbon and 12 x 40 carbon for temperatures of 5, 10, 15 and 20 °C and once again, for all seven layers. Included is the design backwash rate specified by the design engineer and the actual backwash rate measured at the plant.

The results are graphically depicted in Figures 5.2.6 and 5.2.8. Figures 5.2.7 and 5.2.9 respectively give the results of the sieve analyses of the GAC for both sizes. Using Figures 5.2.6 and 5.2.7 one can now see what percentage of the bed is fluidised at a certain minimum fluidisation rate.

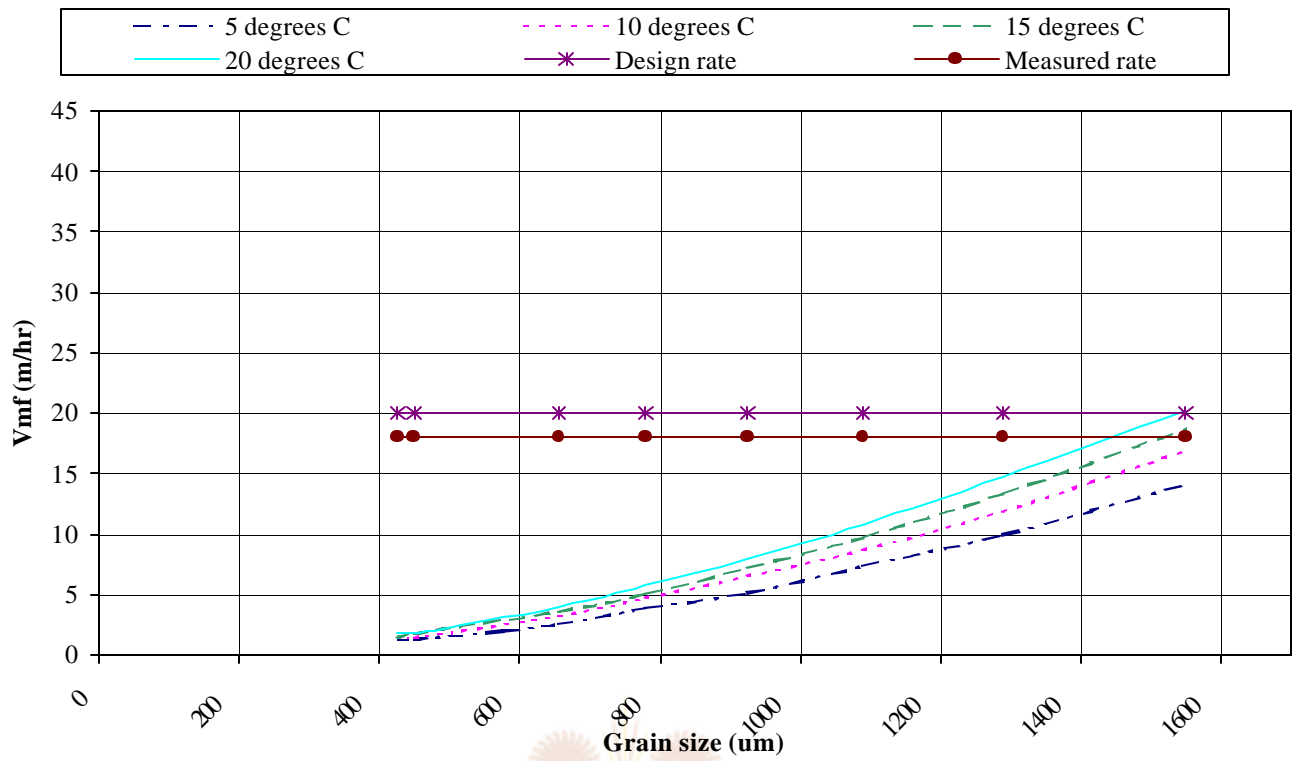


Figure 5.2.6 Minimum fluidisation vs. grain size – 12 x 40 grain size

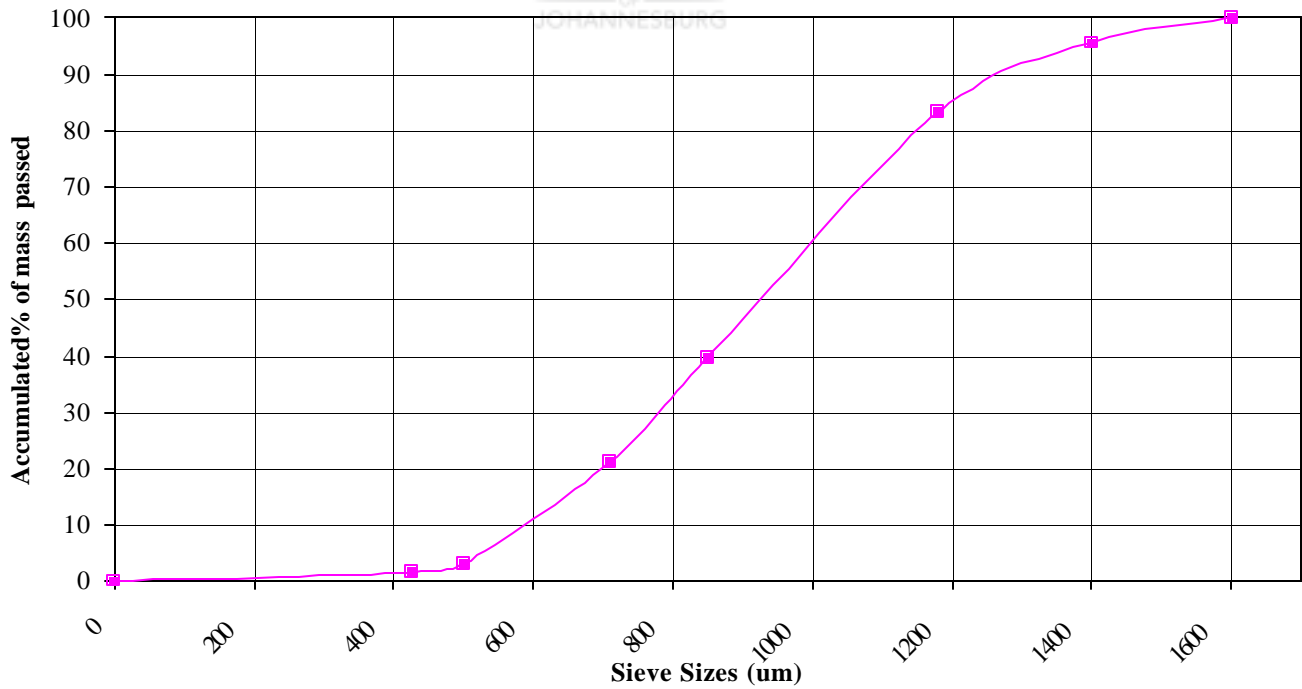


Figure 5.2.7 GAC sieve analyses of the 12 x 40 carbon testing in the laboratory.

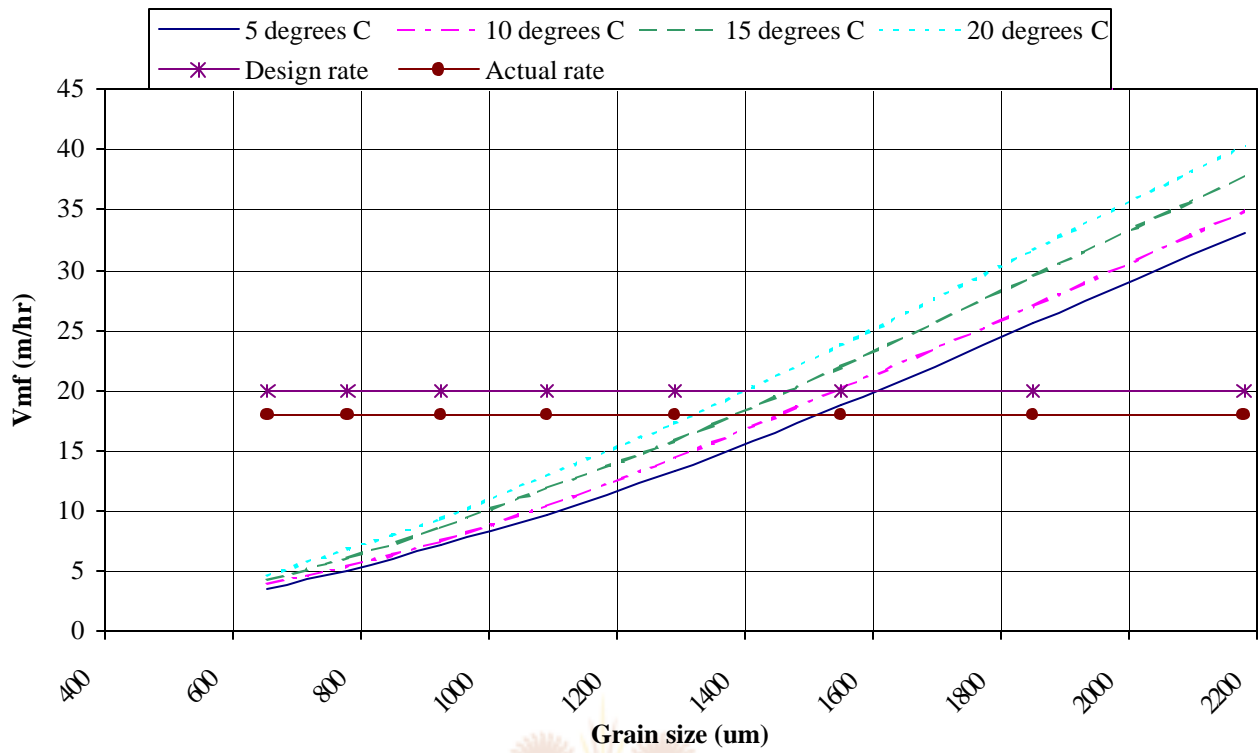


Figure 5.2.8 Minimum fluidisation vs. grain size – 8 x 30 grain size

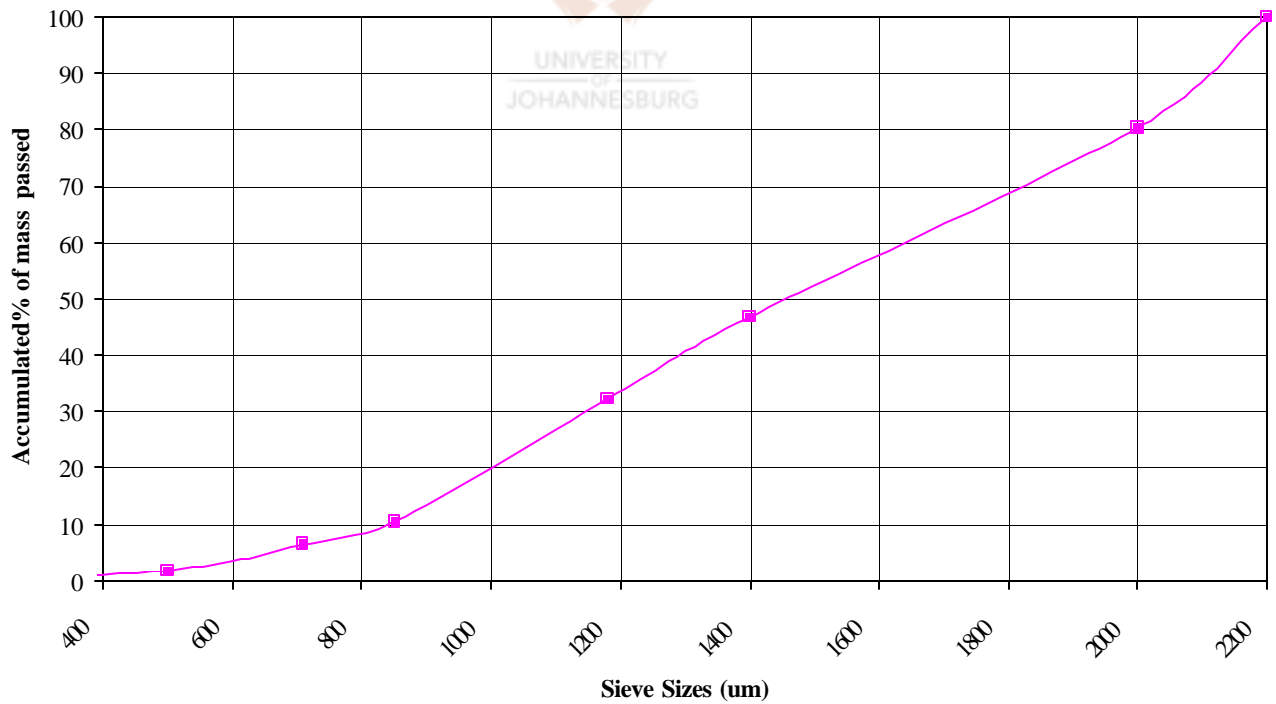


Figure 5.2.9 GAC sieve analyses of the 12 x 40 carbon before testing in the laboratory.

If all the grains are fluidised under the current backwash rate, the bed is still being properly cleaned.

For the 8 x 30 carbon the design rate of 24m/hr only expands 60% of the carbon in summer and 70% in winter. At the actual rate of 18m/hr only 40% is expanded in summer and 55% in winter. For the 12 x 40 carbon the design rate of 20m/hr expands 95% of the carbon in summer and winter, as well as at the actual rate of 18m/hr.

Thus, the current backwash rate for the 12 x 40 carbon is adequate but falls short with the 8 x 30 carbon and these filters are not being adequately cleaned.



5.3 CHANGES IN PHYSICAL PROPERTIES OF GAC THROUGH THE PATHWAYS

The following questions arise in this section:

- How do the physical properties of the GAC change during the washout sequence?
- How do the physical properties of the GAC change during the regeneration sequence?
- Is there a relationship between physical properties and adsorption capacity?

It has already been established that there are two possible routes that the GAC follows. One is through the GAC plant from the GAC filters over the weir into the channel and then washed to the sump. The other is from the GAC filters to the drainage tanks, transport bags, truck, volumetric bin at the regeneration plant and then into the regeneration kiln. After that the GAC is screened, placed back into the bags, transported back to the water treatment plant on a truck and placed back in the filter with a venturi hopper. It was noticed that the properties of the GAC changed significantly during these two pathways.

5.3.1 On site pathway - Washout sequence

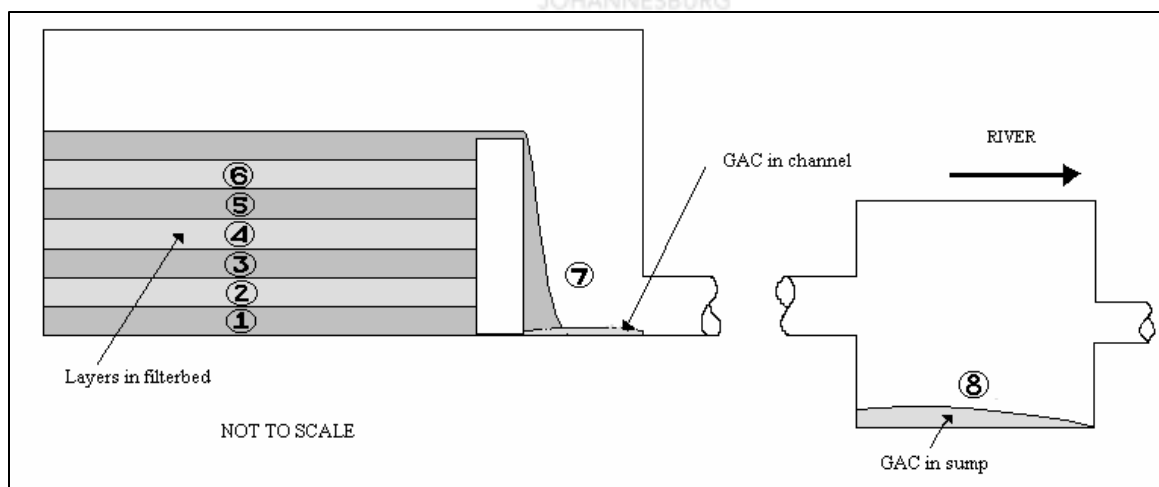


Figure 5.3.1 Physical washout sequence

To establish the stratification of the filter bed, core samples were taken from Filter 1. These once-off core samples were then tested for apparent density and a sieve analyses was done. In this manner, different layers in the filter bed could be analysed. Numbers 1– 6 represent these layers in the washout sequence (Figure 5.3.1). During a test to establish how much GAC is lost during backwashing, a sieve was placed in front of the outlet of the filter and the channel next to the weir was cleaned before and after backwashing. The GAC collected from the channel after backwashing was once again tested for apparent density and a sieve analyses was done. During the second excavation of the sump, samples were taken of the GAC washed out into it and tested as above. The changes in physical properties seemed significant, and consequently all the above mentioned samples were tested for iodine number as well. All these tests are described in the materials and methods.

The d_{50} and % finer than 500 μm of the sieve analyses and the apparent densities and iodine numbers through the washout sequence are tabulated in Table 5.3.1 and the d_{50} and apparent densities are graphically shown in Figure 5.3.2.

Area on the on-site path	Sequence number	d_{50}	% finer than 500 μm	Apparent density (g/100 ml)	Iodine number (g/mg)
Bed	1	780	9	45.0	627
Bed	2	970	5.2	48.2	650
Bed	3	1030	2.7	48.8	641
Bed	4	1040	2.2	48.8	618
Bed	5	1060	2.1	48.8	638
Bed	6	1025	2.11	48.7	615
Channel	7	640	20.7	57.3	534
Sump	8	750	10.5	56.1	388

Table 5.3.1 The d_{50} and % finer than 500 μm of the sieve analyses and the apparent densities and iodine numbers through the washout sequence

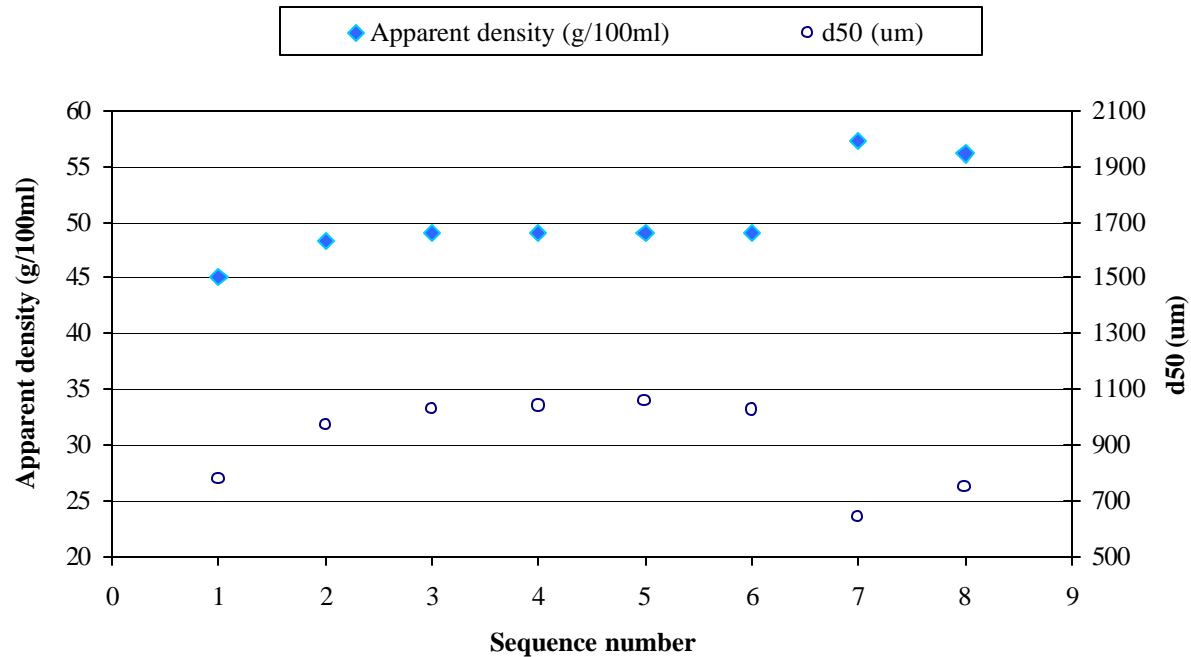


Figure 5.3.2 The d_{50} and apparent densities through the washout sequence

The GAC on the bottom of the carbon bed is finer than the GAC higher in the bed, having 9% and 5% fines in layers 1 and 2 compared to around 2% in the rest of the bed. A stratification backwash, whereby the backwash flow is slowly decreased so that the smaller particles are the last to settle and thus settle on top, can correct this. The carbon in the channel and sump seems to be finer than the GAC in filter, having fines of 20% and 10% respectively. This could be because of the backwash performed right after the GAC is placed back in the filter after regeneration, whereby all the fines generated by regeneration is washed out of the bed.

The apparent density of the GAC in the channel and sump also seemed significantly higher than in the filter bed. This indicates that this carbon had absorbed more organic material than the GAC in the bed. This could possibly be because of dirty backwash water washing over this GAC during every backwash. This is also reflected by the iodine numbers, which indicates that the GAC in the channel and sump has less available adsorption capacity than the GAC in the filter bed, where the adsorption capacity seems homogenous.

It seems that there is a link between apparent density and iodine number, and as apparent density can be measured within minutes after the GAC is dried, it might be a quick indicator to give an idea of the adsorption capacity left, which may be checked later by the long and tedious method of iodine number analyses.

5.3.2 Off site pathway - Regeneration sequence

To analyse the change in physical properties during the regeneration sequence, samples were taken during the sequence once for both the fluidised and the continuous bed methods. These samples were taken in the filter, drainage tanks, bags, at the plant just before regeneration and just before the GAC is placed back in the bags after regeneration and screening. These samples were placed through a sample splitter and tested as in the previous section (described in materials and methods).

The d_{50} and % finer than 500 μm of the sieve analyses (Appendix 8.4) through the regeneration sequence for both methods are tabulated in Table 5.3.2. The apparent densities and iodine numbers through the regeneration sequence for both methods are tabulated in Table 5.3.3 and the d_{50} and apparent densities are graphically shown in Figures 5.3.3 and 5.3.4. The five numbers in these figures refer to the five steps in Table 5.3.3.

FLUIDISED BED METHOD				CONTINUOUS BED METHOD	
Area on the off-site path	Sequence number	d ₅₀	% finer than 500 um	d ₅₀	% finer than 500 um
Filter itself	1	945	0.9	953	0.9
Tank	2	990	0.5	1058	0.6
Bags	3	1095	1.6	1133	1.2
Spent	4	1087	0.5	1103	1.0
Reactivated & Screened	5	1065	1.7	1035	3.7

Table 5.3.2 The mean diameter and percentage fines for the two regeneration methods during the regeneration cycle.

FLUIDISED BED METHOD				CONTINUOUS BED METHOD	
Area on the off-site path	Sequence number	Apparent density (g/100 ml)	Iodine number (g/mg)	Apparent density (g/100 ml)	Iodine number (g/mg)
Filter itself	1	46.69	524	50.58	525
Tank	2	49.40	480	52.22	520
Bags	3	49.54	584	51.26	523
Spent	4	49.54	533	57.91	564
Reactivated & Screened	5	45.85	757	51.97	774

Table 5.3.3 Apparent densities and iodine numbers for the two regeneration methods during the regeneration cycle.

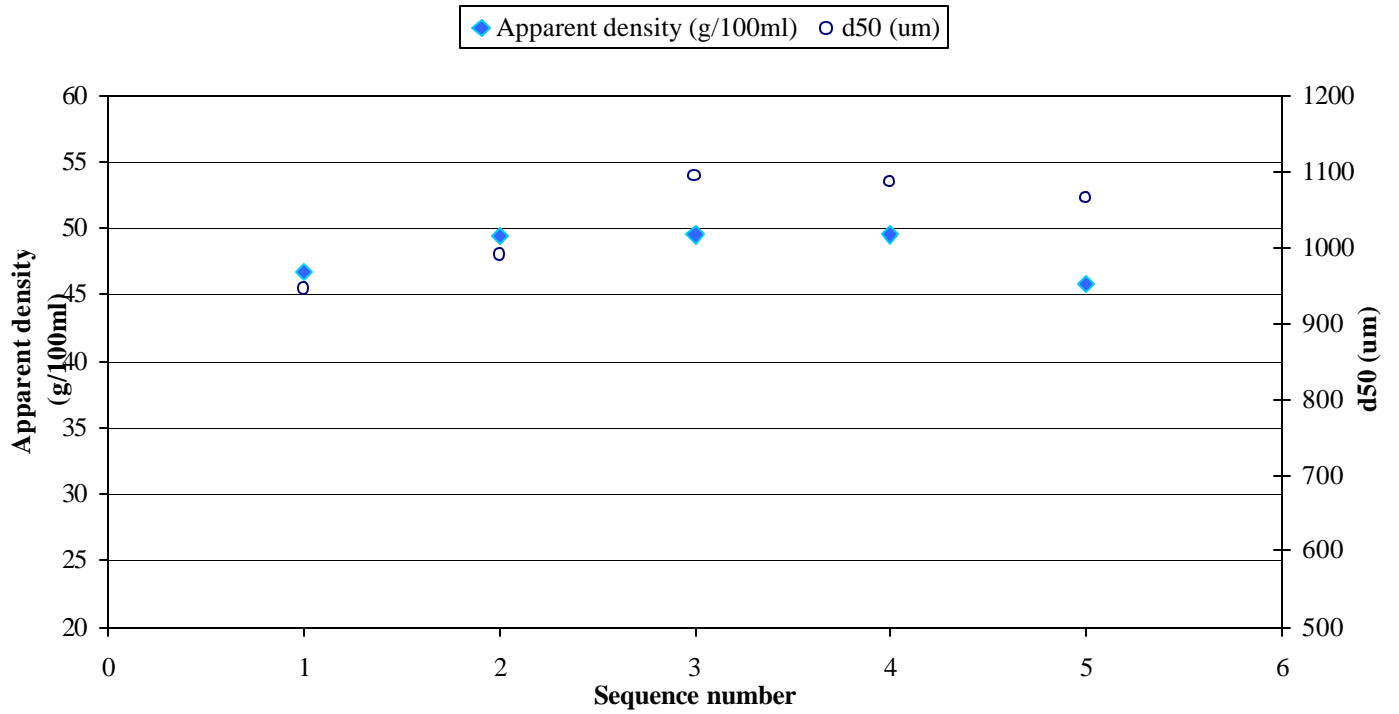


Figure 5.3.3 The d_{50} and apparent densities through the regeneration sequence - fluidised bed method

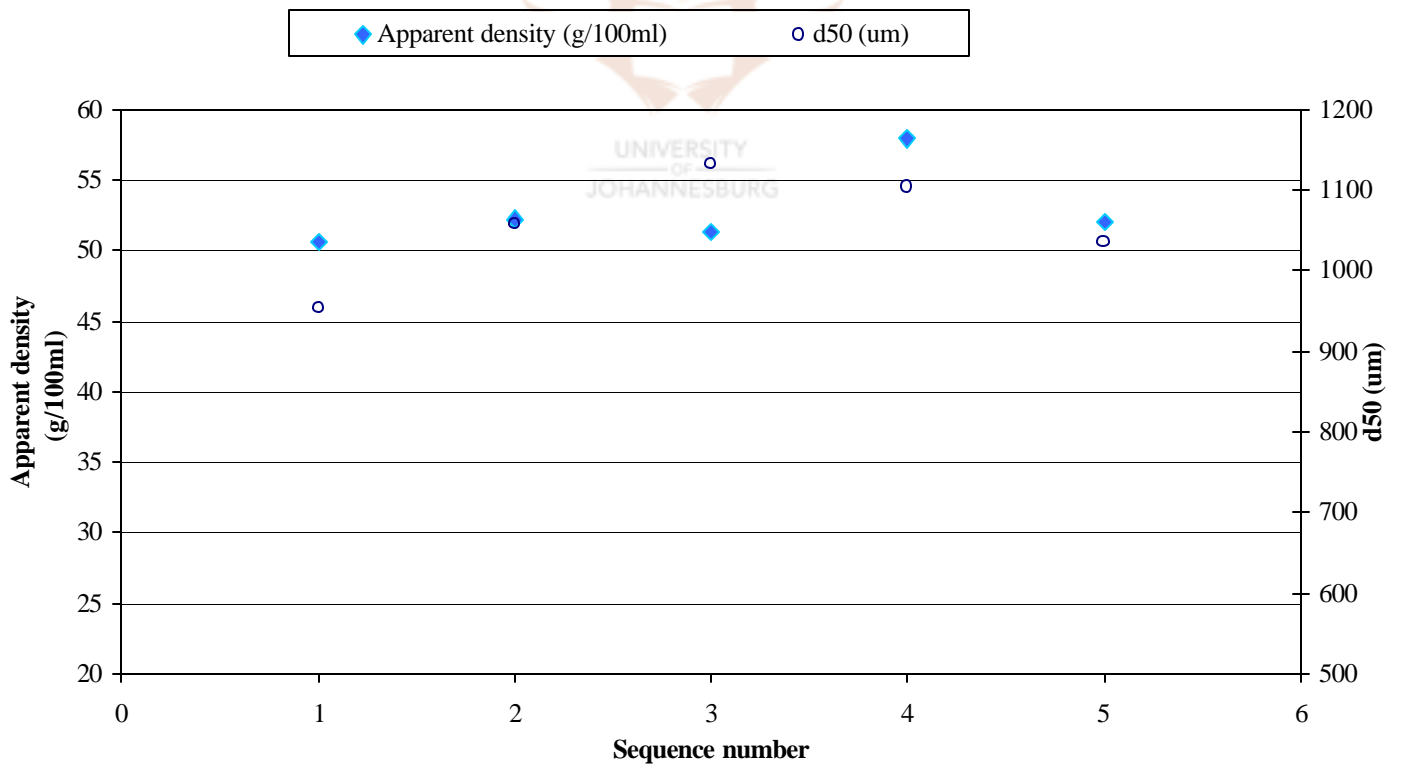


Figure 5.3.4 The d_{50} and apparent densities through the regeneration sequence – continuous bed method

There seems to be no breaking up of the carbon or generation of fines during the removal and transport of the carbon during the regeneration sequence of both methods, but during the regeneration process, it seems marginally more fines are generated during the continuous bed method, with a slightly lower d_{50} .

With the fluidised method, we can once again see a correlation between the apparent density and iodine number, but with the continuous bed method this does not seem so apparent. The regeneration performance in terms of adsorption capacity seems to be the same for both methods. In terms of apparent density, it may be that some standardisation of the method is needed. However, looking at Figure 5.3.3 and 5.3.4, these graphs seem very similar and follow the same trend, thus in terms of the relationship between apparent density and d_{50} , the two methods are similar.



5.4 EVALUATING THE GAC CONDITION BY ANALYSES OF THE CARBON QUALITY

The following questions arise in this section:

- How do the in-situ adsorption properties of the GAC change during normal filter operation and when is the GAC saturated?
- How do the adsorption properties of the GAC change during regeneration and which is the optimum regeneration method?

5.4.1 In-situ iodine number behaviour

Every GAC filter was sampled across the bed by means of extracting carbon from the middle of the bed with an injection-type sampler on 19 October 2001. The samples were mixed and its remaining adsorption capacity was measured by the laboratory staff of the Rietvlei water treatment plant (the uniformity of the adsorption capacity vertically through the bed has been tested). The adsorption capacity (measured in mg/g) was then compared with the amount of days the filter had been in operation.

The iodine number and the ratio of iodine number initially and as of 19 October 2001, versus days that the filter had been in operation is shown in Figure 5.4.1. This graph shows iodine adsorption values sampled by one person, measured by one person at the Rietvlei lab on one day. This eliminates any possible discrepancies of different people performing the experiment under different circumstances.

- Figure 5.4.1 indicates that over 550 days, the iodine adsorption had on average decreased from 630 to 430 mg/g.
- It also indicates that the ratio has followed the same trend as the iodine adsorption on 19 October 2001 versus days in operation, of 0.78 to 0.55 over 550 days.

This graph hasn't evened out, which indicates that there is still adsorption capacity left after 550 days, but as previously discussed, the regeneration contractor prefers the iodine number not to

drop below 400. Thus, looking at the trend, the iodine number should reach 400 in approximately 600 days.

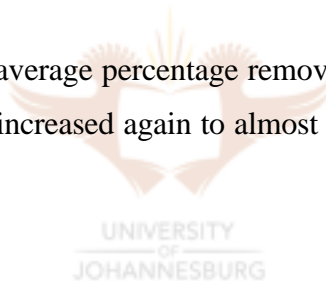
The iodine number versus days in operation was then extended for all available data for experiments done on the filters at any time by anyone in Figure 5.4.2.

- Figure 4.4.2 indicates that over 700 days, the iodine adsorption had on average decreased from 590 to 500 mg/g.

The deterioration of the GAC seems to be less than in the previous graph, but still follows the same trend. This may be ascribed to the discrepancies between laboratory methods and personnel. This may also be ascribed to initial inexperience of personnel in performing this complicated procedure.

The percentage TOC (total organic carbon) removal versus days running as of 5 December 2001 is shown in Figure 5.4.3.

- It seems after 500 days the average percentage removal has decreased from 14% to 11%. After day 550, the removal increased again to almost 16%.



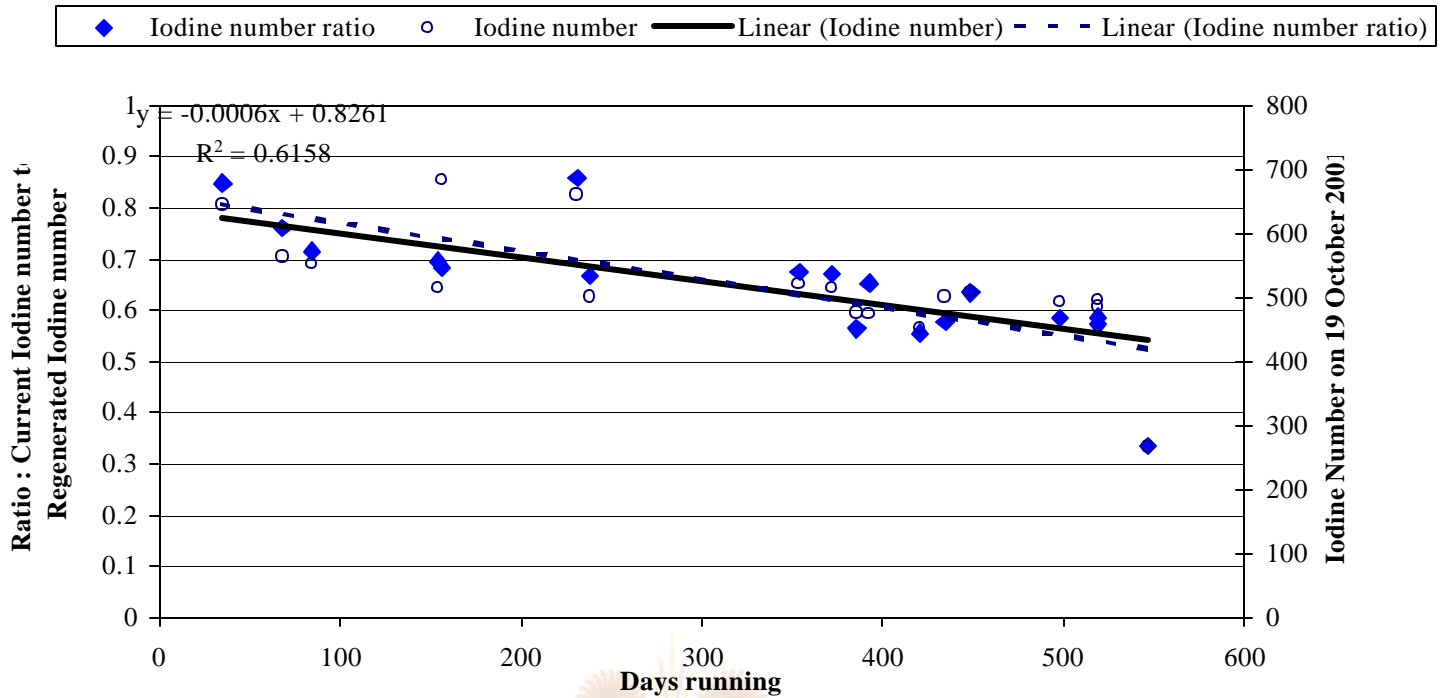


Figure 5.4.1 The ratio of iodine adsorption initially and as of 19/10/01 and iodine number as of 19/10/01 versus the number of days the filter has been in operation

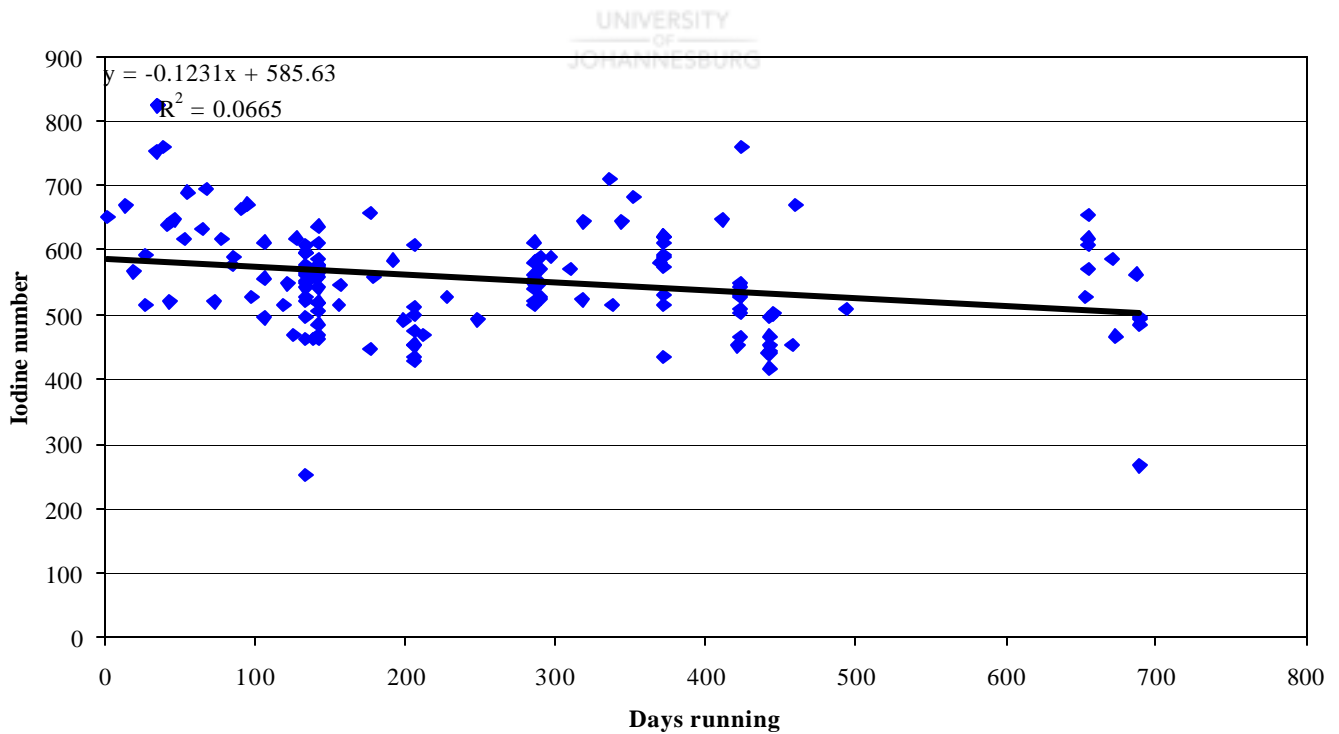


Figure 5.4.2 Iodine adsorption versus number of days that filter is in operation

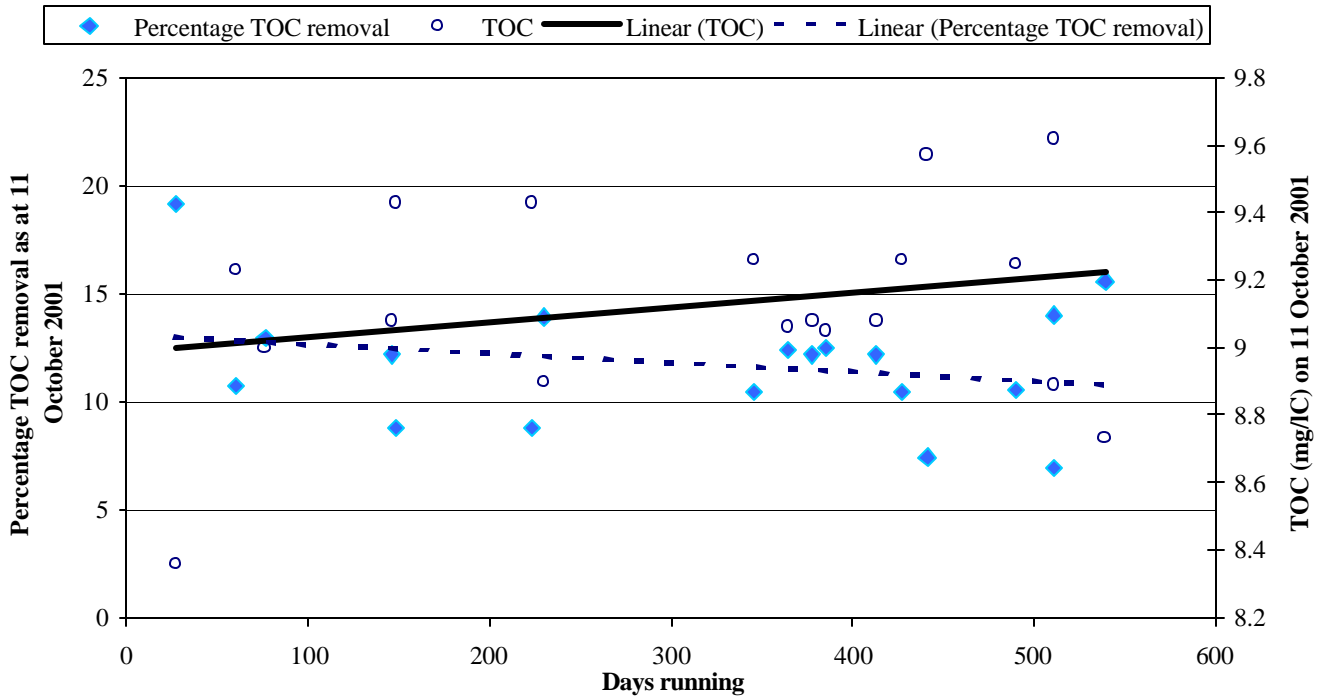


Figure 5.4.3 Percentage TOC removal and actual TOC in the effluent on 11 October 2001 versus number of days that the filter is in operation



5.4.2 Iodine number and Methylene blue number during regeneration

The iodine and methylene blue adsorption for the fluidised bed and continuous bed methods are shown in Tables 5.4.1 – 5.4.2.

- The average iodine no. before regeneration for the fluidised bed method is 397 and after is 770, a 38% increase (19 data points, first and second regenerations).
- The average methylene blue no. before regeneration for the fluidised bed method is 83 and after is 152, a 83% increase (19 data points, first and second regenerations).
- The average iodine no. before regeneration for the continuous bed method is 661 and after is 828, a 26% increase (6 data points, first and second regenerations).
- The average methylene blue no. before regeneration for the continuous bed method is 196 and after is 223, a 14% increase (6 data points, first and second regenerations).

Looking at these figures, it seems from an if iodine number were the only performance indicator, and the only concern of the engineer, the fluidised bed method would be most favorable.

However, more information on the continuous bed method is needed to make certain decision.

The iodine adsorption through the regeneration cycle for the both regeneration methods are shown in Figure 5.4.4. Both methods were measured only once. The iodine adsorption before and after 1st and 2nd regenerations is shown in Figure 5.4.5.

- Over a typical regeneration cycle the iodine number increases from 524 to 806 mg/g, a 54% increase (19 data points, first and second regenerations). The difference between these results and the previous section (first bullet) might be ascribed to the fact that these results were obtained over a long period of time, which may include initial difficulties in doing the test.
- The iodine numbers before the first and second regenerations seem similar, between 350 mg/g to 400 mg/g (17 data points for first regeneration, 4 for second regeneration).
- The iodine numbers after the first and second regenerations also seem similar, between 725 mg/g to 775 mg/g (17 data points for first regeneration, 4 for second regeneration).

It seems there is no increased deterioration of the adsorption capacity after the second regeneration. The GAC of certain filters at Rietvlei have only been regenerated twice and any

further deterioration of the adsorption capacity after 3^d or successive regenerations will have to be investigated further.

INPUT			OUTPUT	
Filter no	Iodine nr	Methylene blue no	Iodine nr	Methylene blue no
13	412	83	794	161
11	405	83	894	185
6	371	83	800	178
9	396	83	804	161
8	527	83	869	168
16	398	83	815	157
18	415	83	726	128
12	420	83	845	161
19	398	83	766	137
2	396	83	726	136
4	419	83	760	160
5	383	83	735	137
7	392	83	772	140
15	368	83	751	145
17	355	83	768	139
sump	388	83	721	141
20	377	83	740	144
1	423	83	741	144
2	356	83	749	183
3	370	83	771	185
Average	397	83*	770	152

Table 5.4.1 Regeneration data before and after regeneration for the fluidised bed method (Primary data as measured by Thermex - all according to date). *minimum possible measurement

INPUT			OUTPUT	
Filter no	Iodine nr	Methylene blue no	Iodine nr	Methylene blue no
3	805	253	907	249
14	710	218	844	221
10	689	174	844	225
4	603	172	830	220
sump	590	177	755	207
5	569	183	788	214
Average	661	196	828	223

Table 5.4.2 Regeneration specifications before and after regeneration for the continuous bed method method (Primary data as measured by Cactus - all according to date).



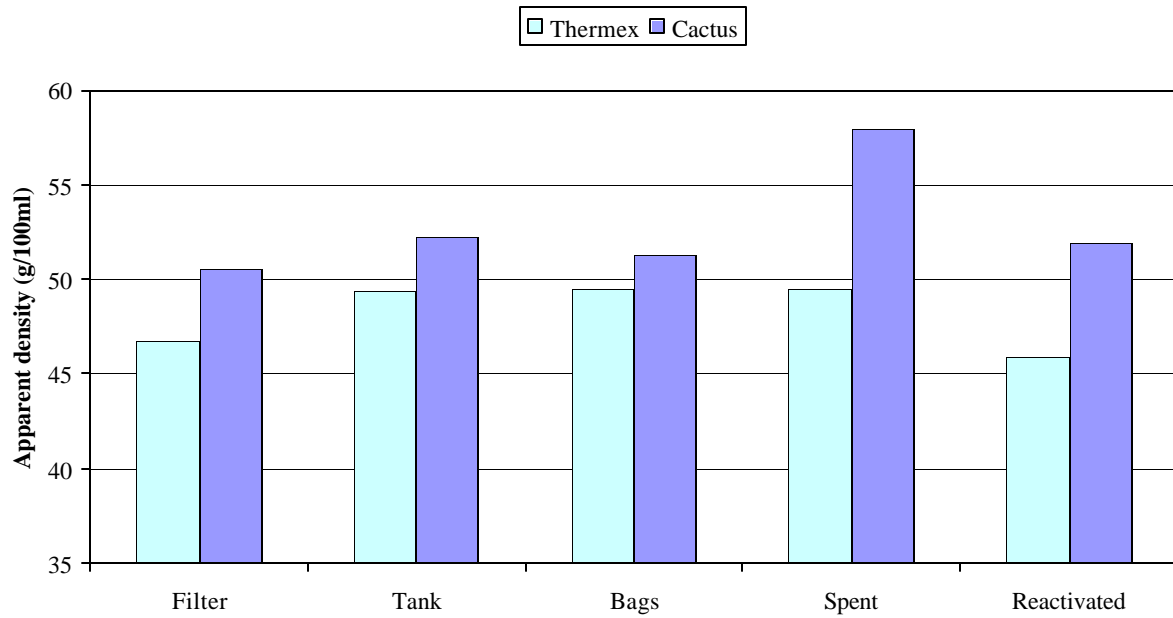


Figure 5.4.4 Change in iodine number through the regeneration sequence for the two regeneration methods

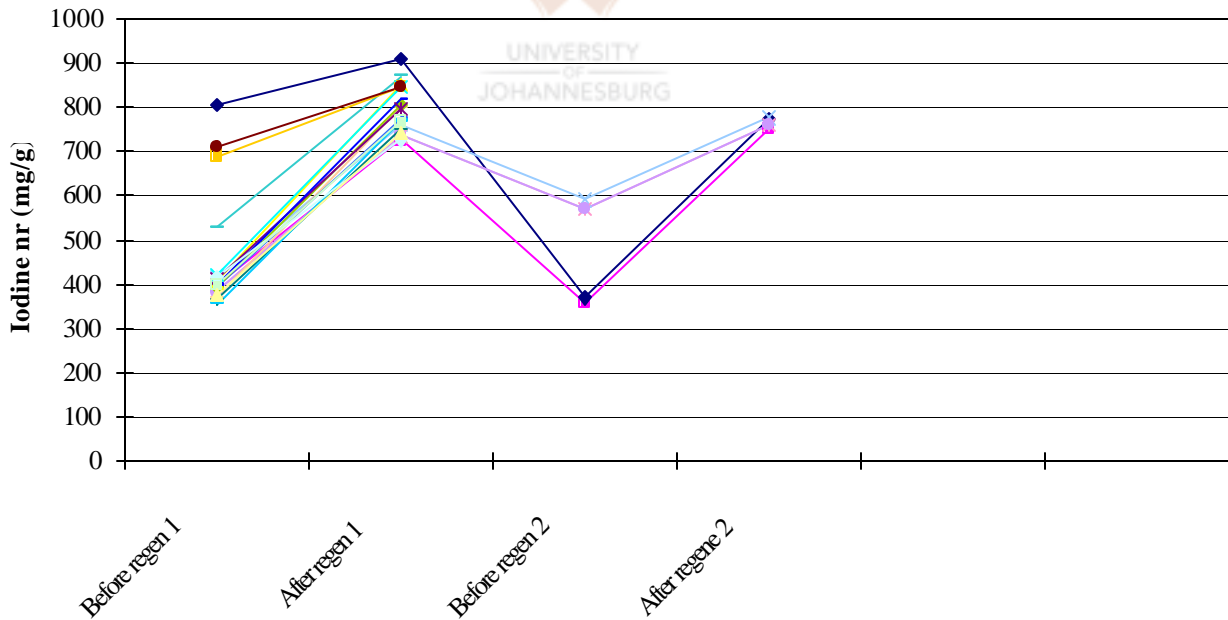


Figure 5.4.5 Change in iodine number before and after the 1st and 2nd regenerations for including both regeneration methods

5.5 EVALUATING THE GAC CONDITION BY ANALYSES OF THE WATER QUALITY

The following questions arise in this section:

- How do the properties (UV_{254} , colour) of the water change during normal filter operation, and when does the water quality deterioration signal the regeneration of the carbon?

Efficient use of activated carbon for the removal of organic contaminants requires the analytical ability to accurately determine the concentration of the dissolved organic compounds of concern. These analytical methods are applied in the preliminary design investigations and during the monitoring of the adsorber performance.

5.5.1 UV adsorption

5.5.1.1 Available data

UV adsorption at the Rietvlei water treatment plant varies greatly on a day to day basis, especially the UV adsorption measured on the raw water coming into the plant (between 12 and 20 adsorption/m).

The actual UV_{254} absorbency values for the after DAFF and after GAC water since commissioning is shown in Figures 5.5.1 and 5.5.2 respectively.



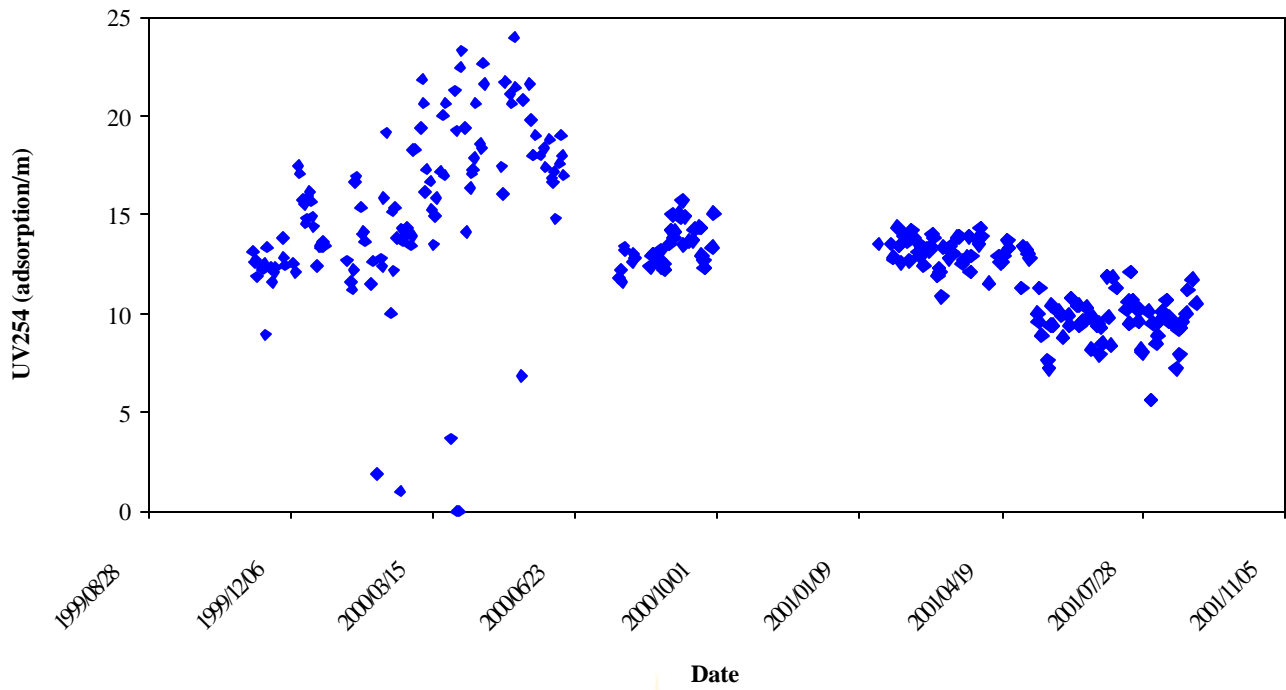


Figure 5.5.1 UV absorbance of the after DAFF water (09/11/99 – 08/07/01)

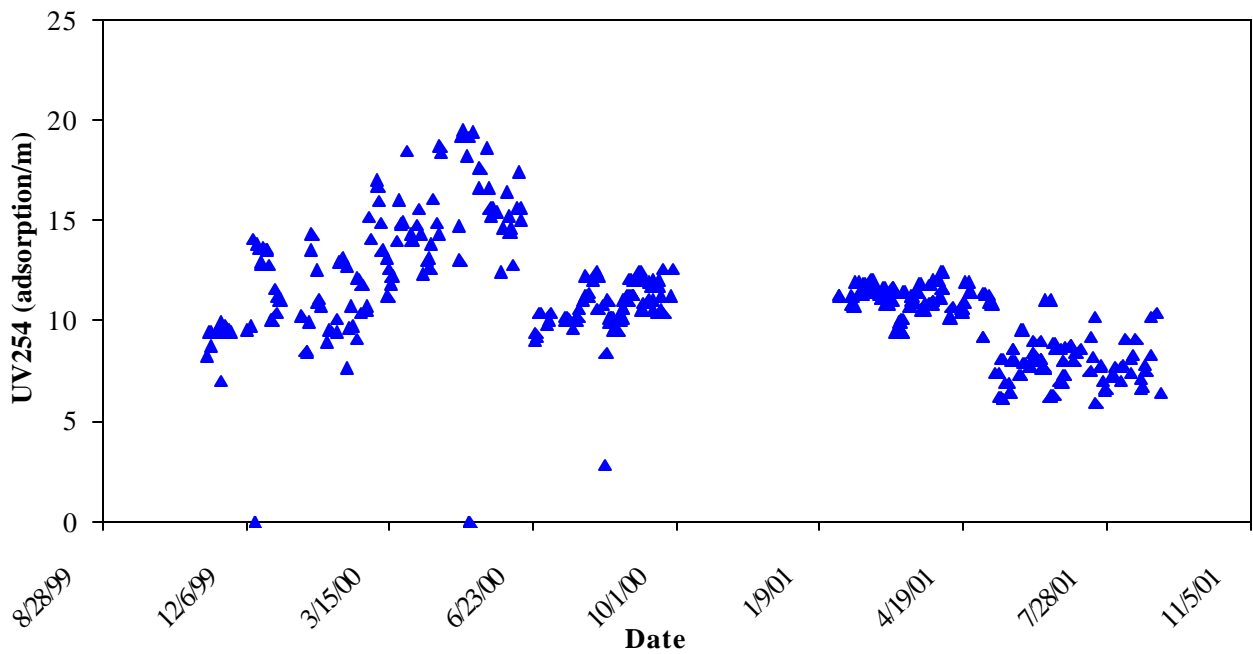


Figure 5.5.2 UV absorbance of the after GAC water (09/11/99 – 08/07/01)

5.5.1.2 Overall trend & removal

A frequency curve showing the UV removal of the raw water and subsequent processes is shown in Figure 5.5.3. Can the UV removal be used as a parameter to check when the GAC should be removed and can a regeneration frequency schedule then be set up?

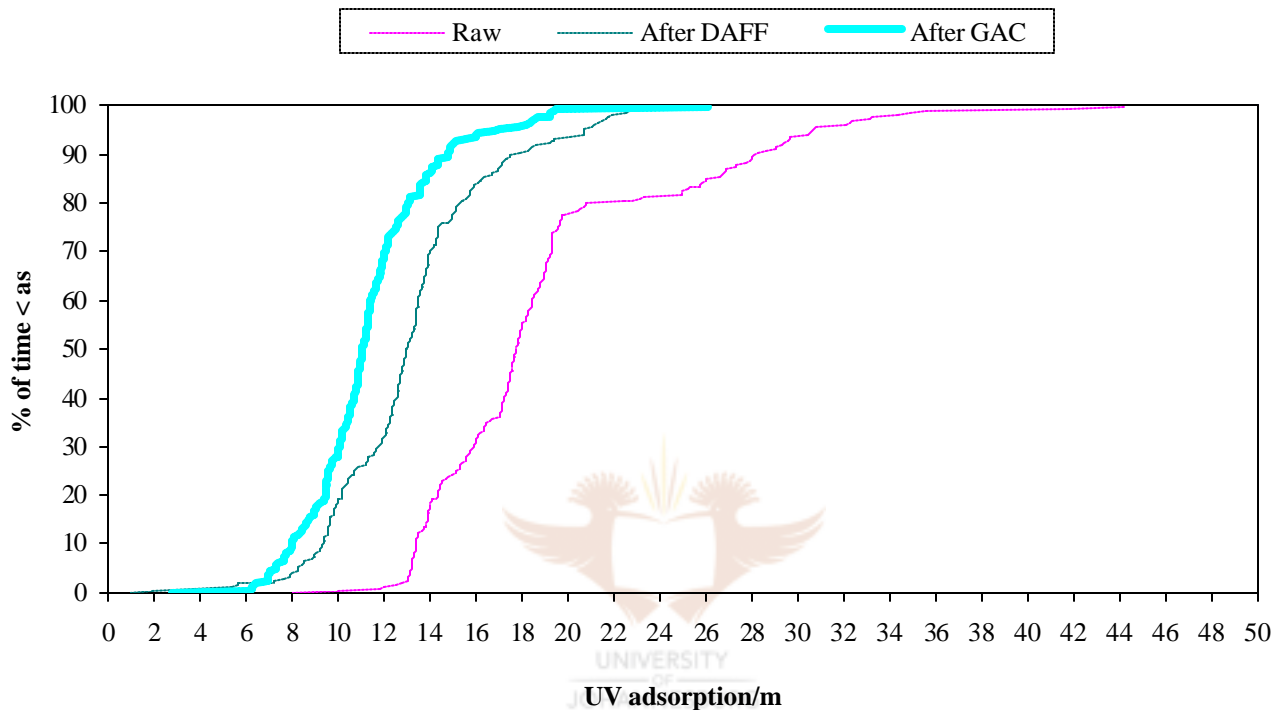


Figure 5.5.3 Frequency graph of the UV removal from commissioning until September 2001 for the Raw, after DAFF and after GAC water

As said before, the UV adsorption measured on the raw water coming into the plant varies greatly (between 12 and 20 adsorption/m). Normal treatment processes significantly reduce UV (by 4 /m). The GAC process then further reduces the UV adsorption (by 2 /m).

Since commissioning, the percentage removal by GAC has greatly fluctuated, between around 5 – 35%. The following was established in the year of close monitoring in 2000 (De Kloe, 2000):

- Percentage removal during pilot plant: 51%
- Percentage removal during monitoring in 2000: 20%

After all this time, is the percentage removal still adequate?

5.5.1.3 Analyses of 01/01/01 – 28/07/01

To investigate these questions, the % removal by the DAFF filters and % removal by the GAC filters for the data available for the first six months of 2001 was calculated.

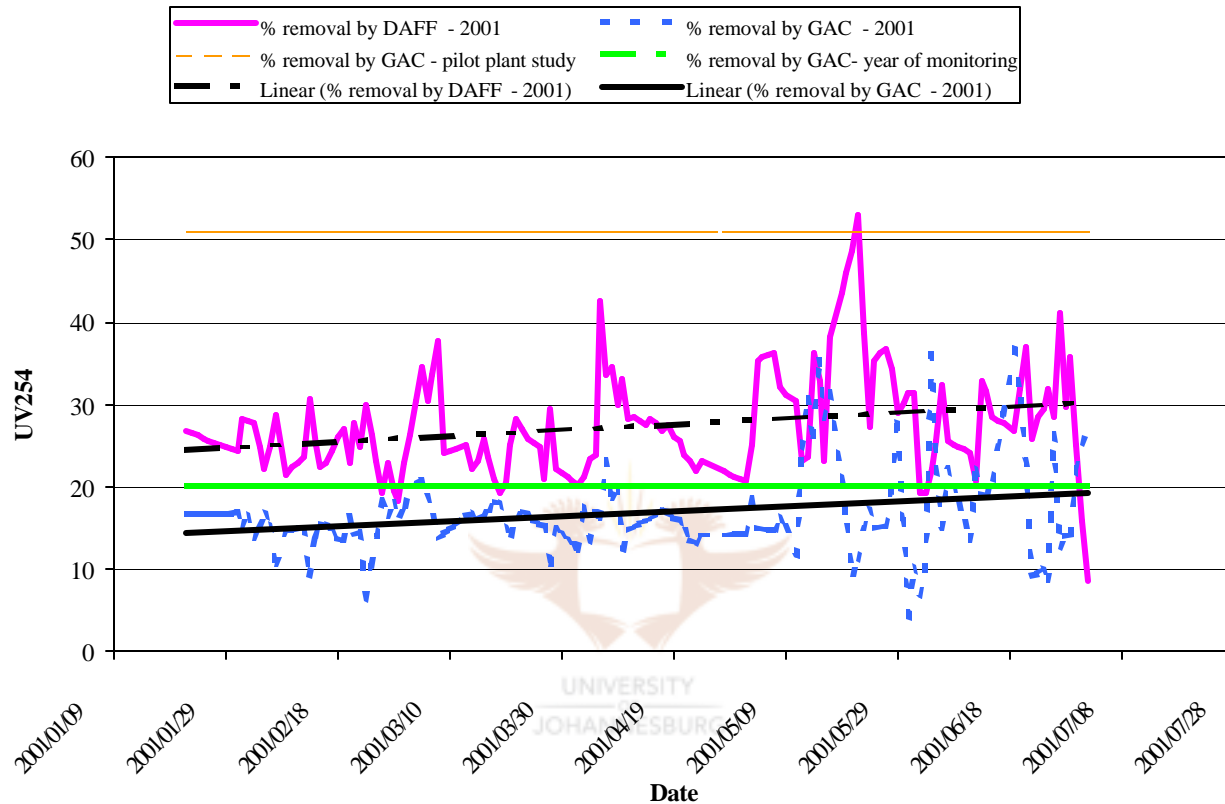


Figure 5.5.4 The percentage UV removal by DAFF and by GAC water versus time, including the percentage removal of the pilot plant study and the year of monitoring

It is clear from Figure 5.5.4 that the DAFF process removes between 25 – 30% of the UV and the GAC process then further removes around 15 - 20%. Two different UV spectrophotometers that was used during the study, one older, one new. The graph can be split in two parts, the first half of the graph is more consistent and second half of the graph much noisier. This is due to a fault that was later detected to one of the new cuvettes. Disregarding the second half of the graph, the current percentage removal by the GAC filters falls slightly short of the 20% removal by GAC measured in the year of monitoring, and falls even shorter of the 51% of the pilot plant study. However, there is a clear increase in the percentage removal by both DAFF and GAC

processes. To decide on a regeneration frequency, it was expected that the percentage removal would decline with time. This is obviously not the case, and this increase in percentage removal might indicate biological activity on the filter media.

For further analyses, C/Co graphs were generated for each GAC filter (1 - 20). These can be viewed in Appendix 8.5. From these graph linear trend lines were generated to give an overall idea of the decline in UV₂₅₄ removal. The average gradient was found to be 0.0002, the average R² was 0.094 and the average starting C/Co (y at t = 0) was 0.78. Using the calculated average gradient, and starting value of 0.78, a prediction table can be set for an estimated time. Figure 5.4.2 (section 5.4.1) seemed to be a good representation of conditions in the filters and as it was done on one day by one person, any possible discrepancies of different people performing the experiment under different circumstances is eliminated. The graph indicated gradient of -0.0006 for the C/Co linear trend line. As all the filters have been regenerated we consider at the average iodine number after regeneration: for the continuous bed method it's 828 and for the fluidised bed method it's 770. Thus a feasible starting iodine number is 800 mg/g.

Regeneration frequency	UV254	UV254	Iodine nr	Iodine nr
(days)	(C/Co)	% removal	(C/Co)	(mg/g)
0	0.78	22	1	800
100	0.8	20	0.94	752
200	0.82	18	0.88	704
300	0.84	16	0.82	656
400	0.86	14	0.76	608
500	0.88	12	0.7	560
600	0.9	10	0.64	512
700	0.82	8	0.58	464
800	0.94	6	0.52	416

Table 5.5.1 Calculated predictions of the % UV₂₅₄ removal and iodine number after subsequent days in operation

It is recommended by the regeneration contractor that the iodine number should not drop below 400, thus the regeneration frequency should not be longer than 800 days. Any UV removal below 10% would not be practically feasible, thus as far as the UV_{254} is concerned, the regeneration frequency should not exceed 600 days.

5.5.2 Colour removal

Another parameter investigated is colour removal. The colour of the effluent of all the filters were measured on 5 December 2001 and compared to the amount of days each filter has been in operation since its last regeneration.

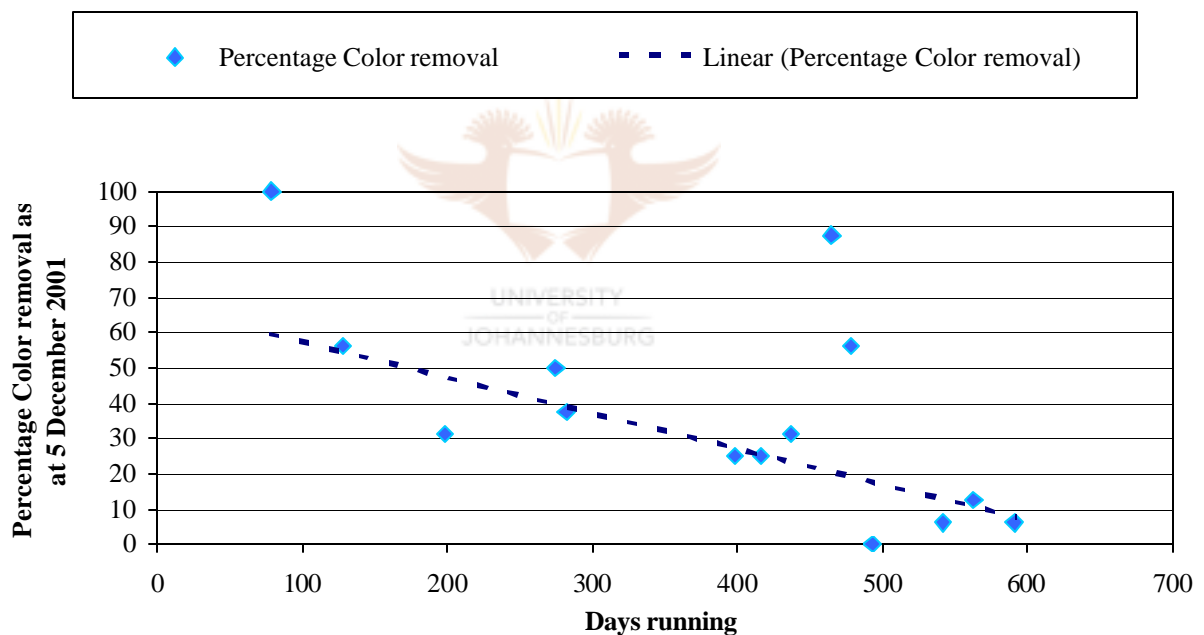


Figure 5.5.5 Percentage colour removal versus days in operation

Here there is a more clear decline in the percentage removal of colour, from around 55 % to almost no removal of colour.

5.6 CURRENT MONITORING PRACTICES

- Henket (California, USA): A composite GAC is collected from the filters annually and farmed out for analyses of Iodine and Molasses number. The numbers decrease and at some point become asymptotic, which indicates the GAC has outlived its useful life. Earlier warnings are the daily Threshold Odour Tests, by the Operators and Customers Complaints. GAC efficiency is monitored by conducting in-house analyses of TOC twice a day. Both the incoming and finished water is tested by the Shimadzu TOC 5000 A analyser.
- Kermeen (UK): Iodine number, density increase calculating volatile matter
- Van der Aa (Amsterdam, Netherlands): The reactivation frequency has been determined at once in every 18 months. This frequency has been determined by pilot-plant research. The research showed that DOC was the critical parameter (and not pesticides). In the real plant all carbon filters are analysed on DOC every month. The collected water from all 26 carbon filters is analysed every week on DOC and every three months on a specific set of pesticides. The criteria is the DOC-concentration of the blended effluents of all 26 carbon filters, which should be $< 3 \text{ mg C/l}$.

CHAPTER 6


CONCLUSIONS & RECOMMENDATIONS

Through the course of this study, it became apparent that to date, the performance of the GAC treatment plant has been satisfactory. However, numerous problems also arose, the most significant being the excessive GAC losses during a regeneration cycle. Through computation, analyses of plant and regeneration records and direct measurements (often difficult and tedious) a better understanding of the whole system was obtained and some preconceived ideas were confirmed. However, some new information has also come to light.

This thesis is a practical guide to give a better understanding of what has been occurring at the plant and of future implementations to be considered. When purchasing GAC the question arises of which size carbon and what hardness is preferable.

6.1 GAC PURCHASING

SIZE

- 
- The theoretical bed expansion model indicates that the predicted bed expansion ranges from 3% to 5%, which translates into 42 mm to 70 mm. At the design backwash rates of 20 to 24m/h (0.006 to 0.007m/s) the expected bed expansion should range from 5 to 15%, or 70 mm to 210 mm. The average freeboard available is 650 mm for the 12 x 40 and 430 mm for the 8 x 30 carbon, indicating that the GAC should comfortably be contained within the filter bays during backwash. This indicates that no GAC should wash over the weir during backwashing. Actual measurements indicated that approximately 0.004% of the 12 x 40 GAC washed over the weir and approximately 0.008% of the 8 x 30 GAC. Thus according to losses over the weir, no one size is better than the next.
 - As the 8 x 30 GAC has not been regenerated yet, no comparison of its performance during regeneration could be made. However, both the regeneration contractors have regenerated 8 x 30 GAC from other water treatment plants and in both cases, these losses

were less than 10%. Thus, according to losses during regeneration, the 8 x 30 GAC might, after further investigation, prove to be a preferable purchase to the 12 x 40 GAC.

- For the 8 x 30 carbon the design rate of 24m/hr only expands 60% of the carbon in summer and 70% in winter. At the actual rate of 18m/hr only 40% is expanded in summer and 55% in winter. For the 12 x 40 carbon the design rate of 20m/hr expands 95% of the carbon in summer and winter, as well as at the actual rate of 18m/hr. Thus, the current backwash rate for the 12 x 40 carbon is adequate but falls short with the 8 x 30 carbon and these filters are not being adequately cleaned.

HARDNESS

- Tests indicate that there is no marked attrition during backwashing for both the GACs, which indicates that the hardness of the GAC is satisfactory. However, only after the 8 x 30 GAC has been regenerated, can a comparison be made about the hardness of the carbon during regeneration, as the regeneration contractors have not regenerated any other 12 x 40 GAC used for water treatment.



6.2 REGENERATION

The GAC also needs to be tracked as it moves through the treatment plant as well as the regeneration plant, whereby losses can be monitored and controlled. In a case like this, the regeneration contract is very important and needs careful consideration.

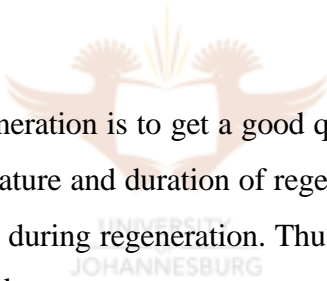
LOSSES

- The overall nett GAC losses of 21 % are excessive and much higher than anticipated, when compared to the original design assumptions as well as literature and experience, thus substantial savings are possible.
- The introduction of a modest 15 % regeneration loss would bring down the monthly cost of GAC to about 25 % per cycle.

TRACKING OF THE GAC INVENTORY

- More attention should be given to the easy and reliable measurement of the GAC inventory as it flows through the system, to allow operators to immediately and accurately pinpoint problems as they happen.
- Current discrepancies about the moisture content of the GAC influencing measurements can be solved by drying the GAC completely before it leaves the water treatment plant. This may be done by inserting a industrial dryer somewhere along the movement of the GAC before it reaches the transport bags.
- By inserting a sieve on the outlet of the sump, the GAC lost to the river has been eliminated (7 % of the monthly GAC cost per cycle), which has been invaluable to be able to track the GAC at the treatment plant.

REGENERATION CONTRACT

- 
- The problem regarding regeneration is to get a good quality regenerated carbon, one needs to increase the temperature and duration of regeneration. However, this also increases the losses incurred during regeneration. Thus a balance between quality and losses needs to be established.
 - A way to minimise the losses is by stipulating in the regeneration contract that the losses during regeneration would be carried by the contractor. This would motivate the contractor to optimise their process for minimal losses. However, to maintain quality, a minimum iodine adsorption capacity after regeneration would also be specified.
 - Discrepancies about the different iodine numbers achieved by different laboratories on the same sample can be solved by introducing the services of an independent laboratory.

6.3 MONITORING

Feasible monitoring parameters are very important. They need to be quick, easy and repeatable. At a water treatment plant, fast action needs to be taken when there are spurts of odour and taste causing compounds in the water. Either the water quality or the remaining adsorptive capacity of the carbon or both are monitored.

- It seems that there is a link between apparent density and iodine number, and as apparent density can be measured within minutes after the GAC is dried, it might be a quick indicator to give an idea of the adsorption capacity left, which may be checked later by the long and tedious method of iodine number analyses.

RECOMMENDED PARAMETERS

- UV_{254} of the water be measured
- DOC/TOC of the water be measured
- Iodine number of the carbon be measured
- Apparent density of the carbon be measured

RECOMMENDED FREQUENCY OF MEASUREMENTS

- UV_{254} measured every week
- DOC/TOC measured every second week
- Iodine number measured every month
- Apparent density measured every month

6.4 REGENERATION FREQUENCY

The regeneration of a filter cannot be done on a whim. This is an activity that needs to be scheduled in advance to facilitate both the plant engineer, operators and the regeneration contractor. The following has been estimated:

Regeneration frequency	GAC bed life	Iodine number (mg/g)	UV ₂₅₄ removal
14 days	280 days	665	17%
21 days	420 days	597	14%
28 days	560 days	535	11%
35 days	700 days	464	8%

The regeneration frequency indicates how many days would pass between the removal and regeneration of subsequent filters. The GAC bed life indicates how long the filter would have been in operation. After careful consideration it is recommended that the GAC be regenerated every 400 to 600 days, depending on the practical constrictions of the engineer.

6.5 CONTINUOUS MONITORING

Discrepancies between laboratories, problems with equipment and measuring difficulties has made the analyses of results very difficult and it is recommended that rigorous monitoring of the losses, water quality and GAC quality is continued.

6.6 FUTURE WORK

- It seems there is no increased deterioration of the adsorption capacity after the second regeneration. The GAC of certain filters at Rietvlei have only been regenerated twice and any further deterioration of the adsorption capacity after 3rd or successive regenerations will have to be investigated further.

-
- During the investigation it became apparent that there is possible biological activity on the GAC. Should this be further investigated, BAC (Biological activated carbon) may be investigated so that the regeneration frequency of the GAC will be extended, which will obviously greatly reduce the operating costs of the GAC.
 - The current study should be repeated periodically to determine the ongoing benefits or detriments of regeneration to establish a standard for the optimum regeneration frequency.



CHAPTER 7

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CHAPTER 8

APPENDICES

- 8.1 Losses
- 8.2 Calculated porosities for sum of squares
- 8.3 Sum of squares (sphericity) for calibration of the mathematical model
- 8.4 Sieve analyses – the two regeneration methods
- 8.5 UV254 C/Co graphs for filters 1 to 20
- 8.6 The UV performance graphs
- 8.7 Iodine numbers for filters 1 - 20



8.1 LOSSES

FLUIDISED BED METHOD

GAC HANDLING DURING

REACTIVATION

Primary data (All according to date)

		13	11	6	9	8	16	18	12	19	2
INPUT											
Volume	m ³	8.5	13.05	14.6	12	12.4	11.75	13.6	13.7	11.25	11.25
Mass	kg	6608	9455	11992	8407	9350	8769	9997	10165	8724	8724
Moisture content	%	37.67	36.51	35.21	30.7	34.97	36.56	38.64	41	36.9	32.89
Volatile content	%	11.53	12.26	12.98	12.98	11.83	9.73	9.77	11.5	10.8	10.8
Apparent density	kg/m ³	524	589	594	598	567	566	573	540	571	521
Iodine No.		412	405	371	396	527	398	415	420	398	396
Methylene blue No.		83	83	83	83	83	83	83	83	83	83
OUTPUT											
Volume	m ³	7.1	9.65	11.2	9.5	10.15	9.85	11.05	10.95	8.6	10
Mass	kg	3479	5515	6516	5071	5292	4853	5358	5081	4415	4632
Moisture content	%	0.03	0.03	0.04	0.04	0.04	0.03	0.02	0.03	0.02	0.02

Volatile content	%	0.07	0.09	0.09	0.09	0.09	0.08	0.09	0.08	0.08	0.08
Apparent density	kg/m ³	493	487	492	511	473	502	504	455	481	465
Iodine No.		794	849	800	804	869	815	726	845	766	726
Methylene blue No.		161	185	178	161	168	157	128	161	137	136

ID % increase	51.53	44.14	34.68	34.45	53.26	43.99	26.70	56.48	34.15	39.35
Mass loss %	47.35	41.67	45.66	39.68	43.40	44.66	46.40	50.01	49.39	46.91
Volume loss %	16.47	26.05	23.29	20.83	18.15	16.17	18.75	20.07	23.56	11.11



FLUIDSED BED METHOD**(CONTINUED)**

GAC HANDLING DURING

REACTIVATION

Primary data (All according to date)

4 5 7 15 17 Sludge 20 1 2 3 Average

INPUT													
Volume	m ³	12.35	11.88	11.35	11.5	9.1	8.3	10.15	10.8	10.7	13.55	11.68	
Mass	kg	8992	8518	8164	8208	7123	5926	7306	7820	7991	9812	8666.00	
Moisture content	%	39.4	35.46	38.9	39.13	38.5	32.36	35.62	37.42	40.85	34.84	36.63	
Volatile content	%	10.27	9.4	8.2	8.7	7.97	8.1	7.73	8.81	7.47	8.63	9.76	
Apparent density	kg/m ³	567	573	580	554	576	561	533	568	572	528	563.44	
Iodine No.		419	383	392	368	355	388	377	423	356	370	397.33	
Methylene blue No.		83	83	83	83	83	83	83	83	83	83	83.00	
OUTPUT													
Volume	m ³	9.1	9.9	7.9	8.05	7.25	7.1	7.5	8.9	8.55	11.95	9.31	
Mass	kg	4211	4607	3943	3894	3519	3200	3564	4197	3925	5382	4536.67	
Moisture content	%	0.02	0.02	0.02	0.04	0.02	0.02	0.04	0.03	0.02	0.01	0.03	
Volatile content	%	0.08	0.08	0.08	0.07	0.08	0.07	0.08	0.07	0.06	0.05	0.08	
Apparent density	kg/m ³	484	482	486	496	486	453	474	450	458	452	478.00	

Iodine No.		760	735	772	751	768	721	740	741	749	771	769.94
Methylene blue No.		160	137	140	145	139	141	144	144	183	185	152.44
ID % increase		34.04	28.27	33.10	35.56	33.33	28.52	38.84	30.46	30.94	46.02	37.89
Mass loss %		53.17	45.91	51.70	52.56	50.60	46.00	51.22	46.33	50.88	45.15	47.43



CONTINUOUS BED**METHOD****GAC HANDLING DURING
REACTIVATION****Primary data (All
according to date)****Average**

		3	14	10	4	SUMP	5	
INPUT								
Volume *	m ³	8.1	7.5	9.7			8.813	8.53
Mass	kg	7440	7460	9840	3868	2152	8840	6600.00
Moisture content	%	43.7	50.6	48.1	43	46	51.6	47.17
Volatile content	%	9.88	10.18	9.35	14.05	24.19	12.76	13.40
Apparent density	kg/m ³	516	490.1	524.9	506	514	497	508.00
Iodine No.		805	710	689	603	590	569	661.00
Methylene blue No.		253	218	174	172	177	183	196.17
OUTPUT								
Volume *	m ³	7.42	6.57	10.58	9.695	4.668	8.364	7.88
Mass	kg	3780	3280	5195	3868	2152	3680	3659.17
Moisture content	%	0.02	0.03	0.02	0.01	0.01	0.01	0.02
Volatile content	%	0.08	0.07	0.08	0.17	0.19	0.1	0.12
Apparent density	kg/m ³	510	499	491	399	461	440	466.67
Iodine No.		907	844	844	830	755	788	828.00
Methylene blue No.		249	221	225	220	207	214	222.67

ID % increase	12.67	18.87	22.50	37.65	27.97	38.49	26.36
Mass loss %	49.19	56.03	47.21			58.37	52.70

*This regeneration plant does not have a volumetric bin, and the masses were recorded on a weigh bridge, from where the volumes were estimated.

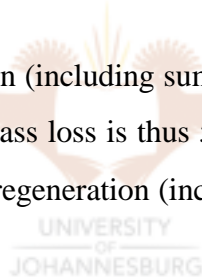


For the fluidised bed method:

- The average volume before regeneration (including sump) is 11.83m^3 and after regeneration is 9.31m^3 . The average regeneration volume loss is thus 20.41%.
- The average mass before regeneration (including sump) is 8666kg and after regeneration is 4537kg. The average regeneration mass loss is thus 47.43%.
- The average volatile content before regeneration (including sump) is 9.76% and after regeneration is 0.03%.
- The average apparent density before regeneration (including sump) is 56.3g/100ml and after regeneration is 47.8g/100ml.
- The average iodine number before regeneration (including sump) is 397mg/g and after regeneration is 770mg/g. The average increase in iodine number is thus 37.89%.

For the continuous bed method:

- The average calculated volume before regeneration (including sump) is 8.53m^3 and after regeneration is 7.88m^3 .
- The average mass before regeneration (including sump) is 6600kg and after regeneration is 3657kg. The average regeneration mass loss is thus 52.70%.
- The average volatile content before regeneration (including sump) is 13.40% and after regeneration is 0.12%.
- The average apparent density before regeneration (including sump) is 50.8g/100ml and after regeneration is 46.7g/100ml.
- The average iodine number before regeneration (including sump) is 661mg/g and after regeneration is 828mg/g. The average increase in iodine number is thus 26.36%.



8.2 CALCULATED POROSITIES FOR SUM OF SQUARES

An example of how the porosities were calculated:

γ		Sphericity = 0.6	
8x30		Calculated porosity	@ 20 °C
A1	0.738273		
Re_B	0.2313		
S_v	9132.42		
ρ	water density (kg/m ³)	998.204	
ρ_s	media density (kg/m ³)	1544	
g	gravitational acceleration	9.81 m/s ²	
e	porosity	0.3565	
μ	dynamic viscosity (N.s/m ²)	0.00102	
V	Backwash rate (m/s)	0.001389	
ψ	sphericity	0.6	
d_g		1095 μ m	0.001095 m

Porosity calculations for sum of squares 12x40

v (m/s)

sphericity = 0.65

Sieve size (μ m)	0.001	0.003	0.004	0.006	0.007	0.008	0.012	0.018
213	0.781	0.8432	0.881	0.9075	0.9273	0.9426	0.9705	0.9903
461	0.577	0.6553	0.7087	0.7494	0.7826	0.8105	0.8699	0.927
596	0.5081	0.5863	0.6404	0.6832	0.7188	0.7492	0.8154	0.884
777	0.4411	0.5168	0.5705	0.6134	0.6493	0.6808	0.752	0.8287
1001	0.3524	0.4543	0.5061	0.5481	0.5838	0.6151	0.6872	0.7688
1285	0.3305	0.3977	0.4468	0.4869	0.5214	0.5519	0.6234	0.7057
1497	0.3017	0.3657	0.4129	0.4517	0.4852	0.5149	0.585	0.6667

8.3 SUM OF SQUARES (SPHERICITY) FOR CALIBRATION OF THE MATHEMATICAL MODEL

12 x 40:

Backwash rate (m/s)	Lab expansion (mm)	0.6	delta	delta ²
0.001	0	0.08	0.08	0.0064
0.002	0	1.9	1.9	3.61
0.004	0	3.4	3.4	11.56
0.005	7.74	6.3	1.44	2.0736
0.007	14.29	10.1	4.19	17.5561
0.008	18.33	16.6	1.73	2.9929
0.012	47.62	43.4	4.22	17.8084
0.018	112.7	146.7	34	1156

1211.61

0.65	delta	delta ²
0.7	0.7	0.49
1.7	1.7	2.89
3	3	9
4.6	3.14	9.8596
8.7	5.59	31.2481
13.8	4.53	20.5209
38.1	9.52	90.6304
125.8	13.1	171.61

336.249

0.66	delta	delta ²
0.7	0.7	0.49
1.7	1.7	2.89
2.9	2.9	8.41
4.5	3.24	10.4976
8.3	5.99	35.8801
13.3	5.03	25.3009
36.9	10.72	114.9184
121.8	9.1	82.81

281.197

0.67	delta	delta ²
0.7	0.7	0.49
1.6	1.6	2.56
2.8	2.8	7.84
4.4	3.34	11.1556
7.9	6.39	40.8321
12.8	5.53	30.5809
35.8	11.82	139.7124
118.1	5.4	29.16

262.331

0.68	delta	delta²
0.6	0.6	0.36
0	0	0
2.7	2.7	7.29
4.2	3.54	12.5316
7.5	6.79	46.1041
12.4	5.93	35.1649
34.7	12.92	166.9264
114.4	1.7	2.89

271.267

0.7	delta	delta²
0.6	0.6	0.36
1.5	1.5	2.25
2.5	2.5	6.25
4	3.74	13.9876
6.8	7.49	56.1001
11.5	6.83	46.6489
32.5	15.12	228.6144
107.1	5.6	31.36

385.571

8 x 30

Backwash rate (m/s)	Lab expansion (mm)	0.6	delta	delta ²
0.001	0	0.6	0.6	0.36
0.002	0	1.5	1.5	2.25
0.004	0	2.5	2.5	6.25
0.005	2.94	3.9	-0.96	0.9216
0.007	5.59	5.9	-0.31	0.0961
0.008	9.225	8.2	1.025	1.050625
0.014	30.29	27	3.29	10.8241
0.018	42.65	56.3	13.65	186.3225

208.075

0.65	delta	delta ²
0.5	0.5	0.25
1.3	1.3	1.69
2.2	2.2	4.84
3.2	0.26	0.0676
5	0.59	0.3481
7.1	2.125	4.515625
22.9	7.39	54.6121
48.3	5.65	31.9225

98.2459

0.66	delta	delta ²
0.4	0.4	0.16
1.3	1.3	1.69
2.1	2.1	4.41
3.1	0.16	0.0256
4.8	0.79	0.6241
6.9	2.325	5.405625
22.1	8.19	67.0761
46.1	3.45	11.9025

91.2939

0.67	delta	delta ²
0.4	0.4	0.16
1.2	1.2	1.44
2.1	2.1	4.41
3.1	0.16	0.0256
4.7	0.89	0.7921
6.7	2.525	6.375625
21.4	8.89	79.0321
44.9	2.25	5.0625

97.2979

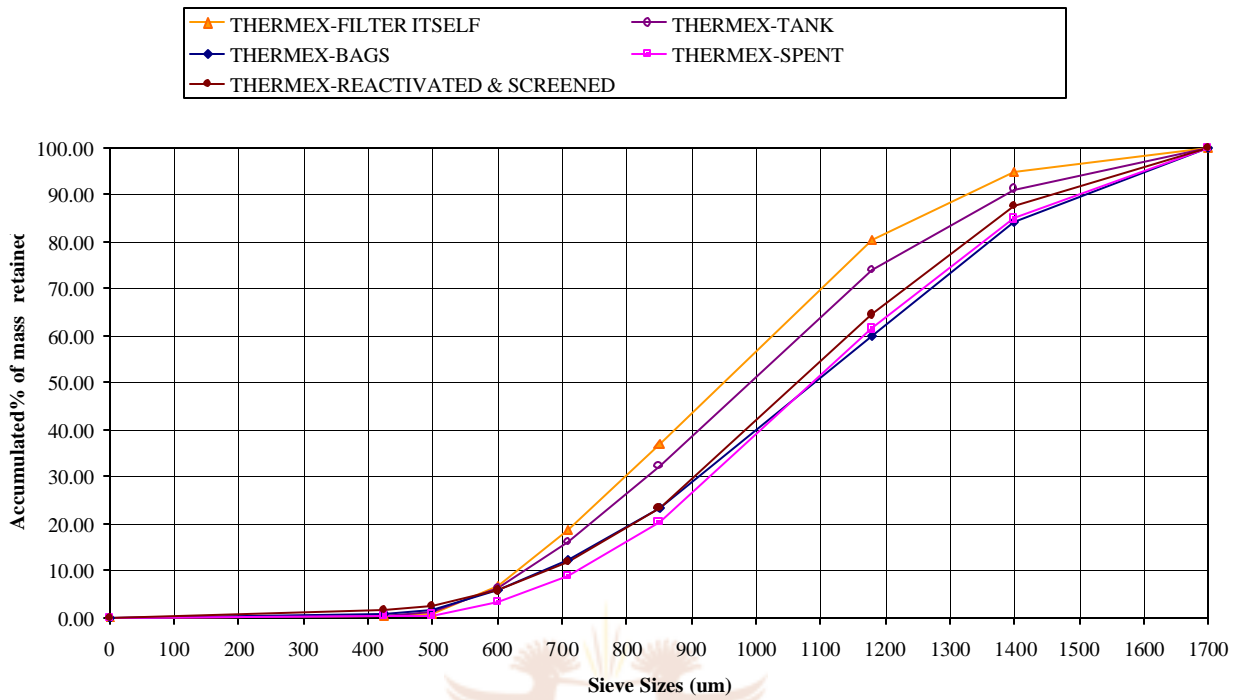
0.7	delta	delta ²
0.3	0.3	0.09
1.1	1.1	1.21
1.9	1.9	3.61
2.8	0.14	0.0196
4.2	1.39	1.9321
6.1	3.125	9.765625
19.3	10.99	120.7801
41	1.65	2.7225

140.13

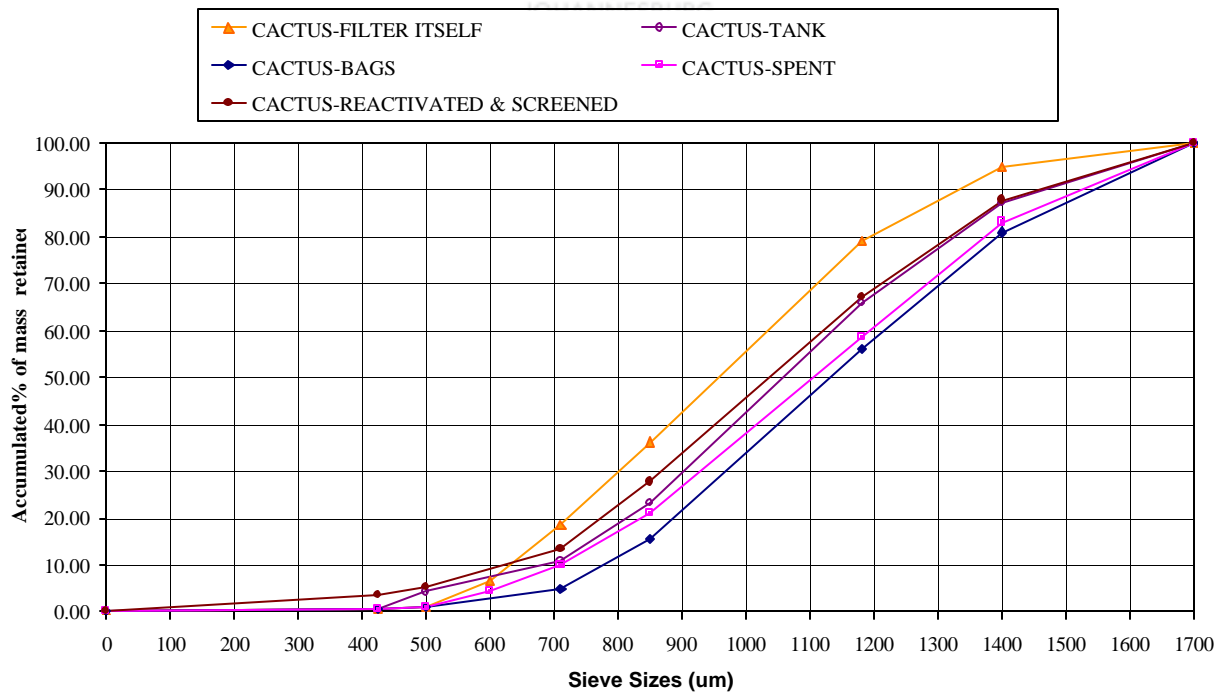
8.4 SIEVE ANALYSES – THE TWO REGENERATION METHODS



Sieve analyses of the regeneration cycle for the fluidised bed method

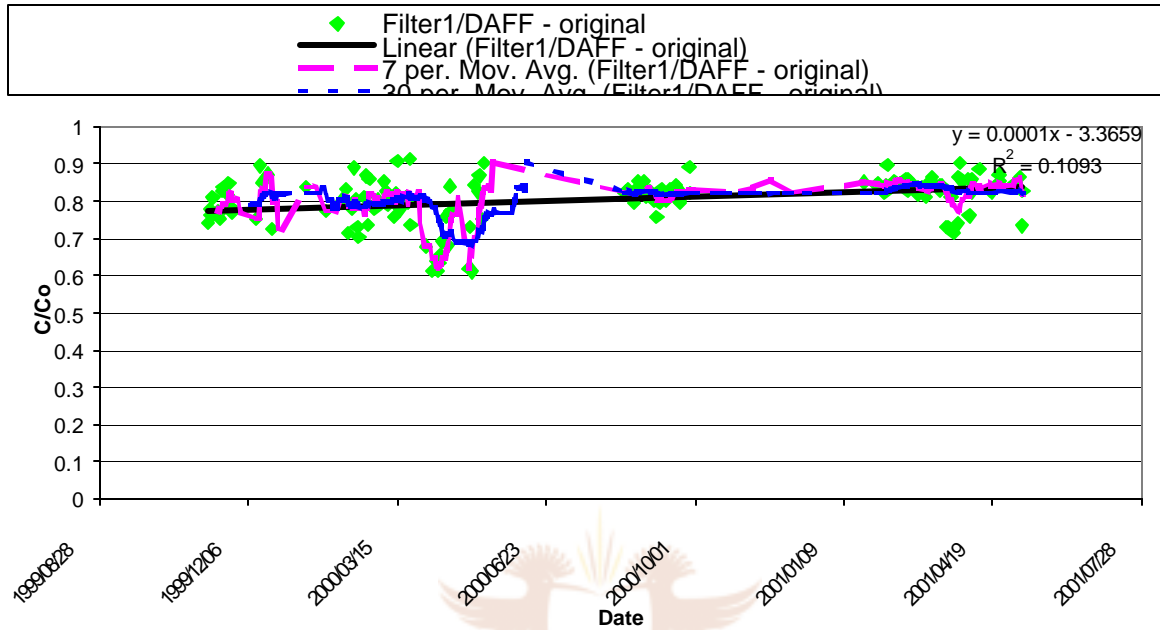


Sieve analyses of the regeneration cycle for the continuous bed method

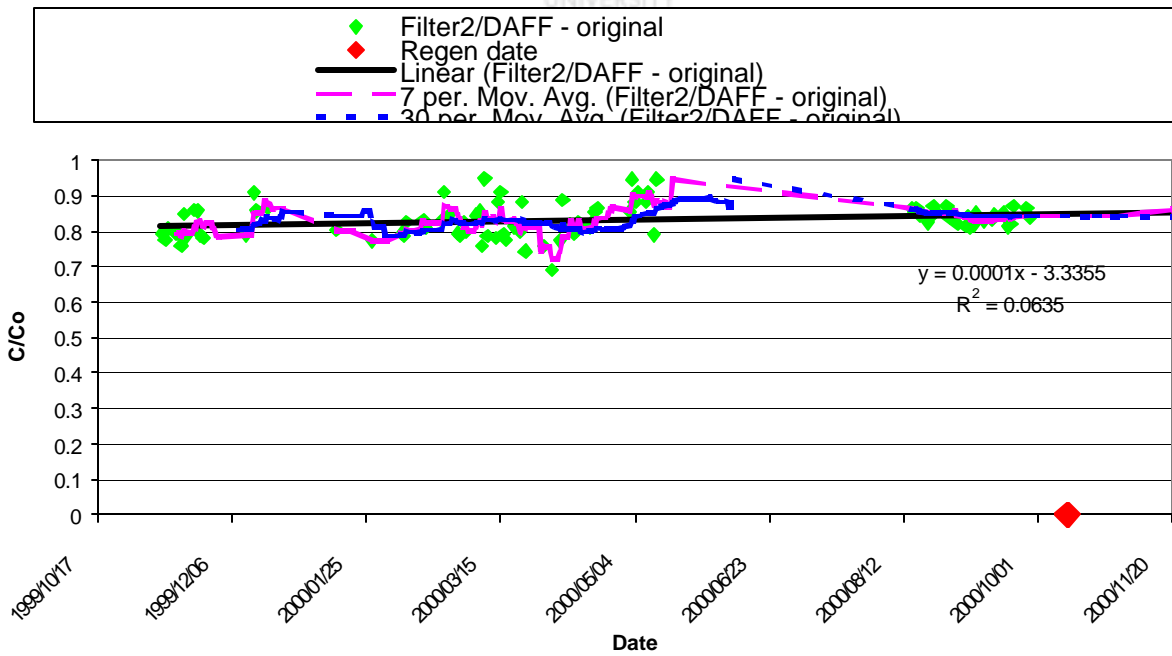


8.5 UV254 C/CO GRAPHS FOR FILTERS 1 TO 20

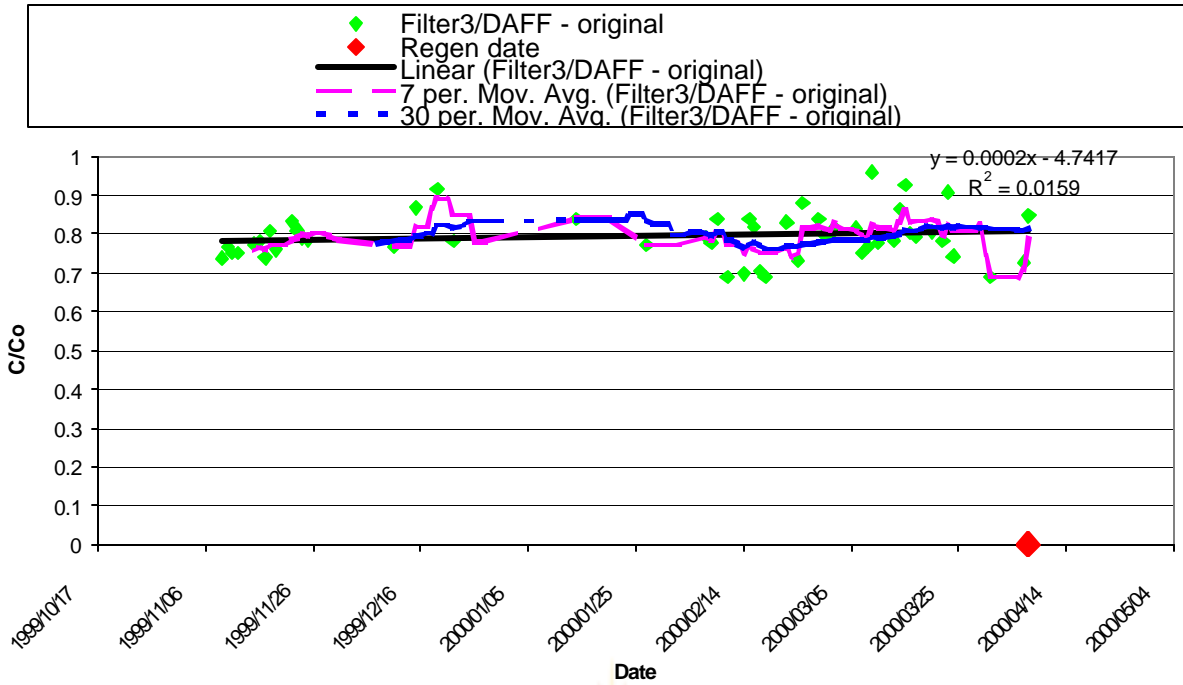
UV Absorbancy (Filter 1)



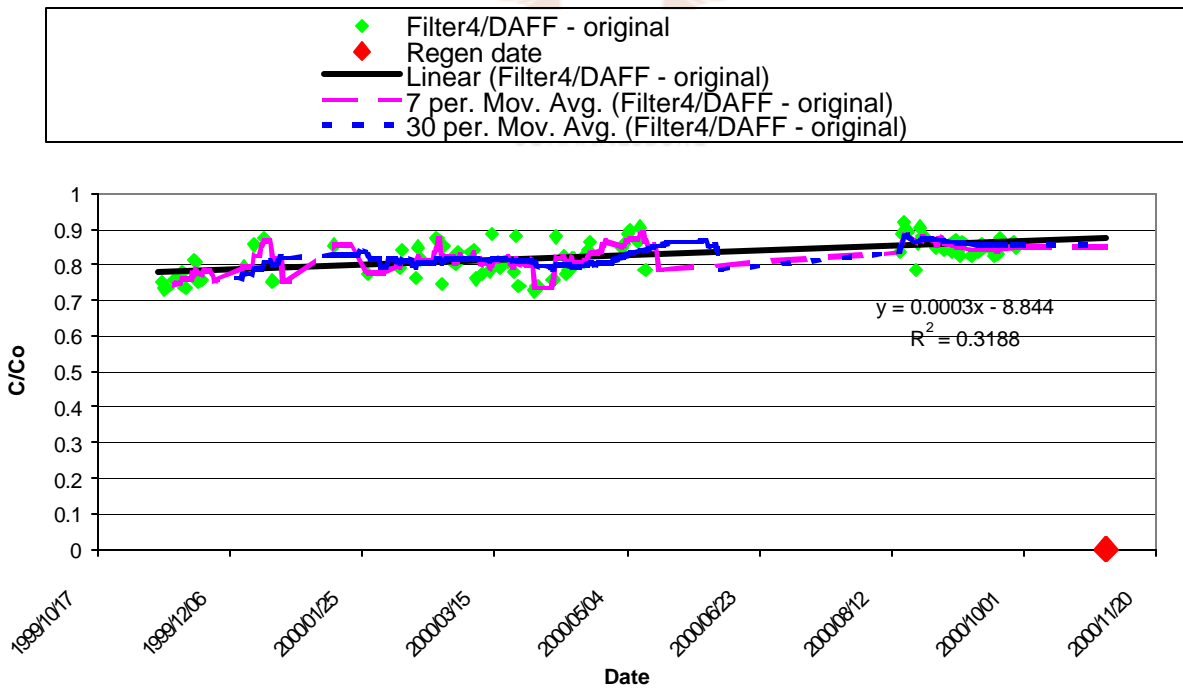
UV Absorbancy (Filter 2)



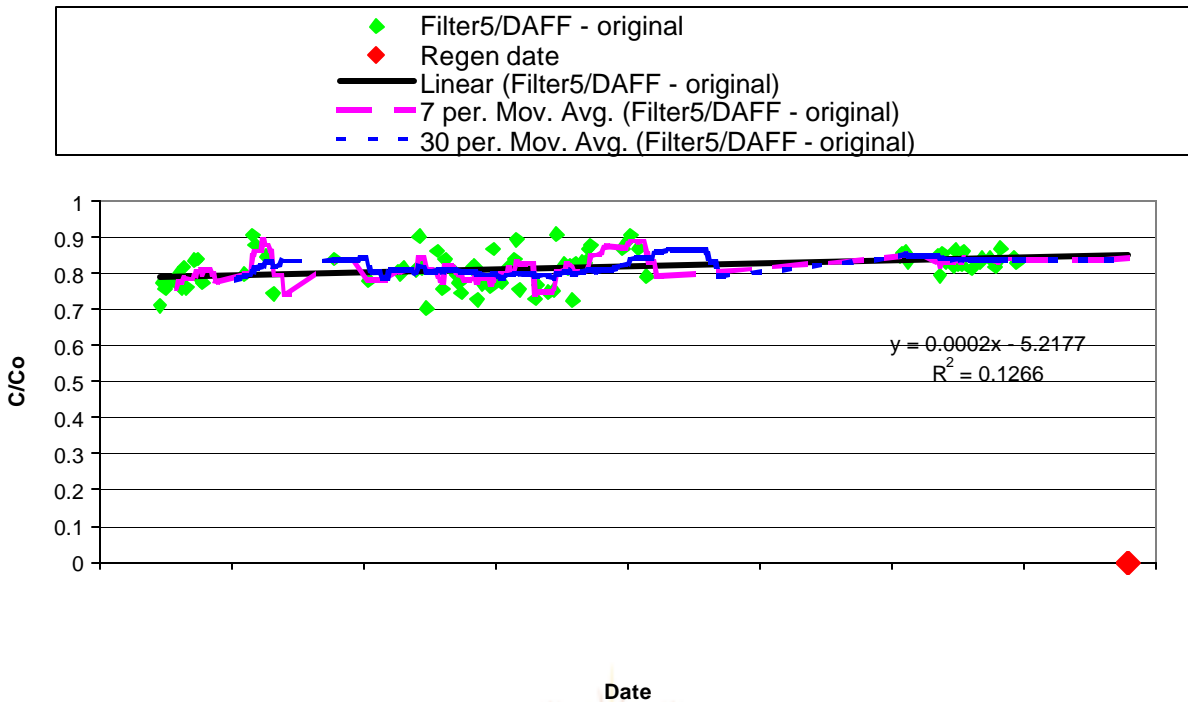
UV Absorbancy (Filter 3)



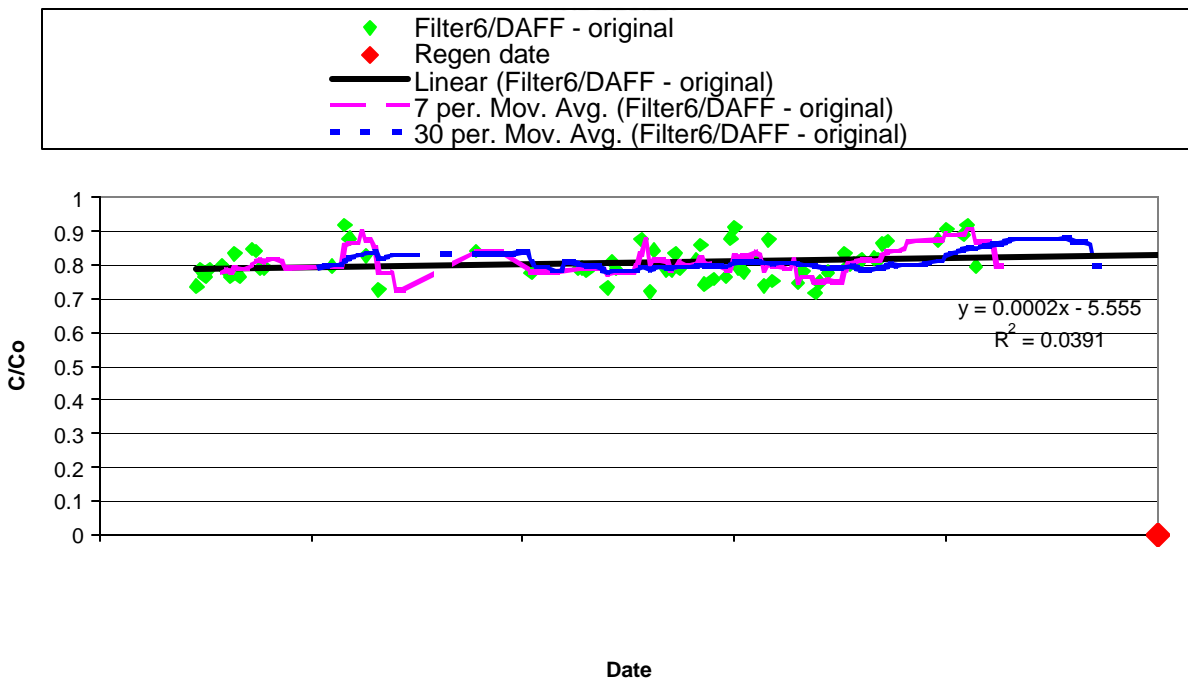
UV Absorbancy (Filter 4)



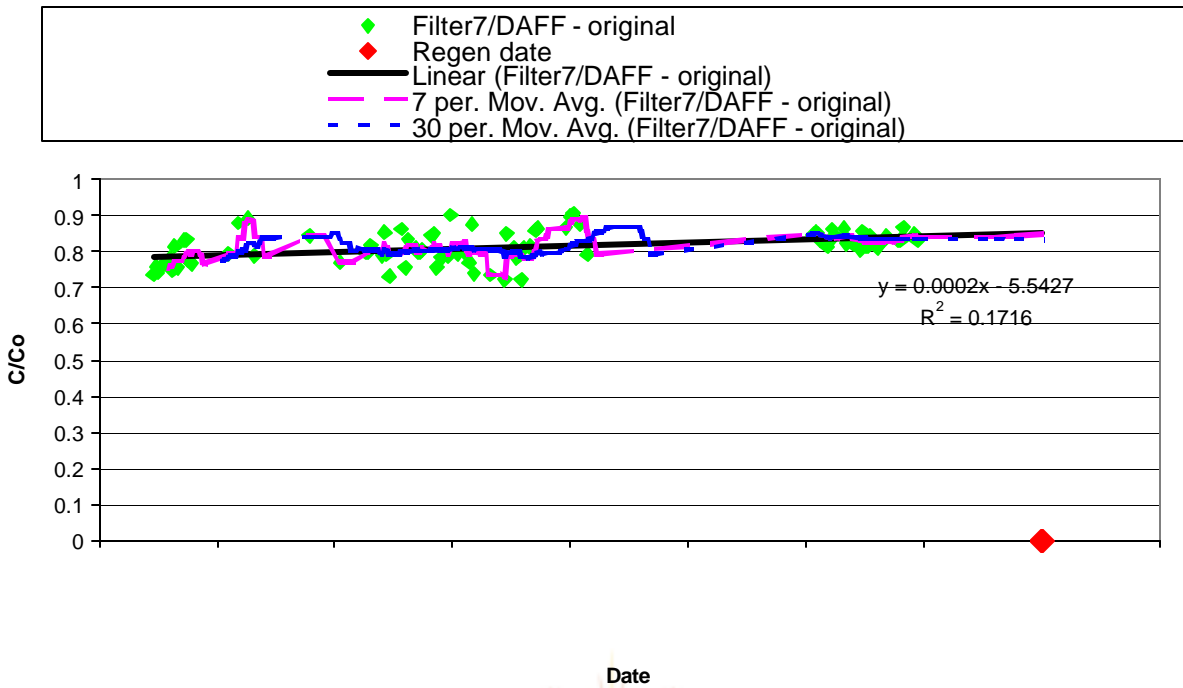
UV Absorbancy (Filter 5)



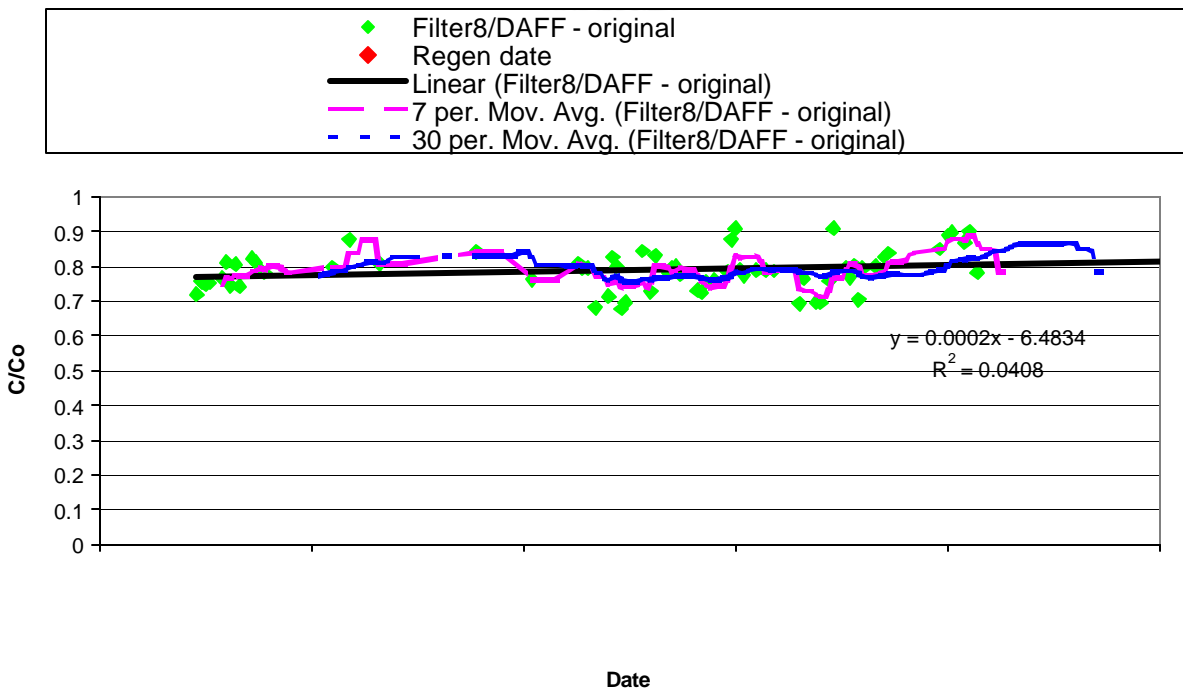
UV Absorbancy (Filter 6)



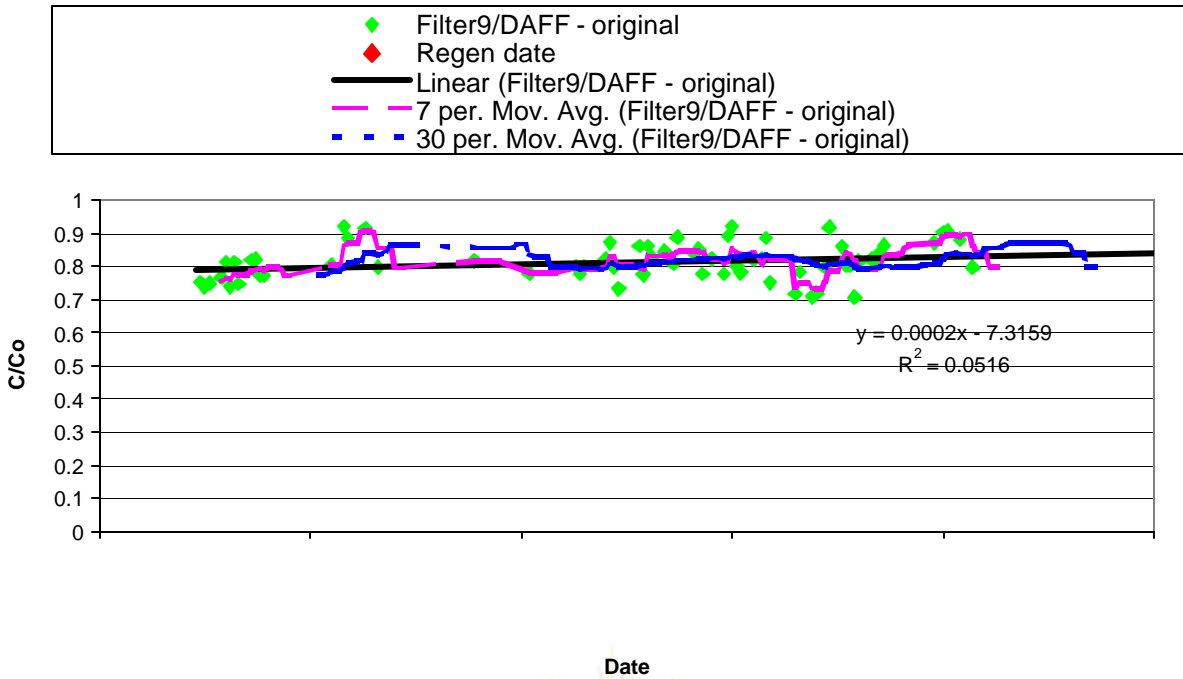
UV Absorbancy (Filter 7)



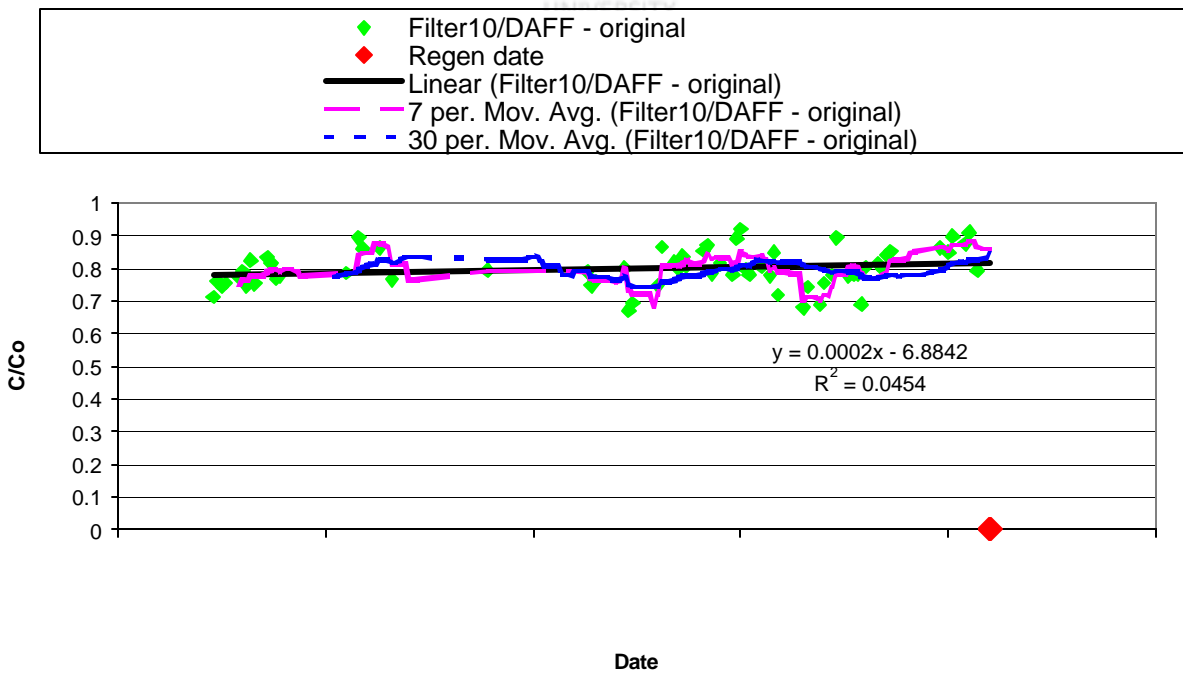
UV Absorbancy (Filter 8)



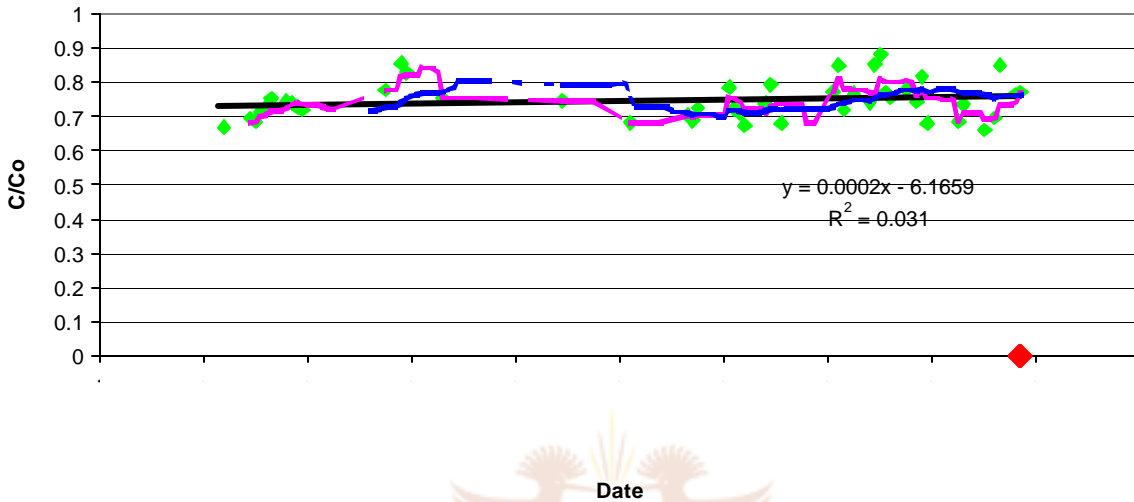
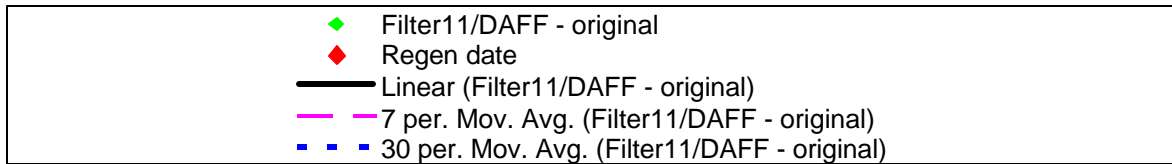
UV Absorbancy (Filter 9)



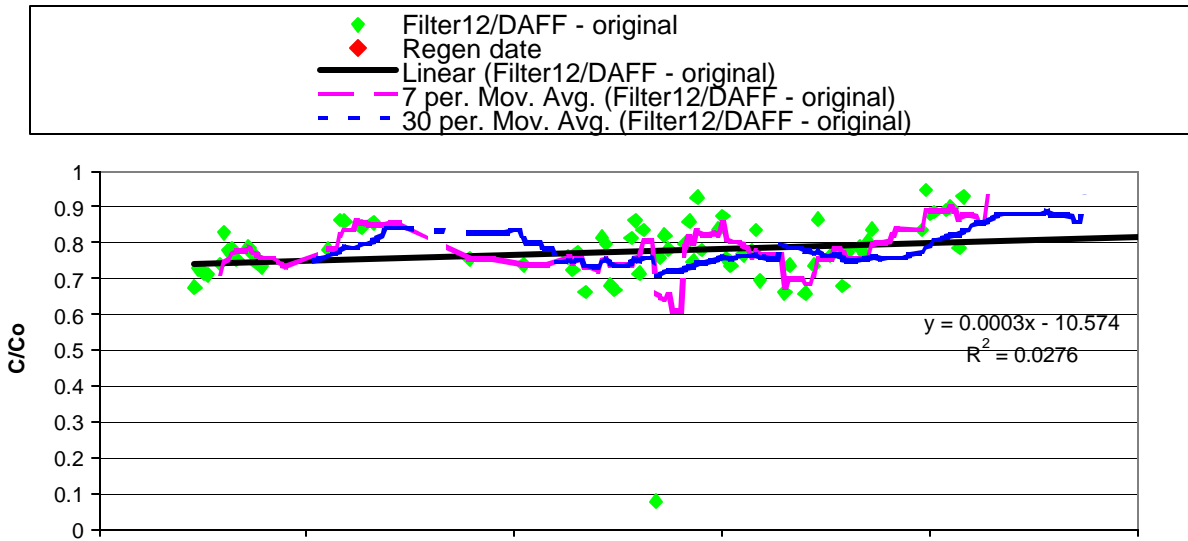
UV Absorbancy (Filter 10)



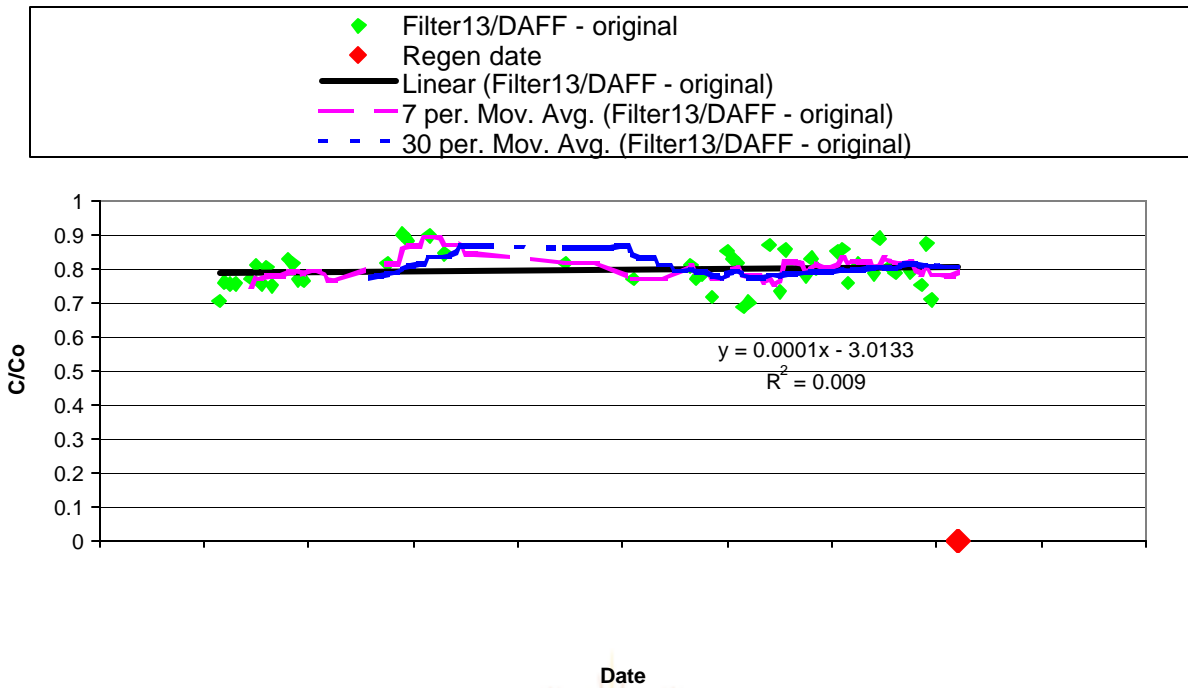
UV Absorbancy (Filter 11)



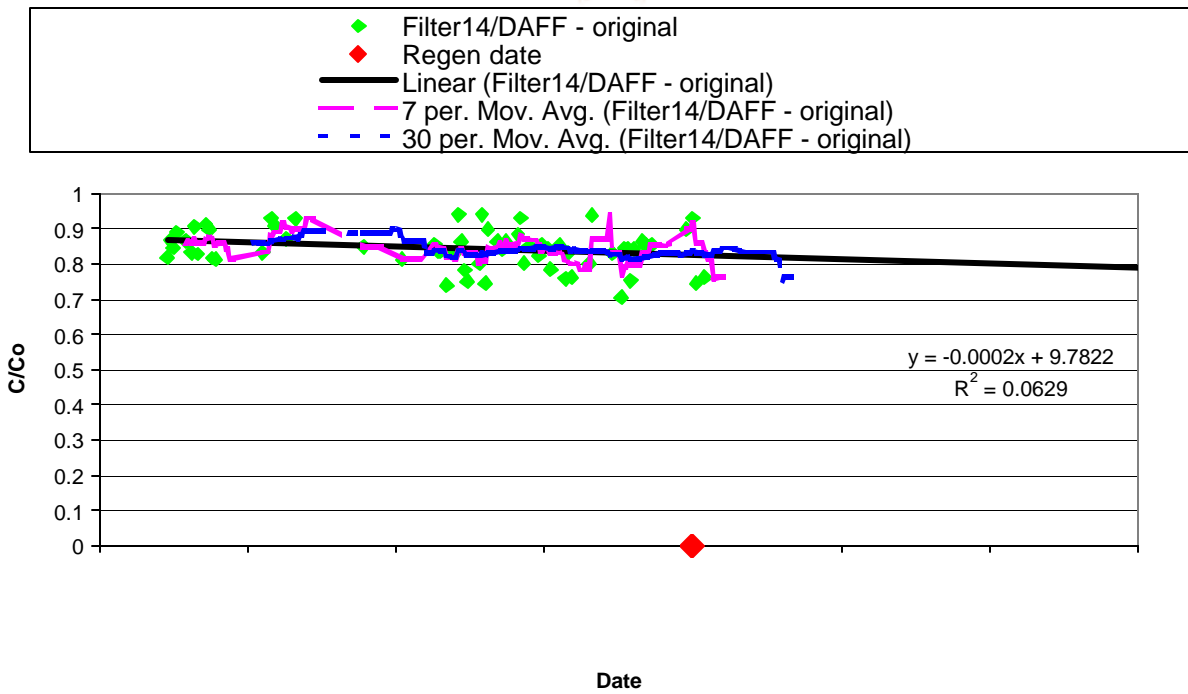
UV Absorbancy (Filter 12)



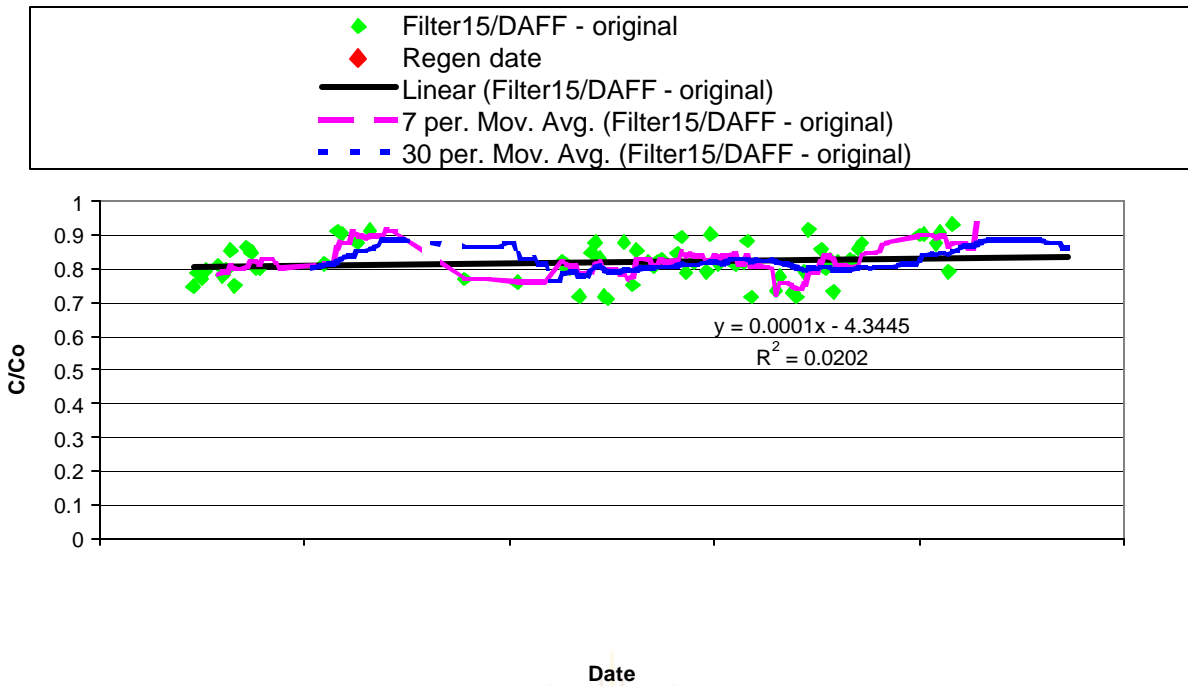
UV Absorbancy (Filter 13)



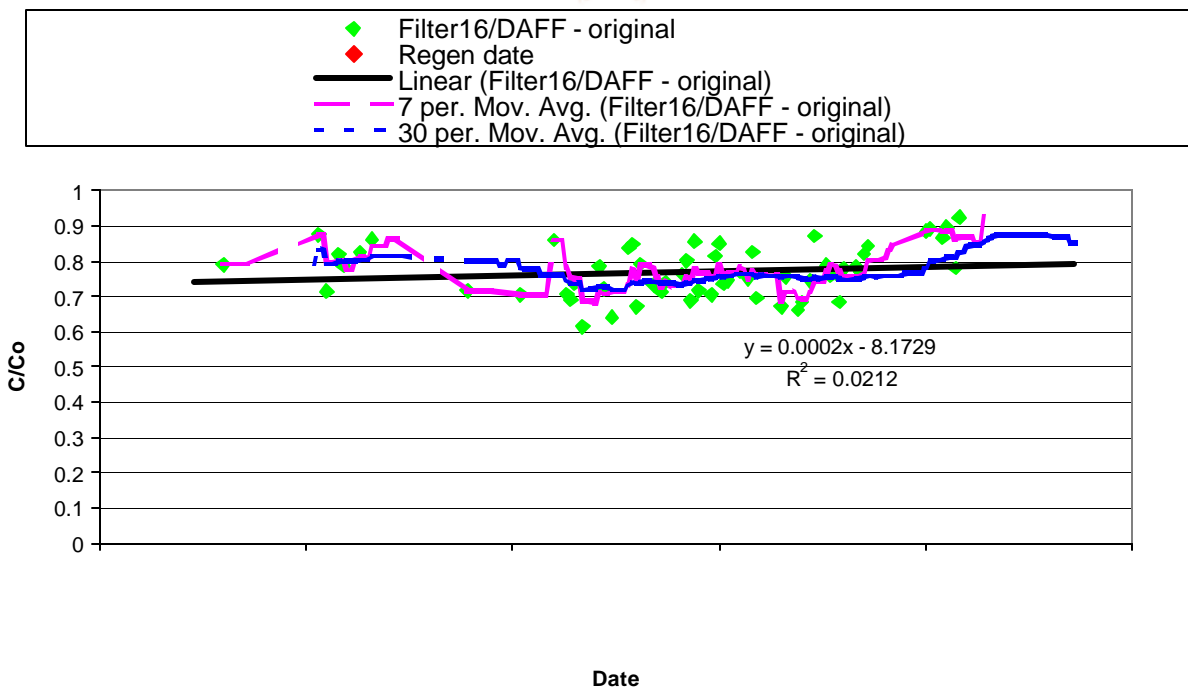
UV Absorbancy (Filter 14)



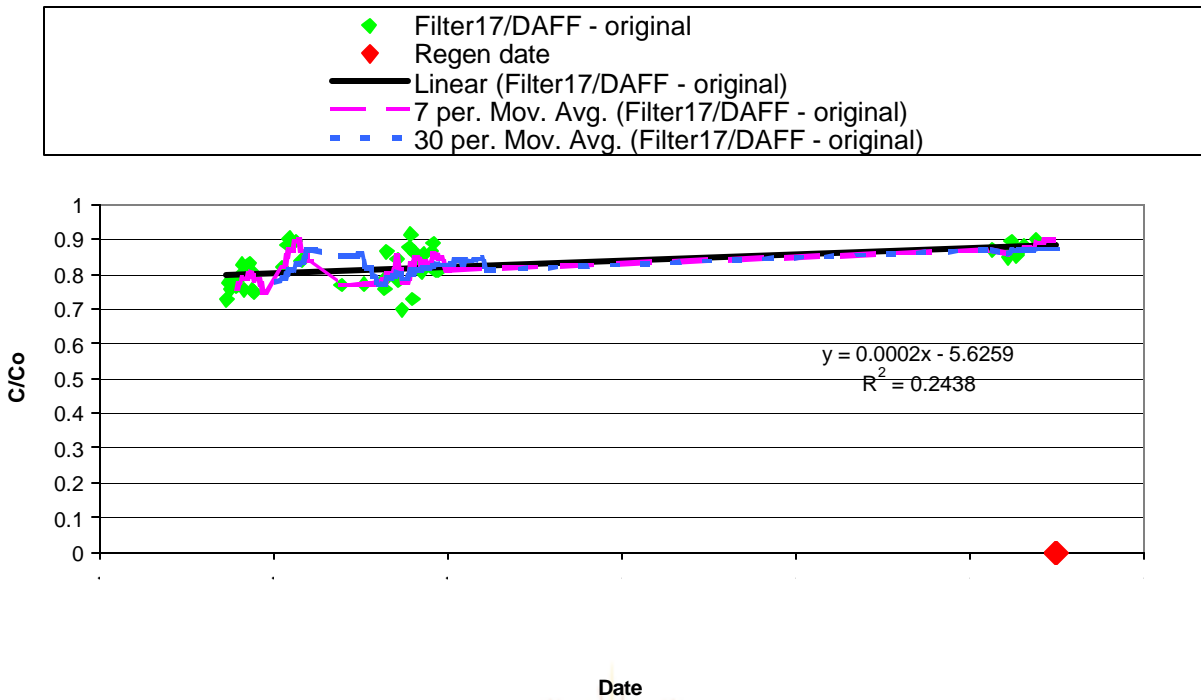
UV Absorbancy (Filter 15)



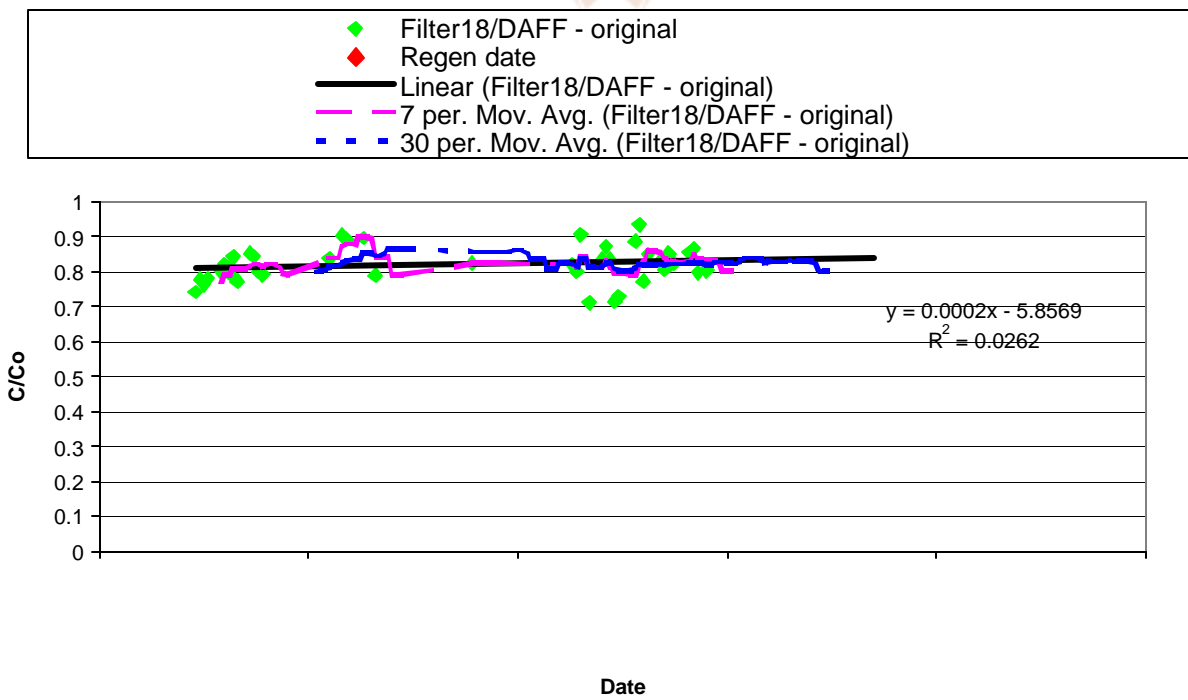
UV Absorbancy (Filter 16)



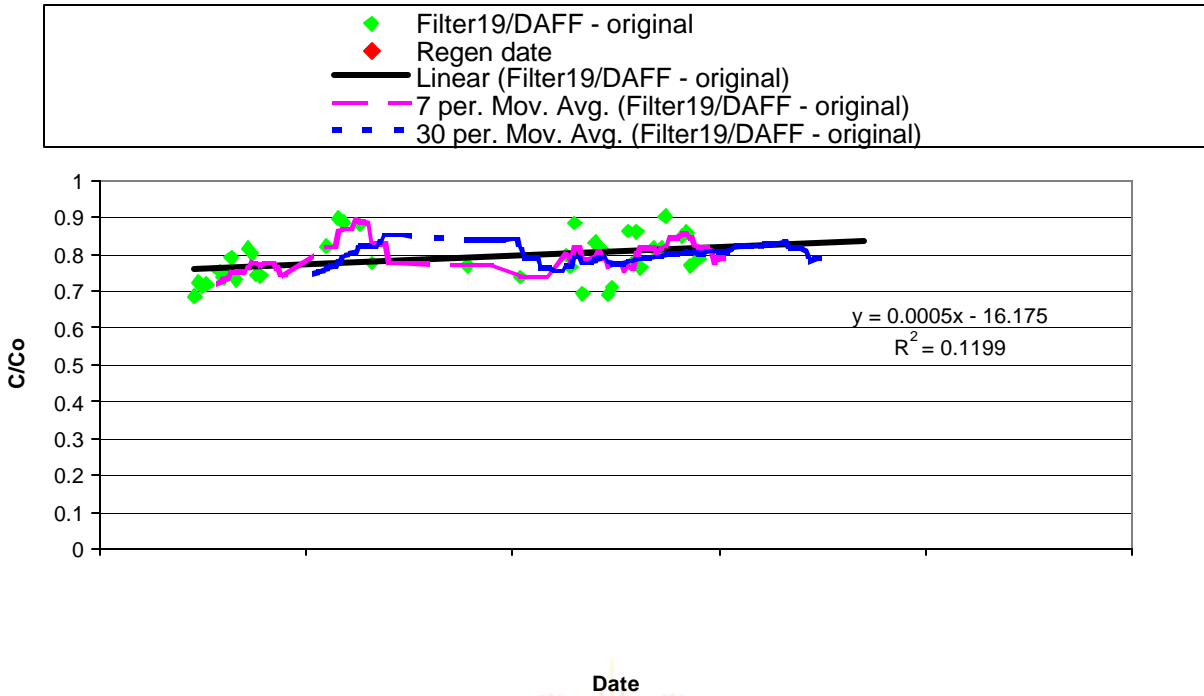
UV Absorbancy (Filter 17)



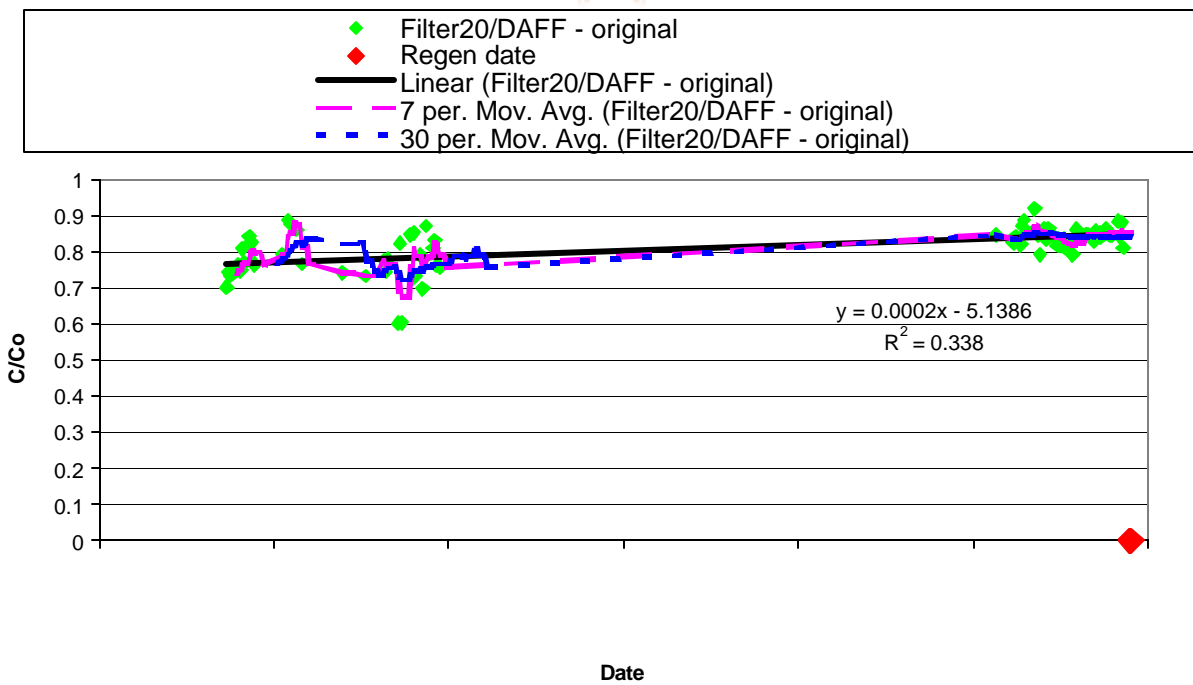
UV Absorbancy (Filter 18)



UV Absorbancy (Filter 19)

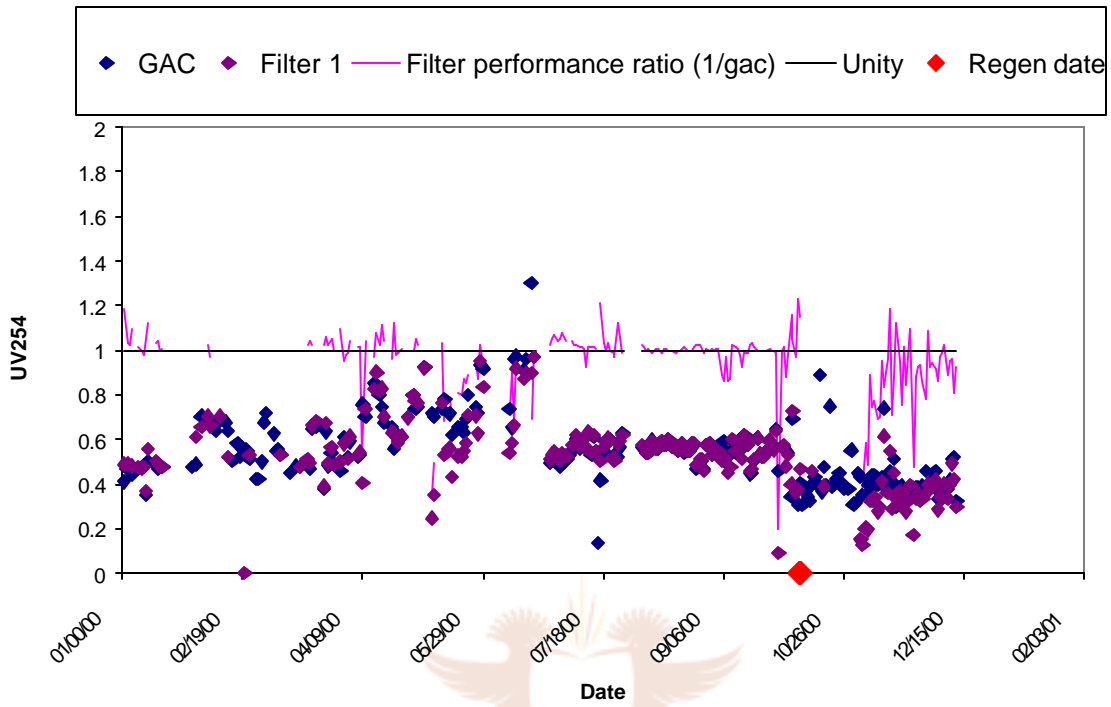


UV Absorbancy (Filter 20)

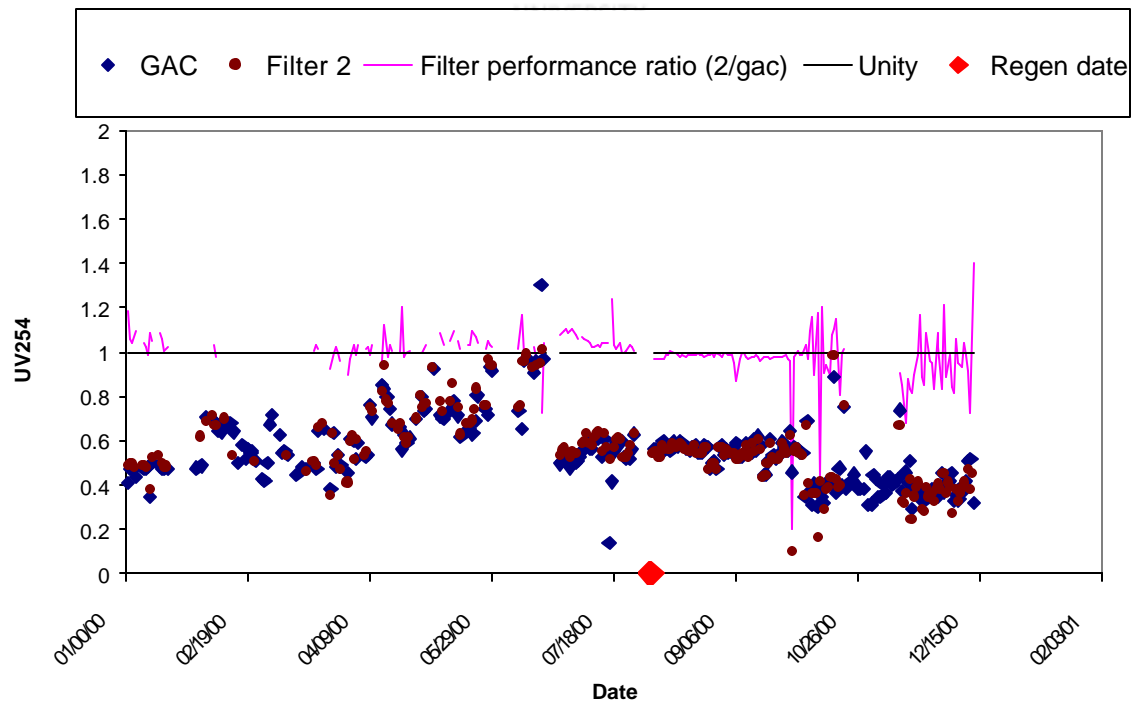


8.6 THE UV PERFORMANCE GRAPHS

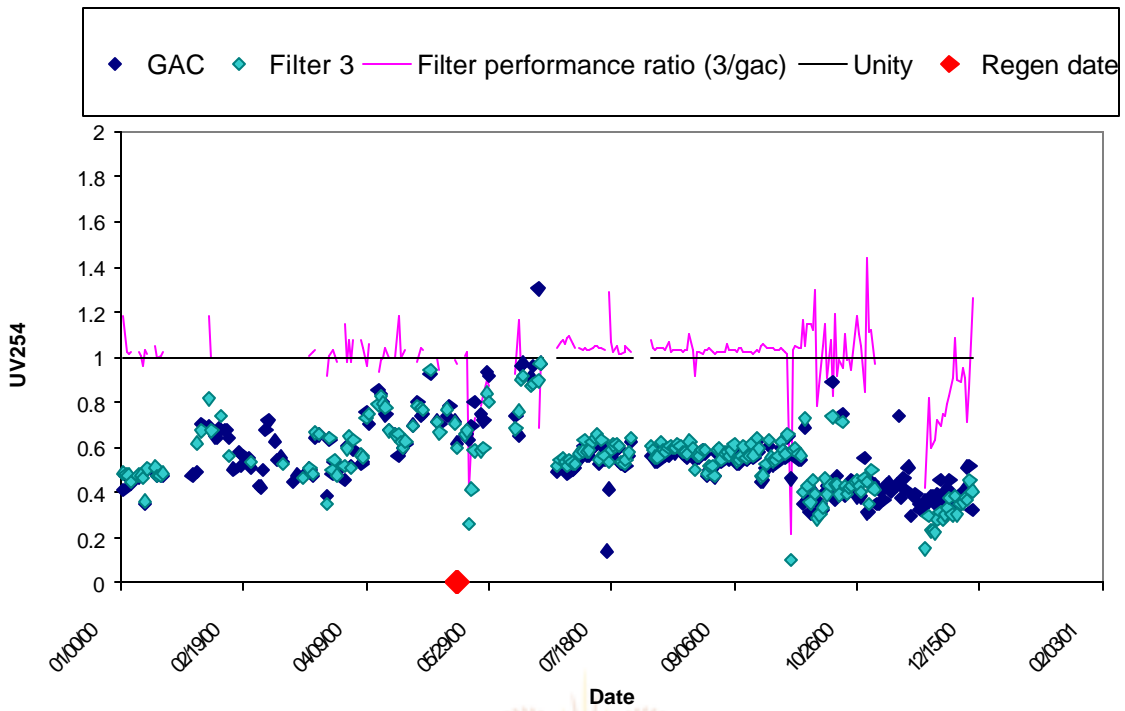
UV Absorbancy (Filter 1)



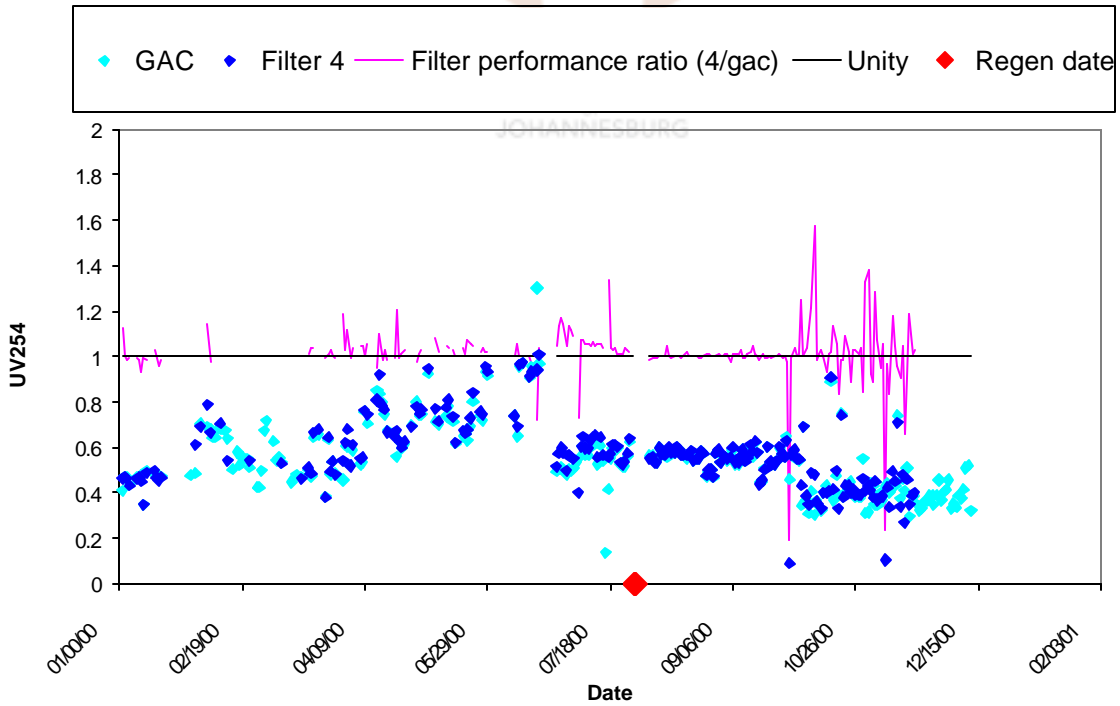
UV Absorbancy (Filter 2)

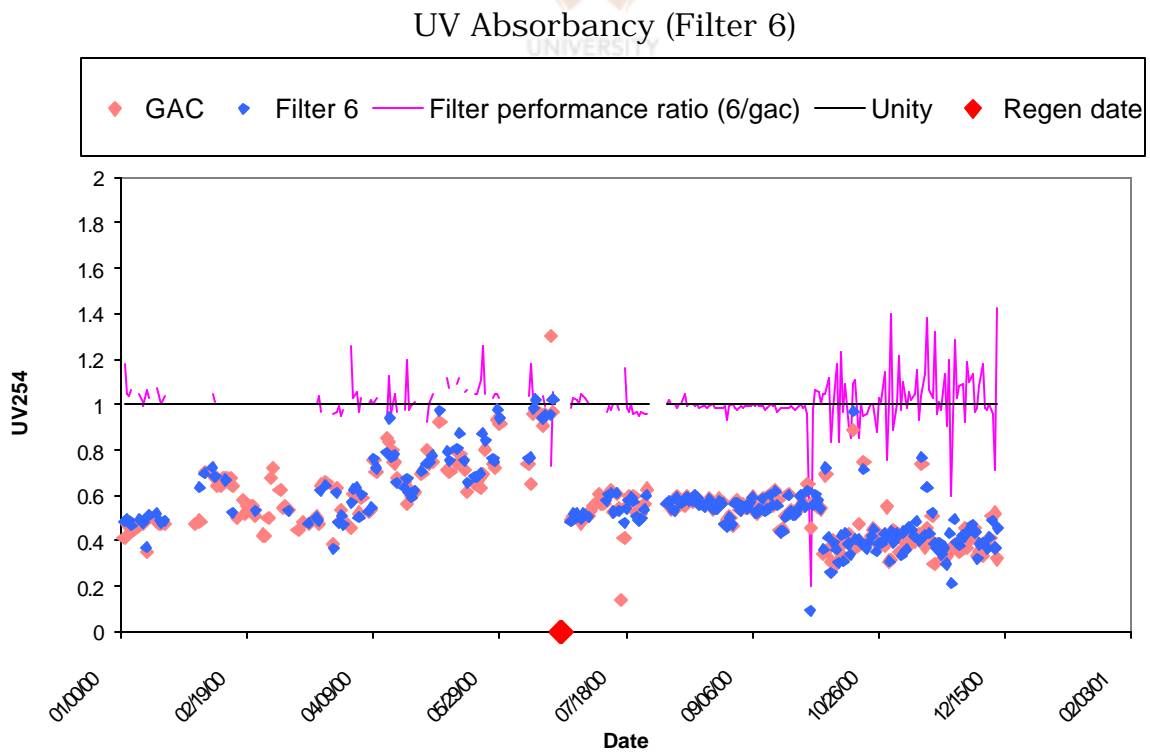
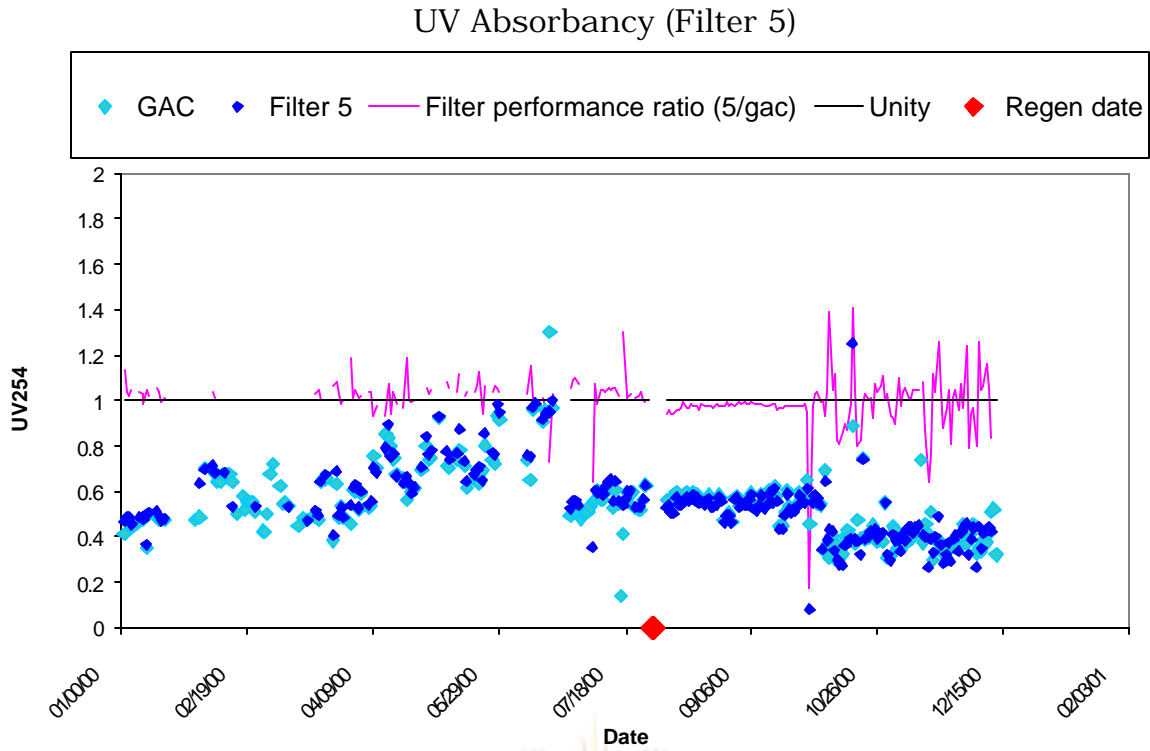


UV Absorbancy (Filter 3)

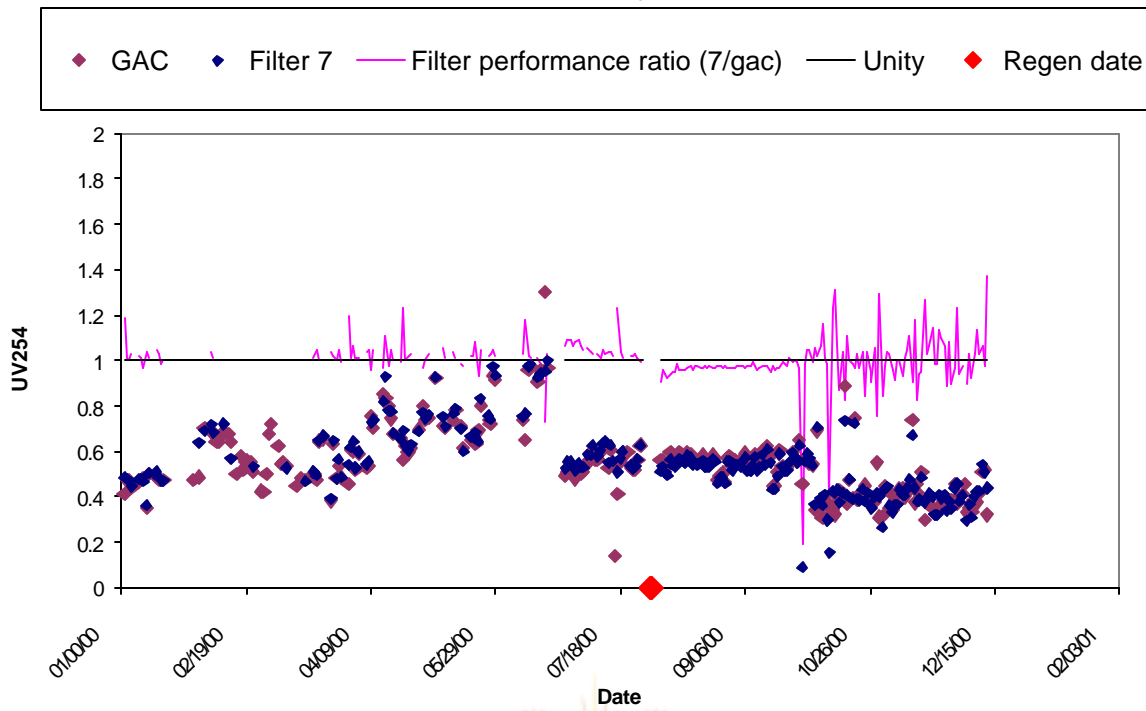


UV Absorbancy (Filter 4)

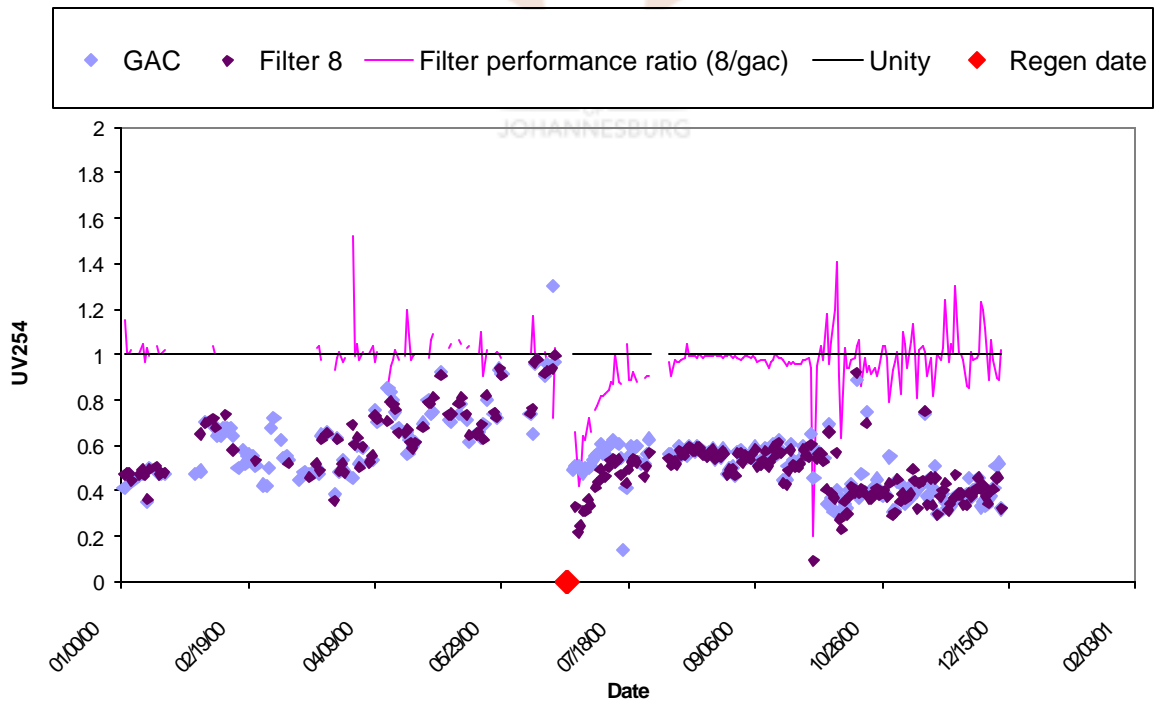




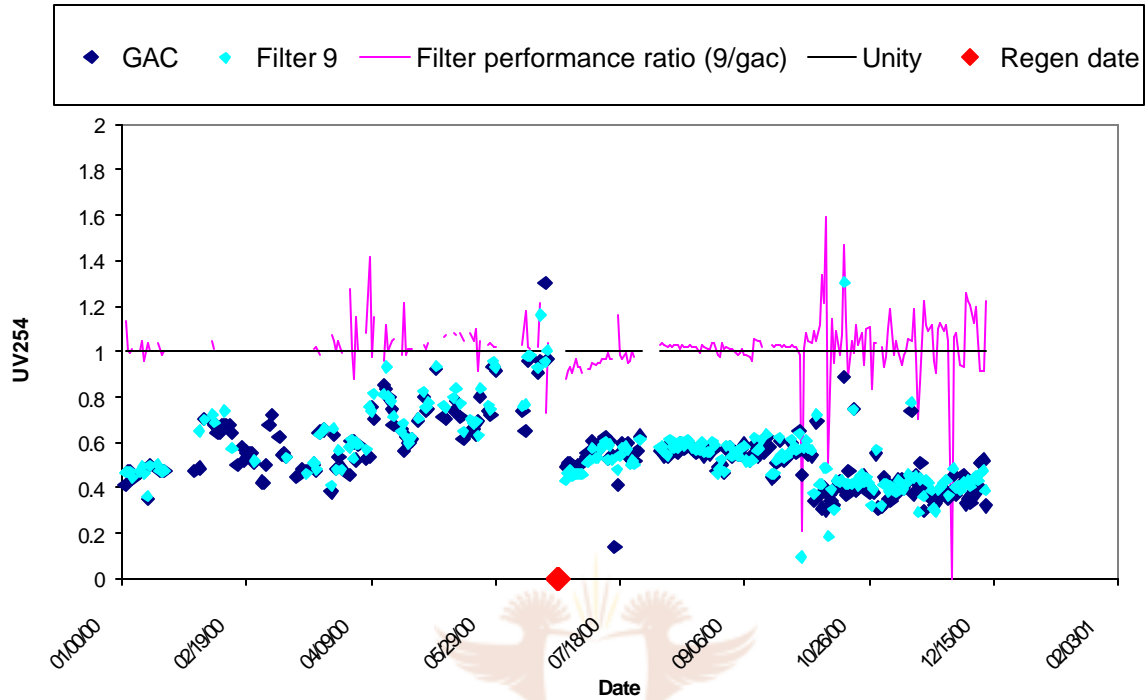
UV Absorbancy (Filter 7)



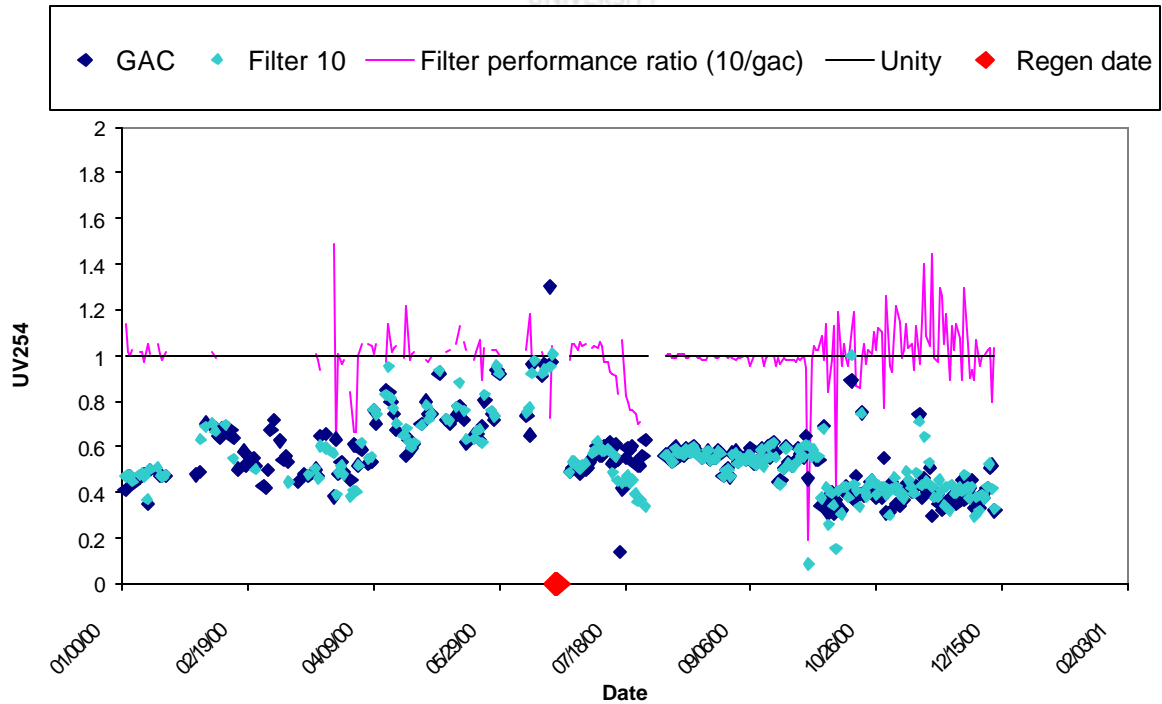
UV Absorbancy (Filter 8)



UV Absorbancy (Filter 9)

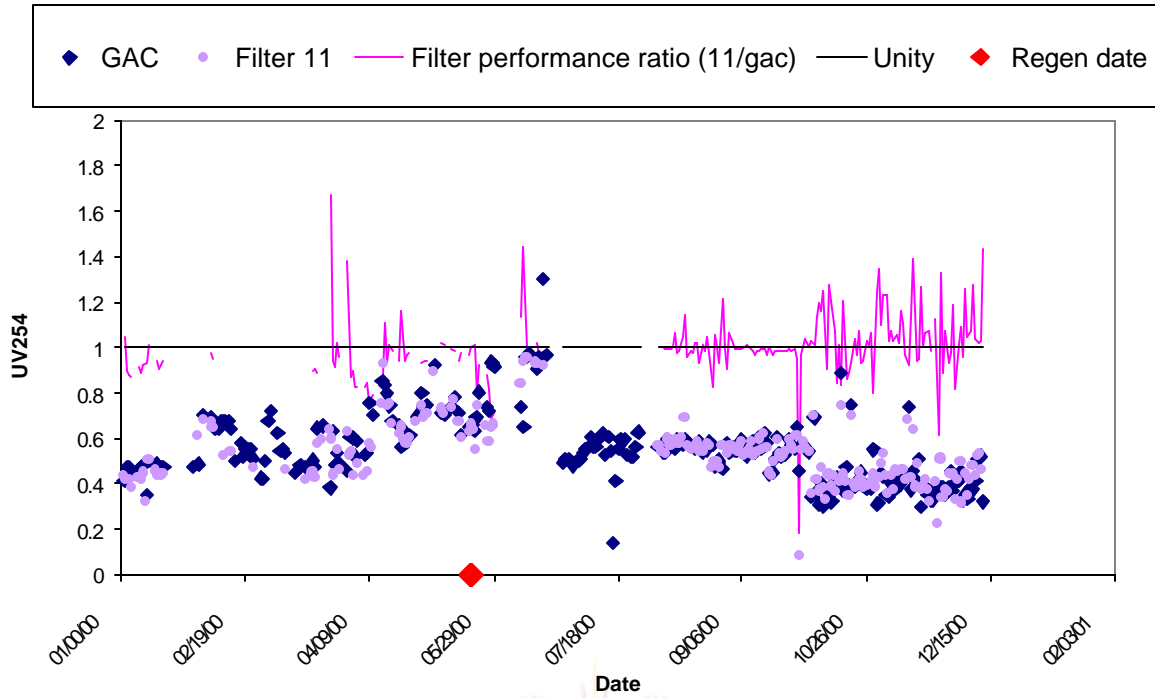


UV Absorbancy (Filter 10)

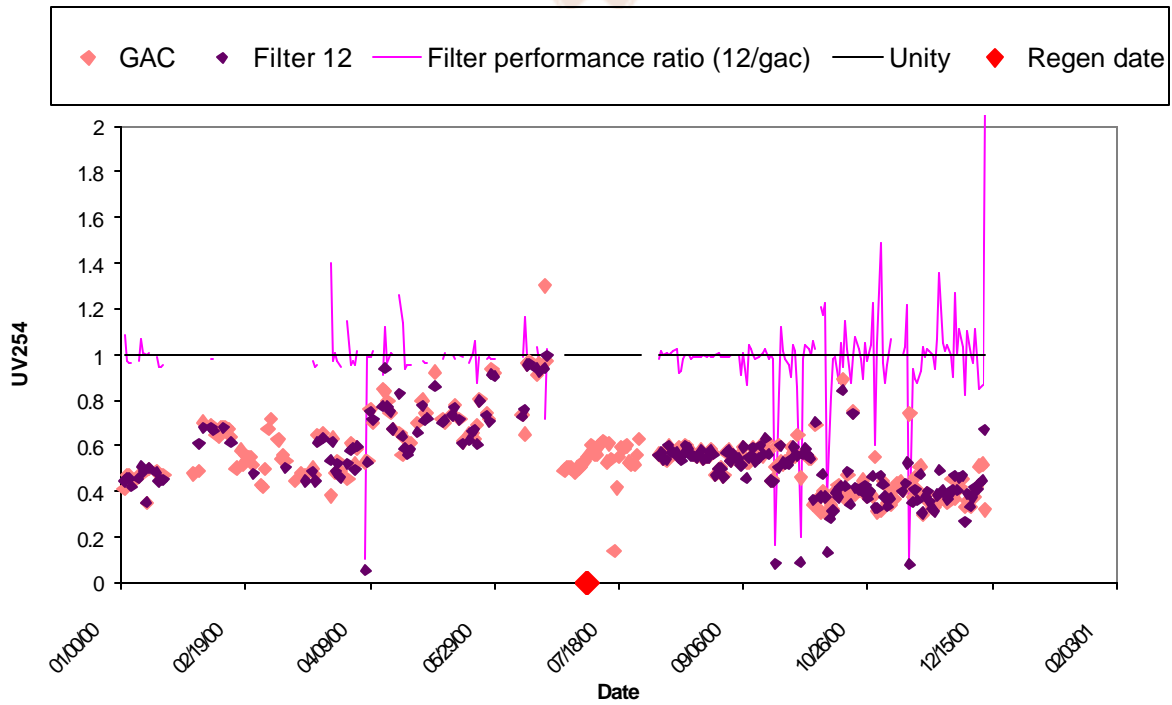




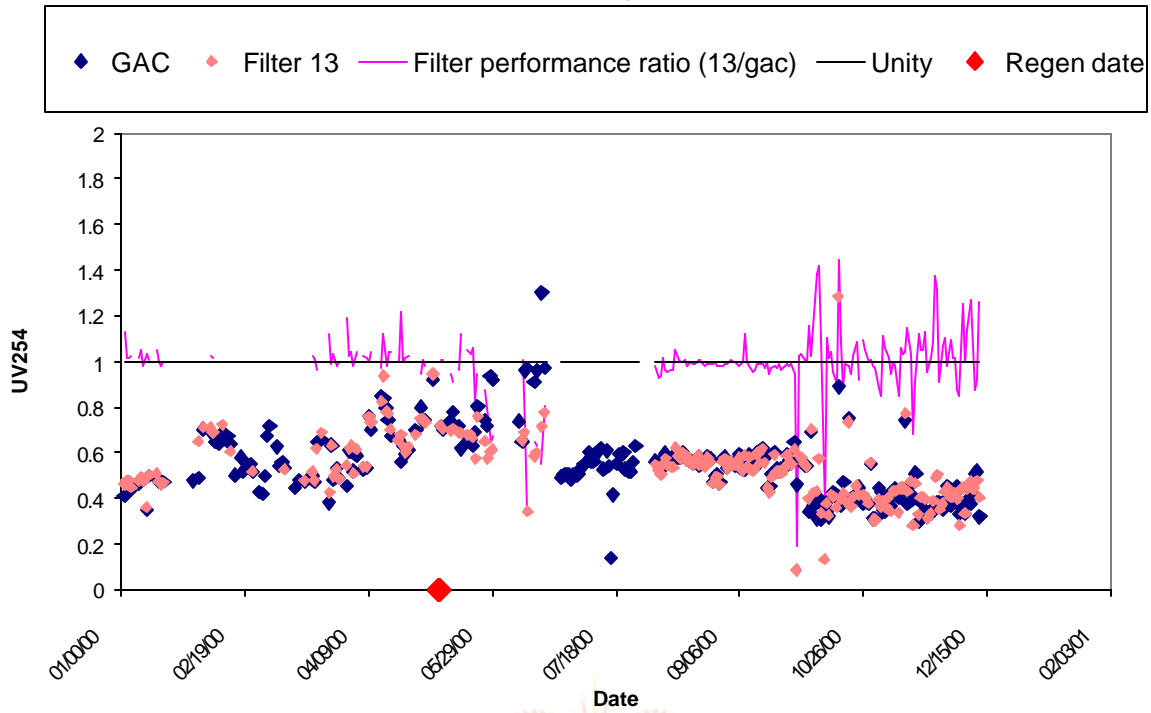
UV Absorbancy (Filter 11)



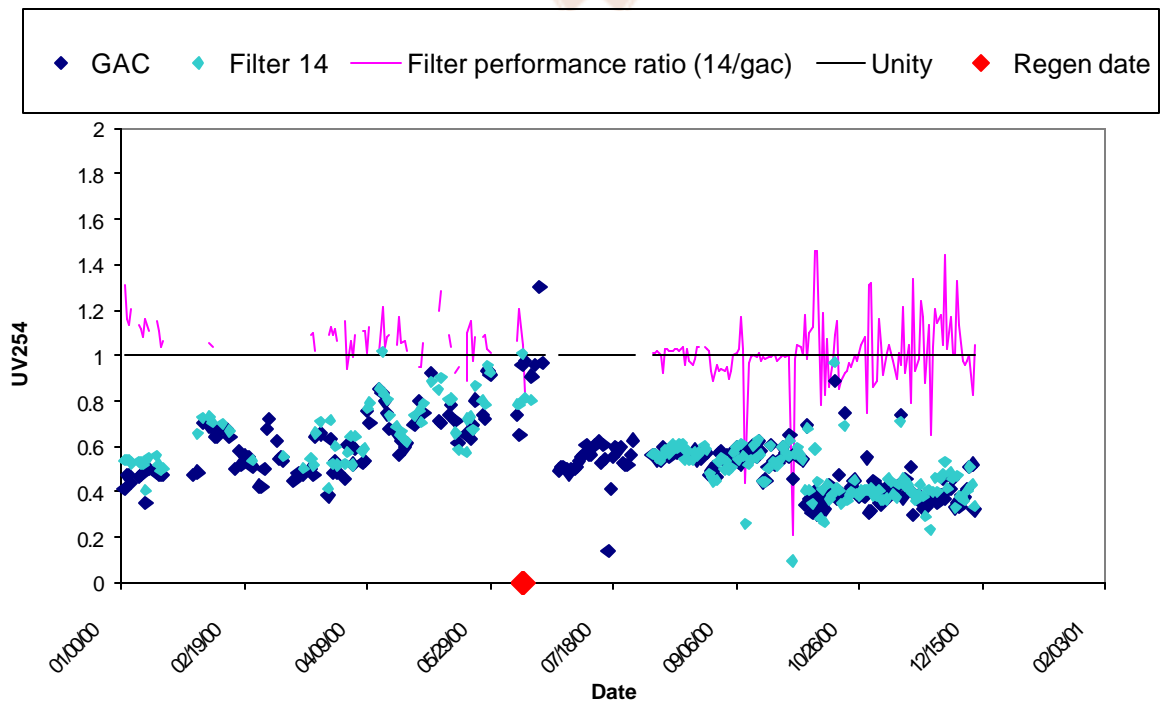
UV Absorbancy (Filter 12)



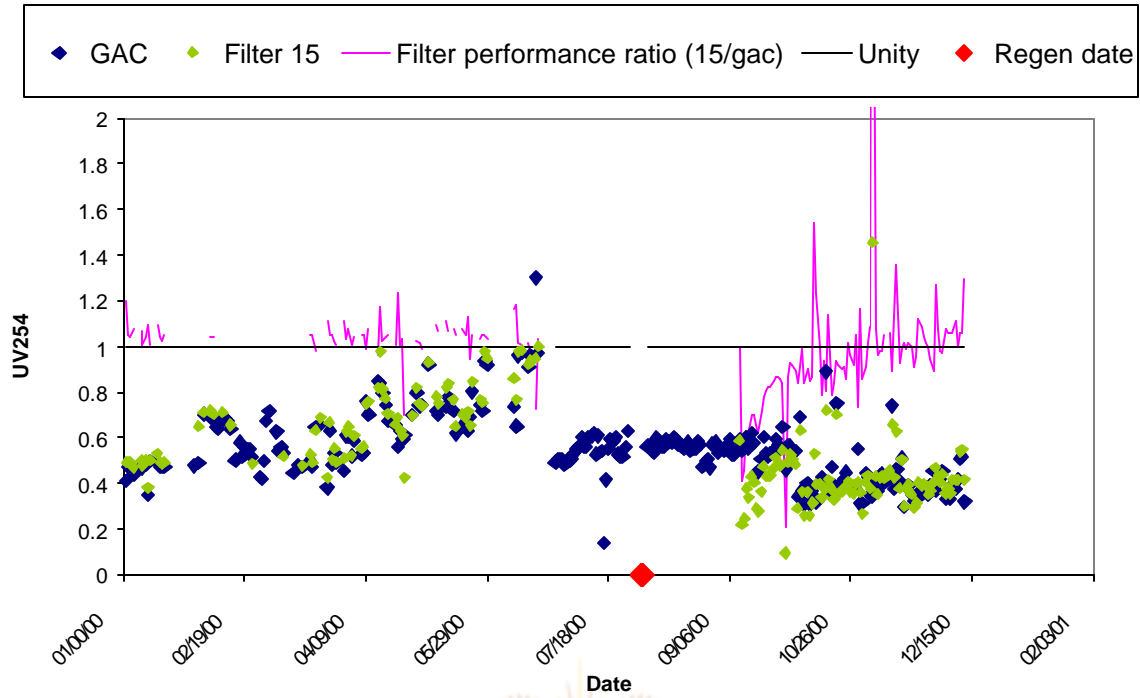
UV Absorbancy (Filter 13)



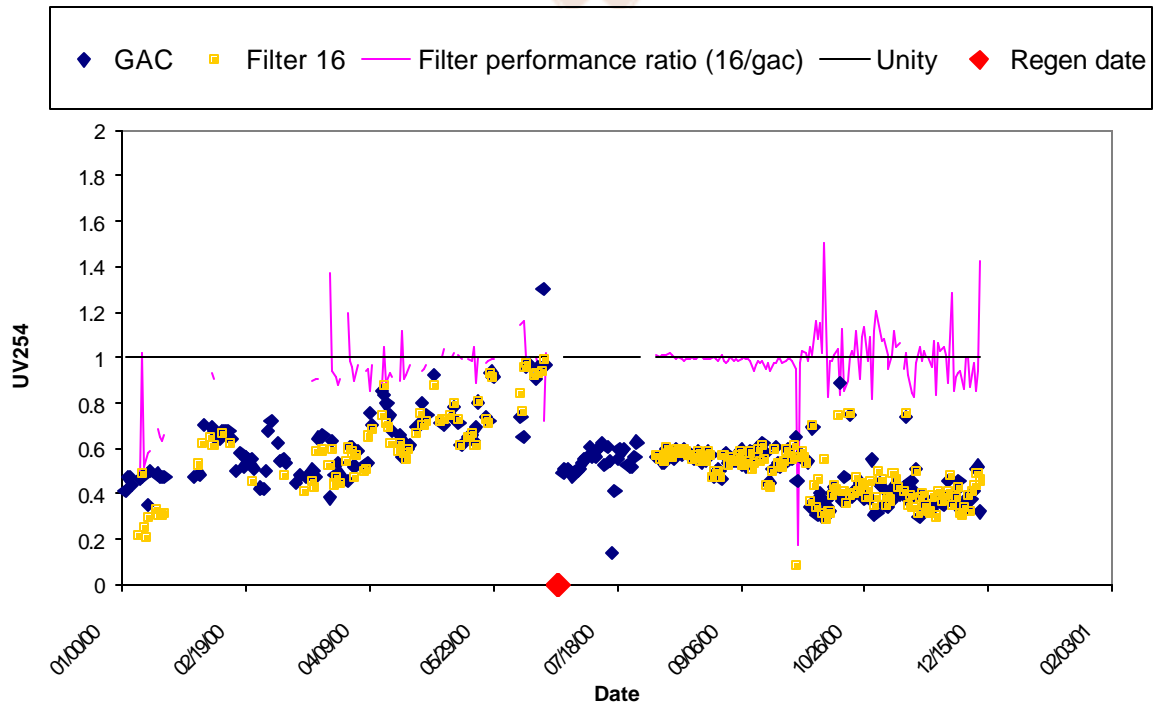
UV Absorbancy (Filter 14)



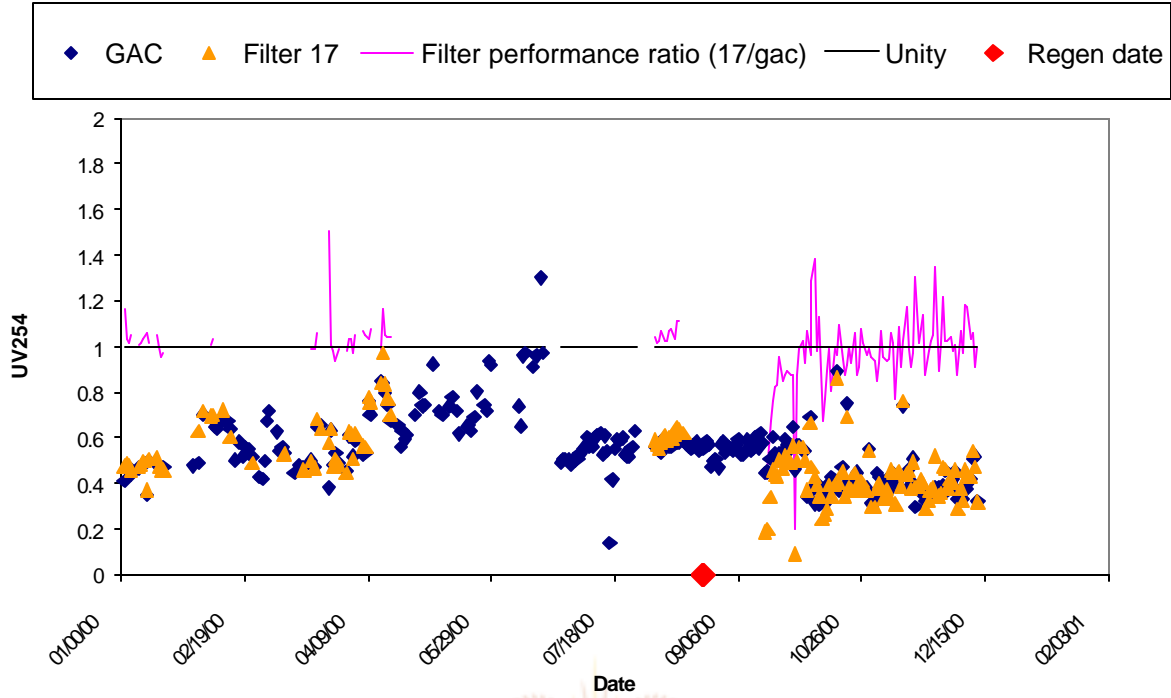
UV Absorbancy (Filter 15)



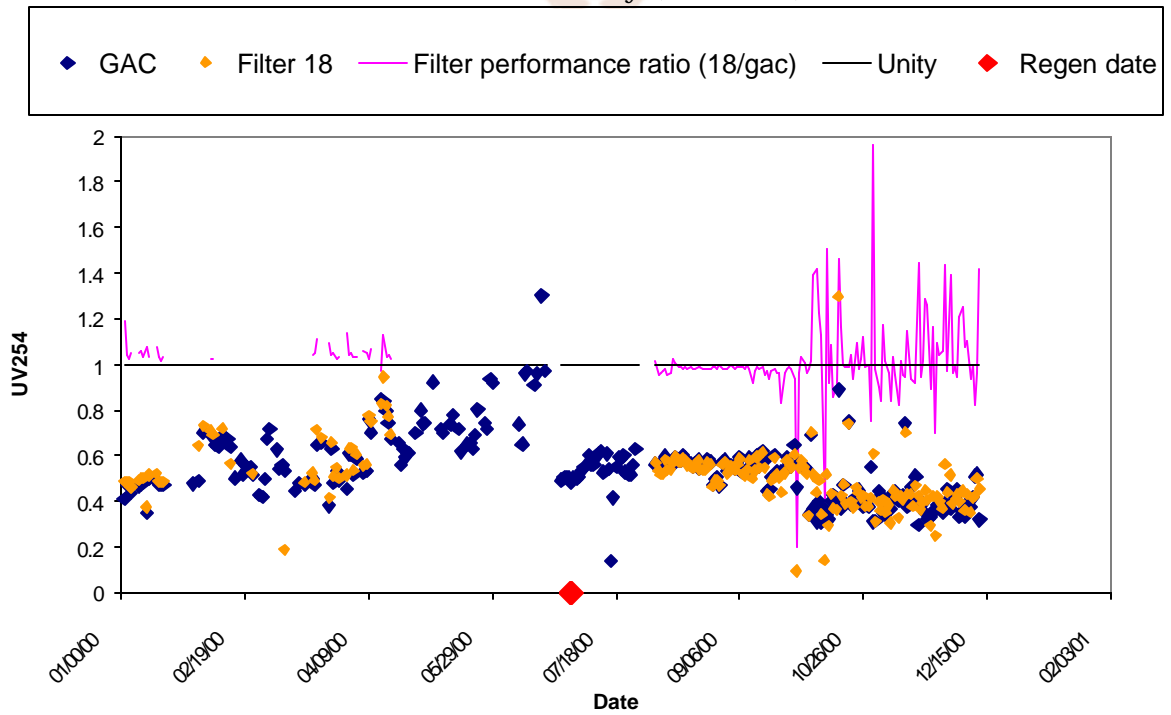
UV Absorbancy (Filter 16)



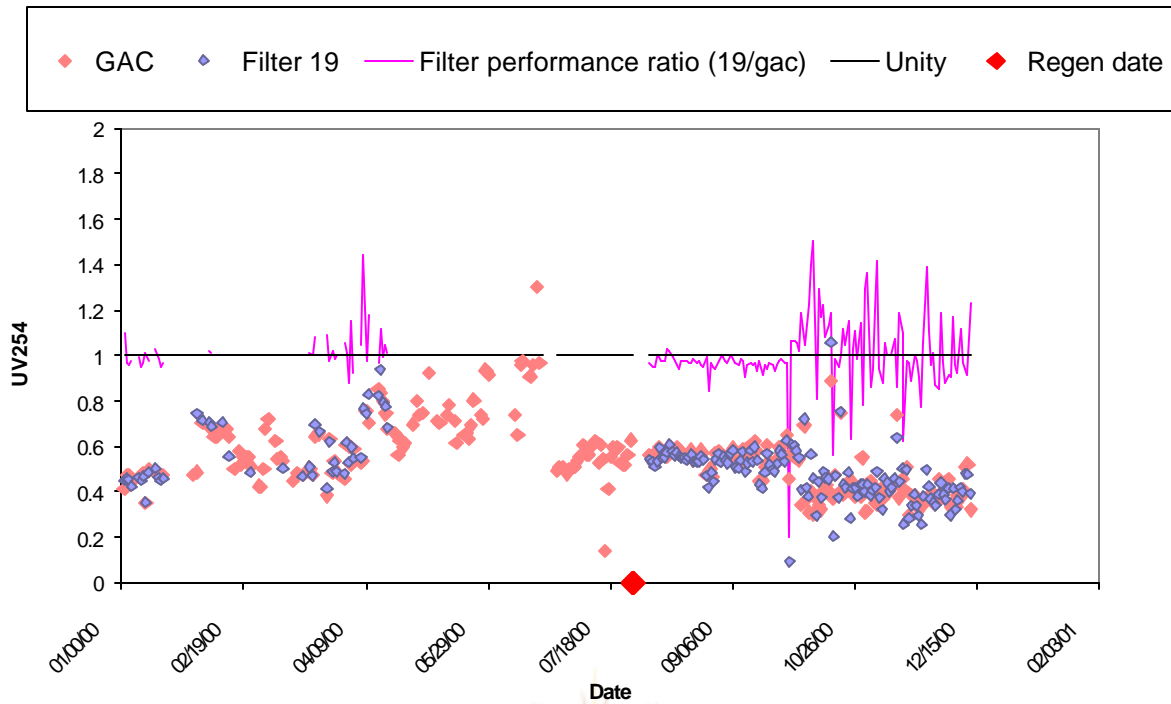
UV Absorbancy (Filter 17)



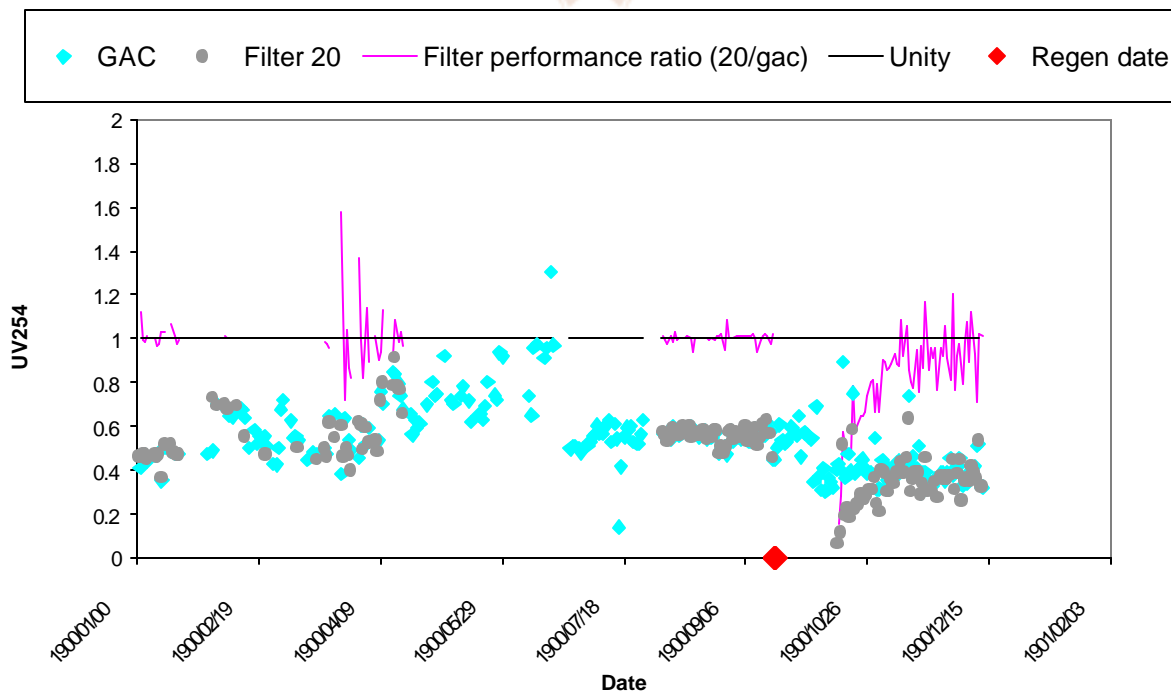
UV Absorbancy (Filter 18)



UV Absorbancy (Filter 19)

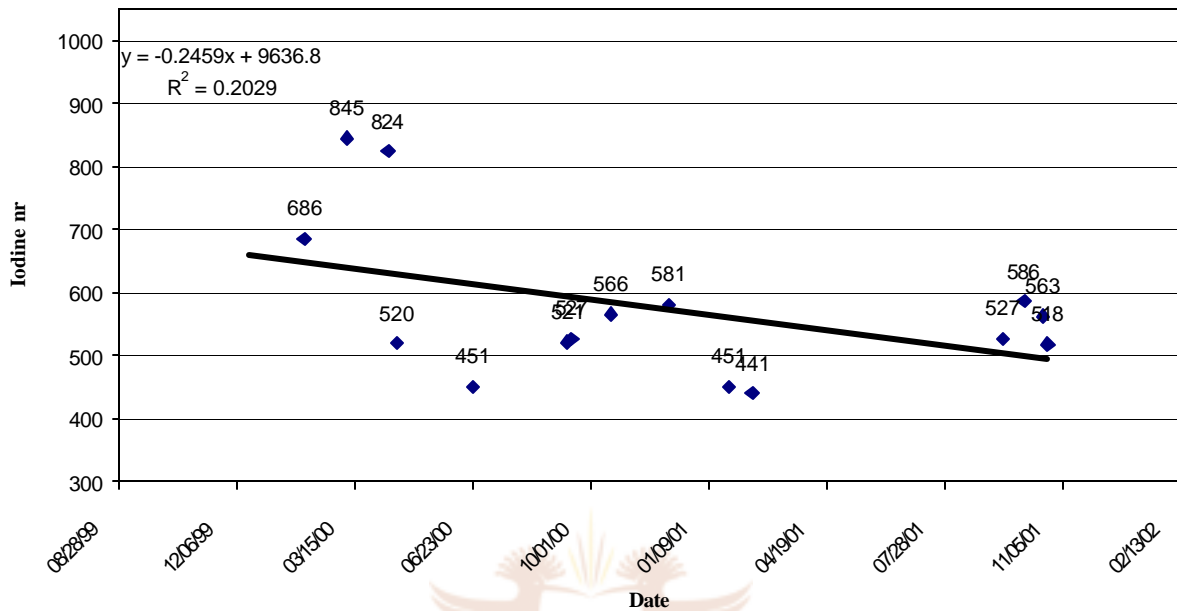


UV Absorbancy (Filter 20)

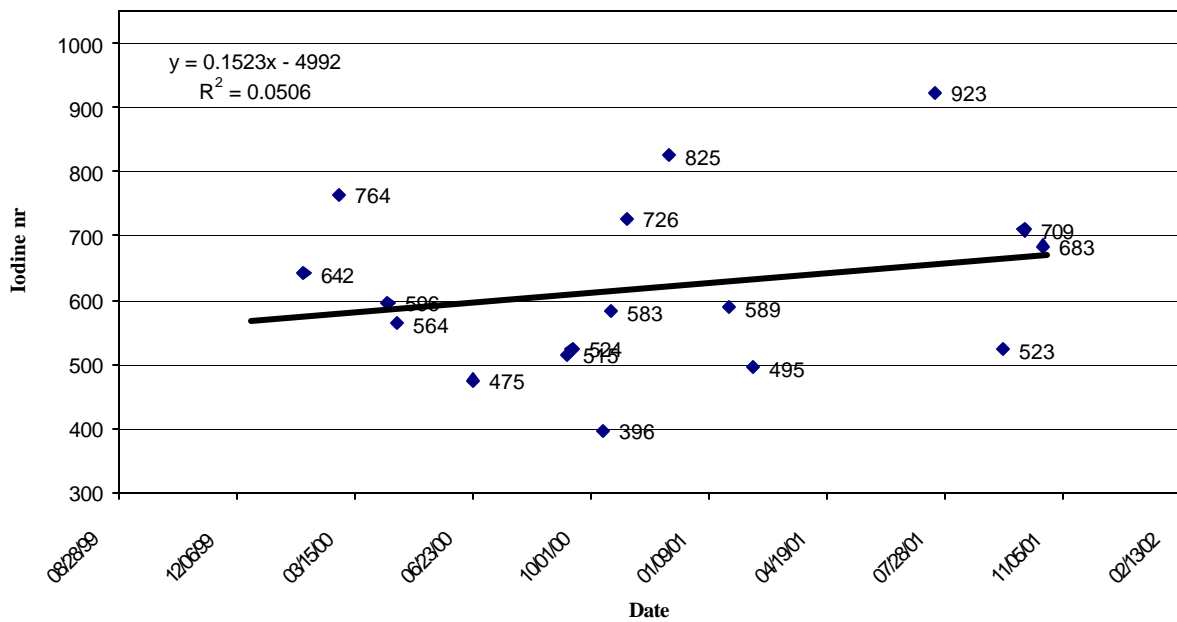


8.7 IODINE NUMBERS FOR FILTERS 1 - 20

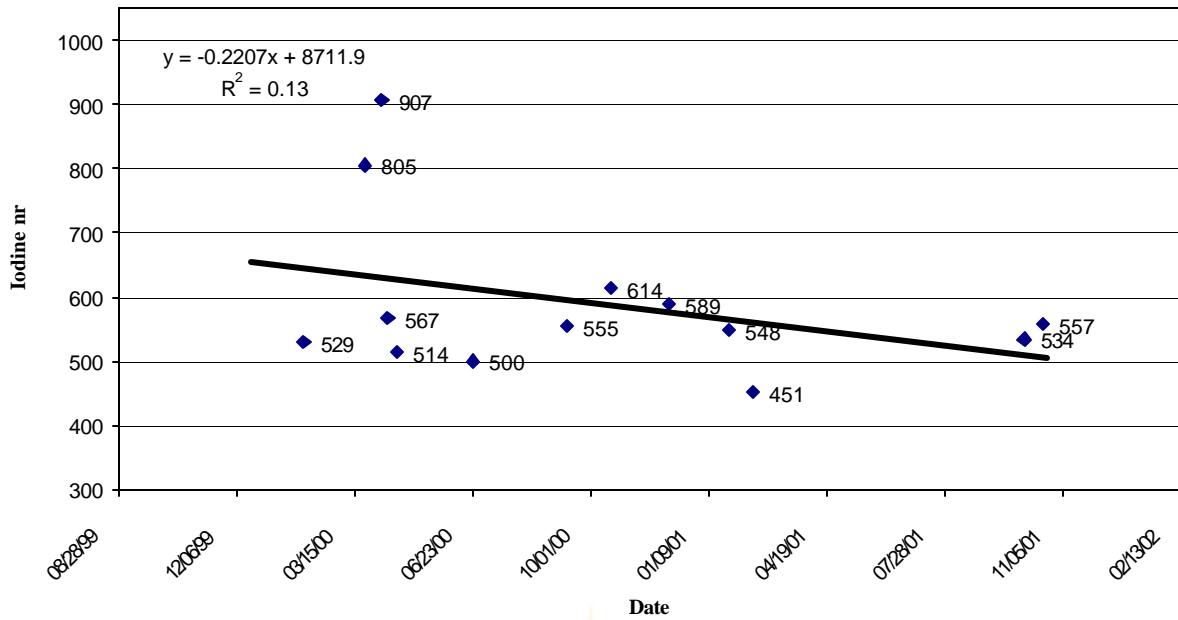
Iodine nr History (Filter 1)



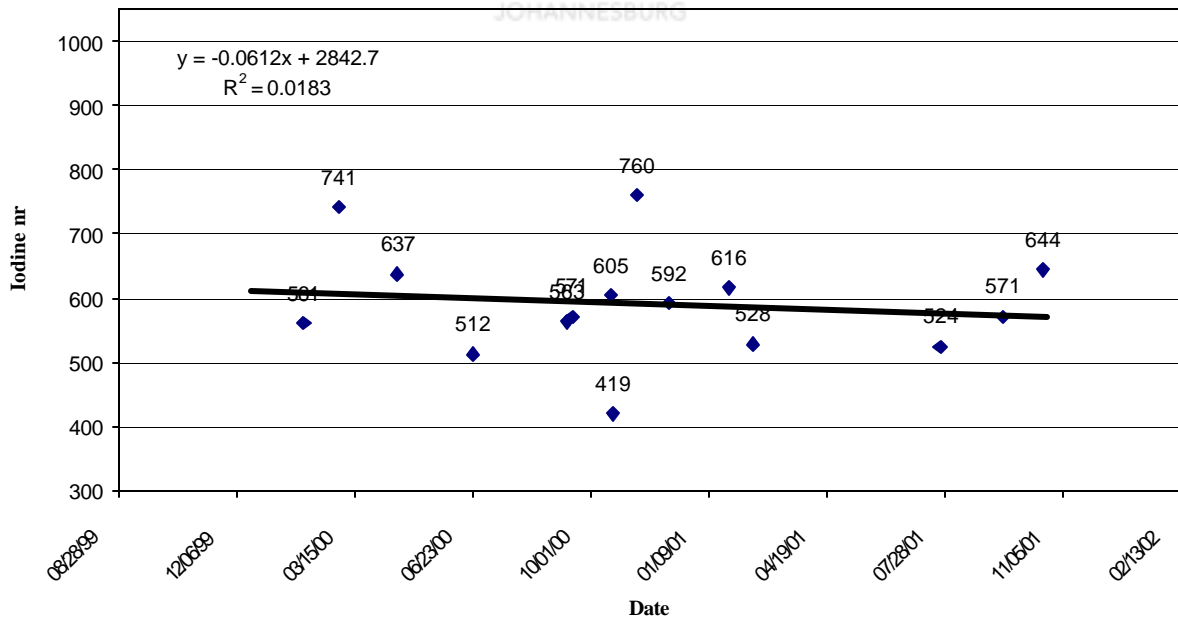
Iodine nr History (Filter 2)



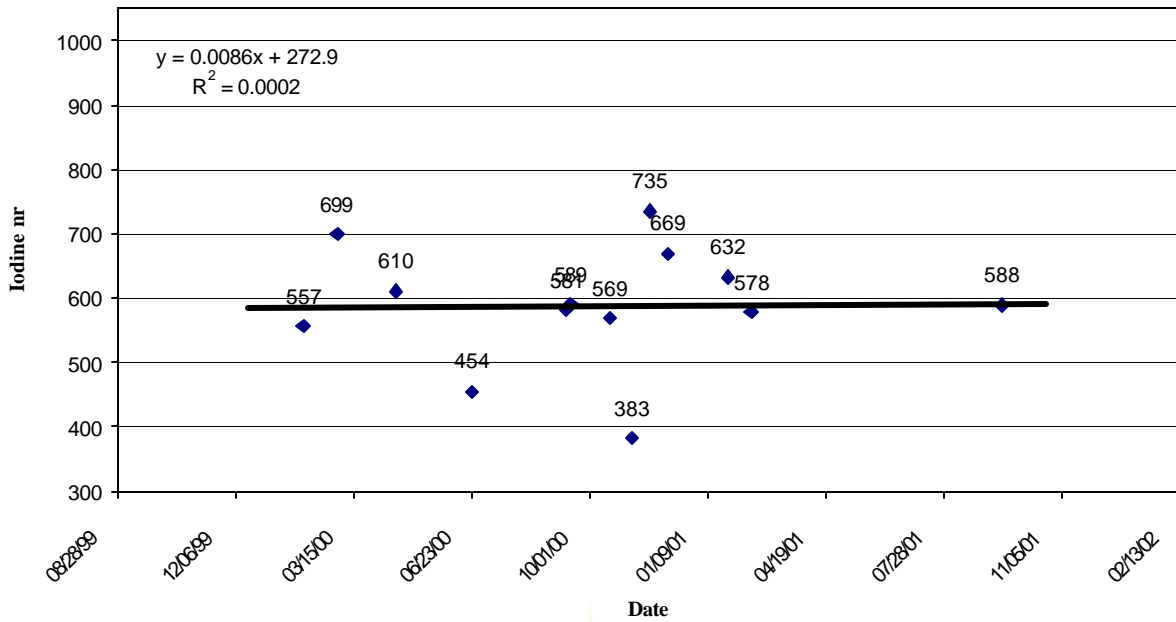
Iodine nr History (Filter 3)



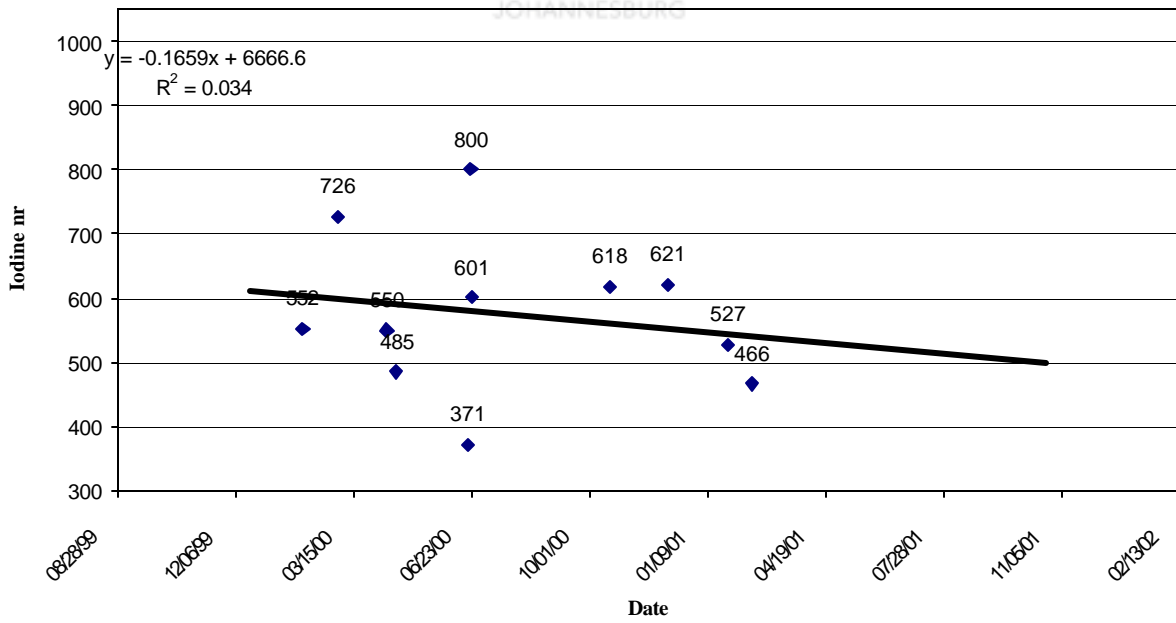
Iodine nr History (Filter 4)



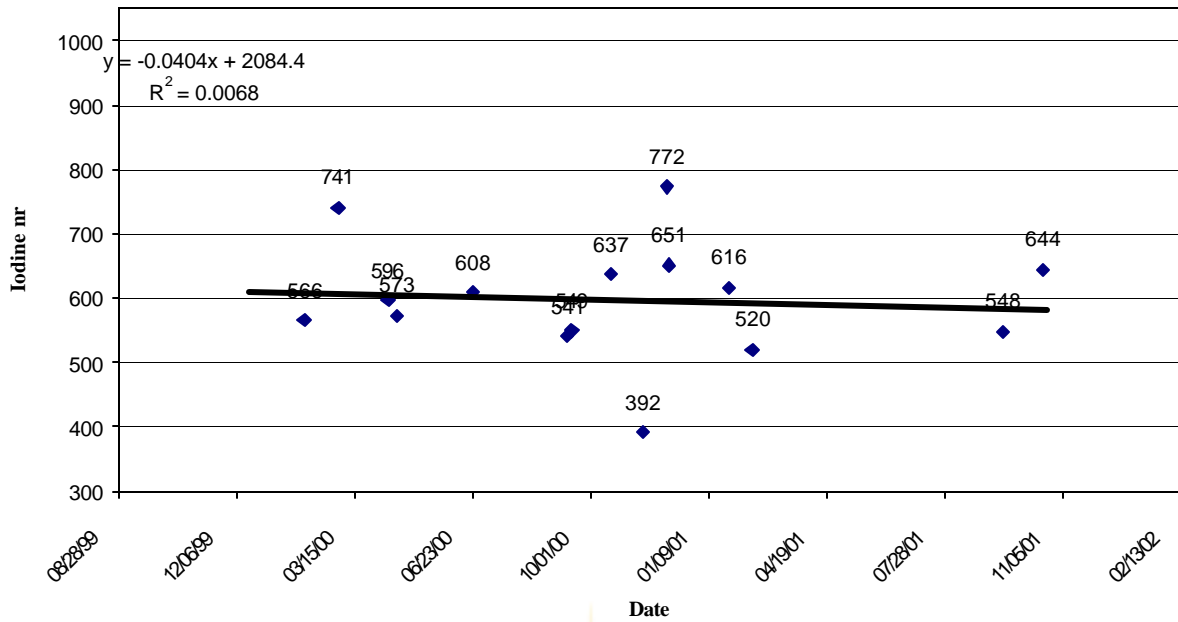
Iodine nr History (Filter 5)



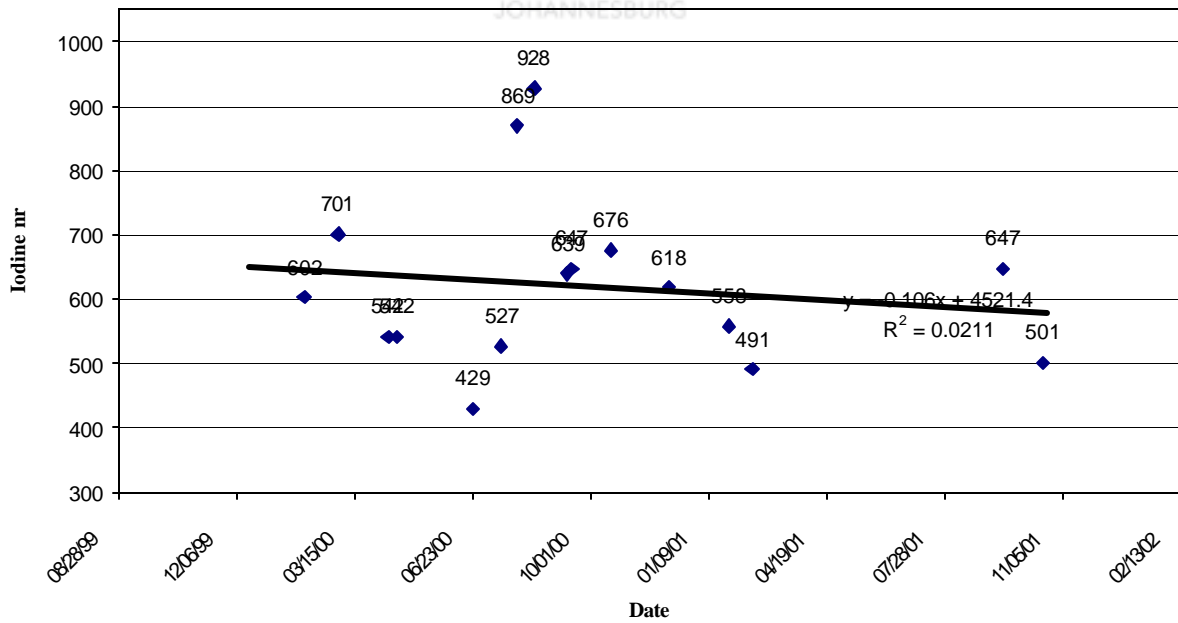
Iodine nr History (Filter 6)



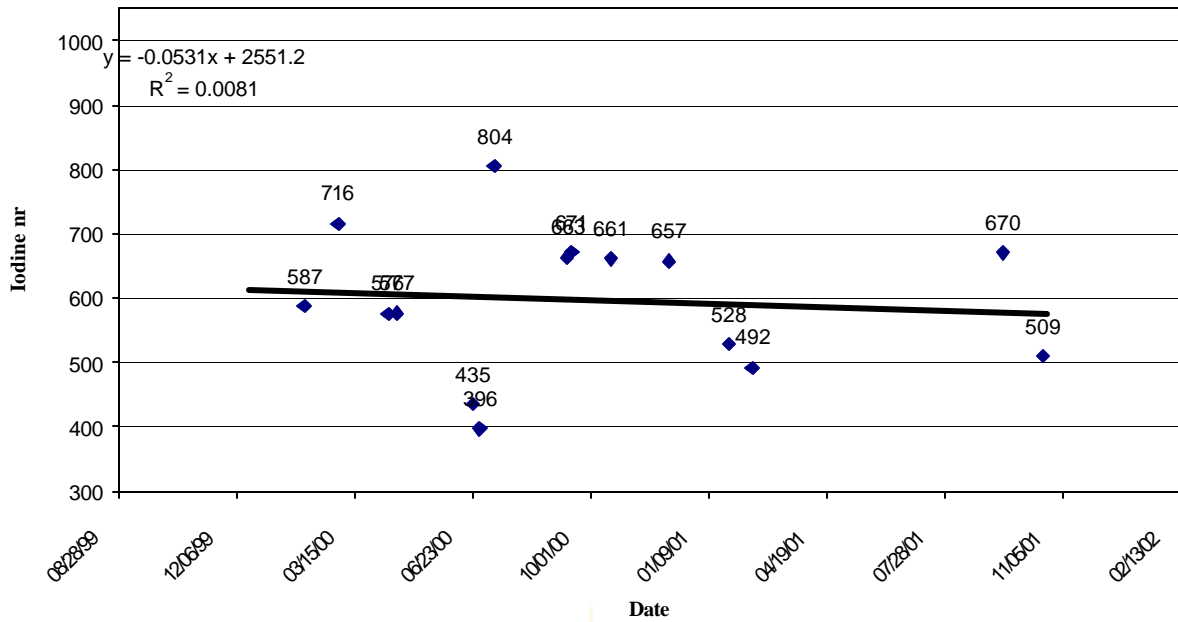
Iodine nr History (Filter 7)



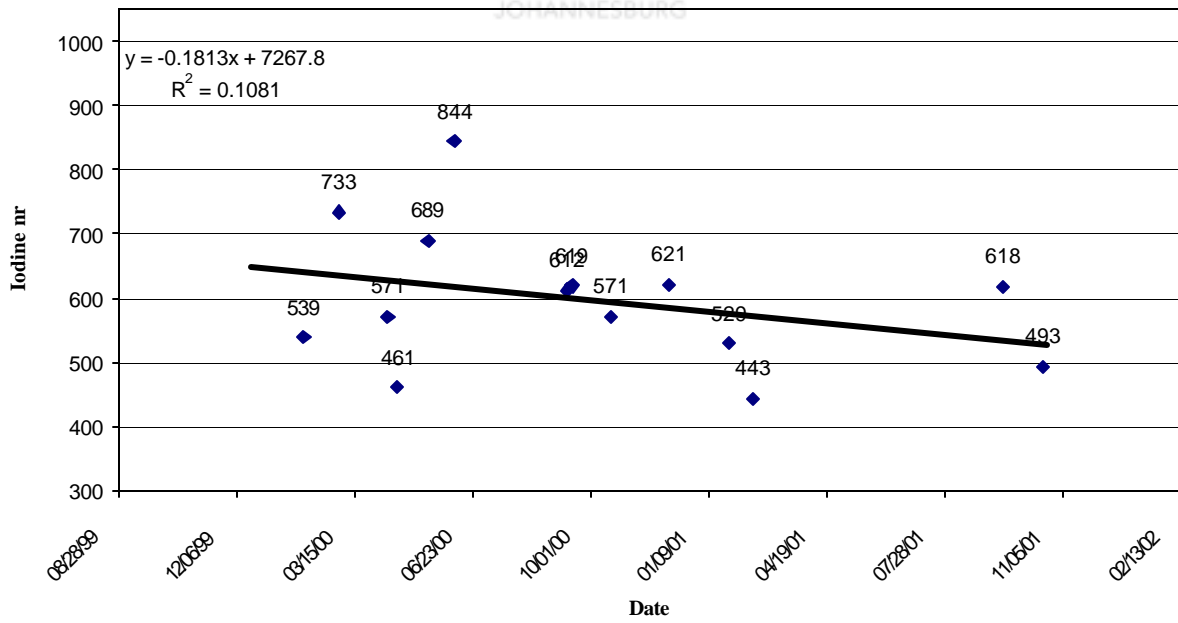
Iodine nr History (Filter 8)



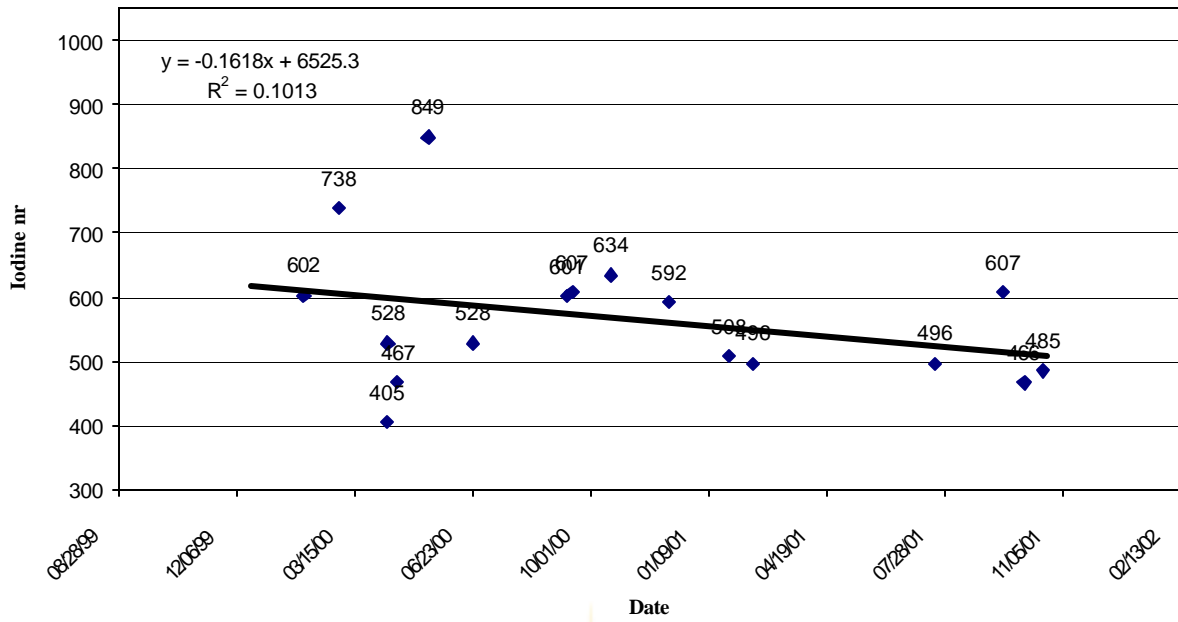
Iodine nr History (Filter 9)



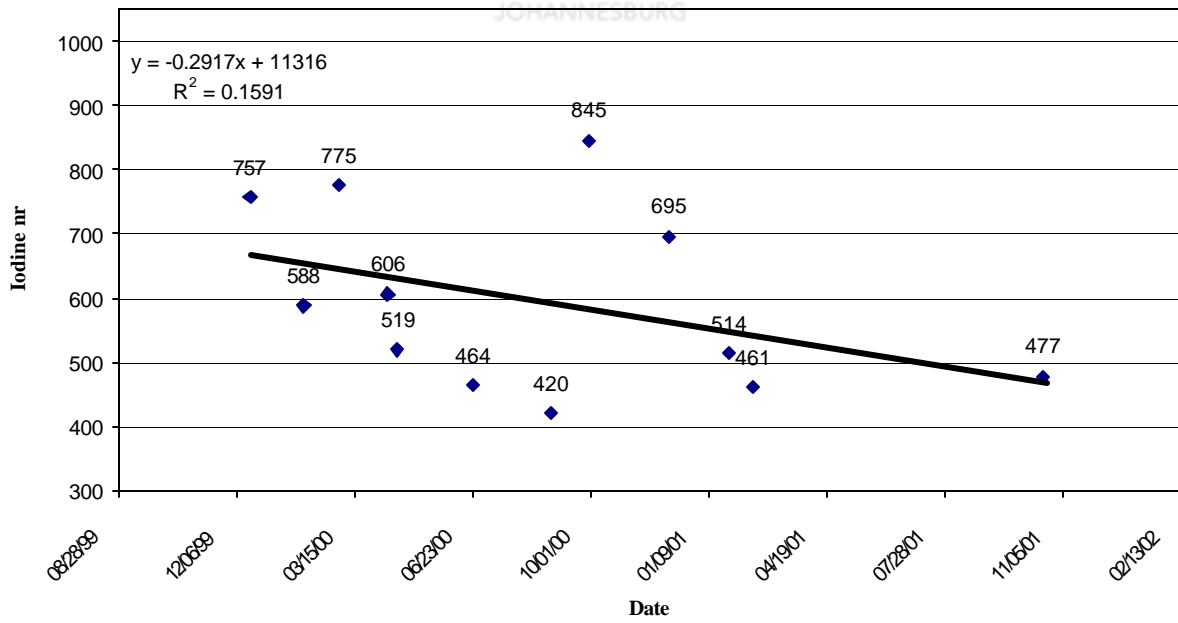
Iodine nr History (Filter 10)



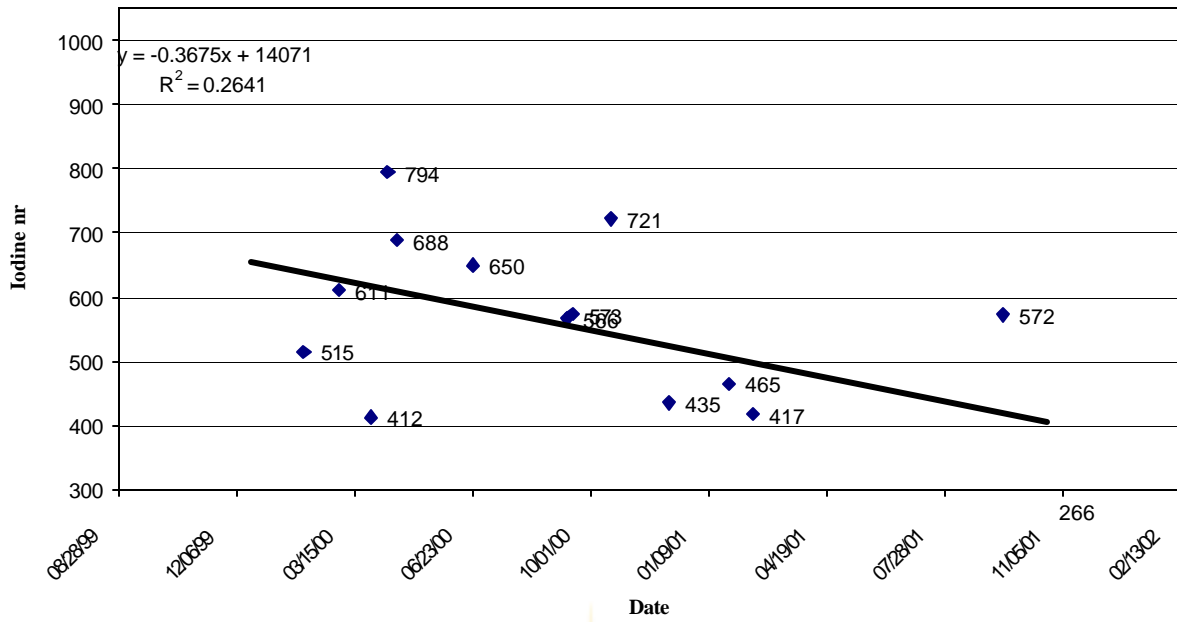
Iodine nr History (Filter 11)



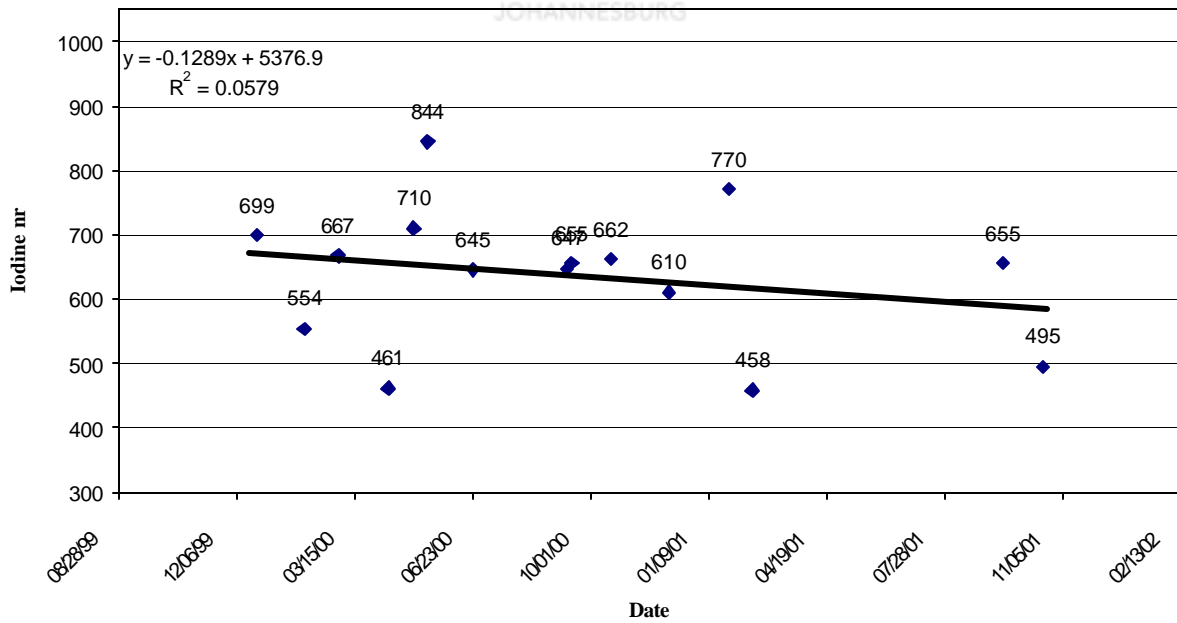
Iodine nr History (Filter 12)



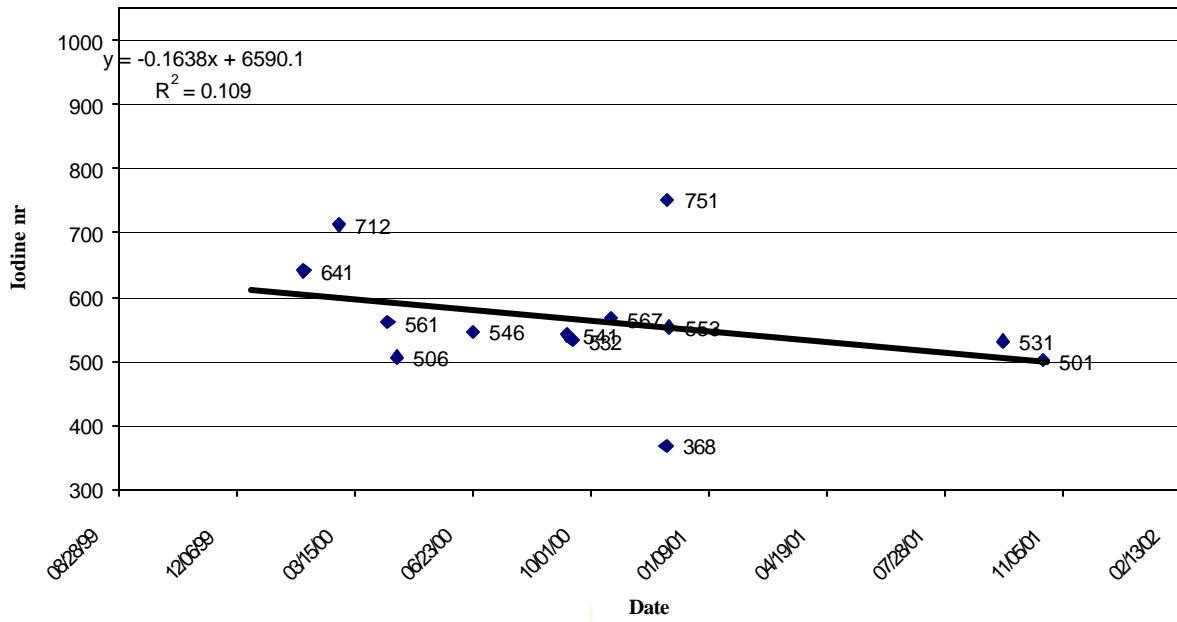
Iodine nr History (Filter 13)



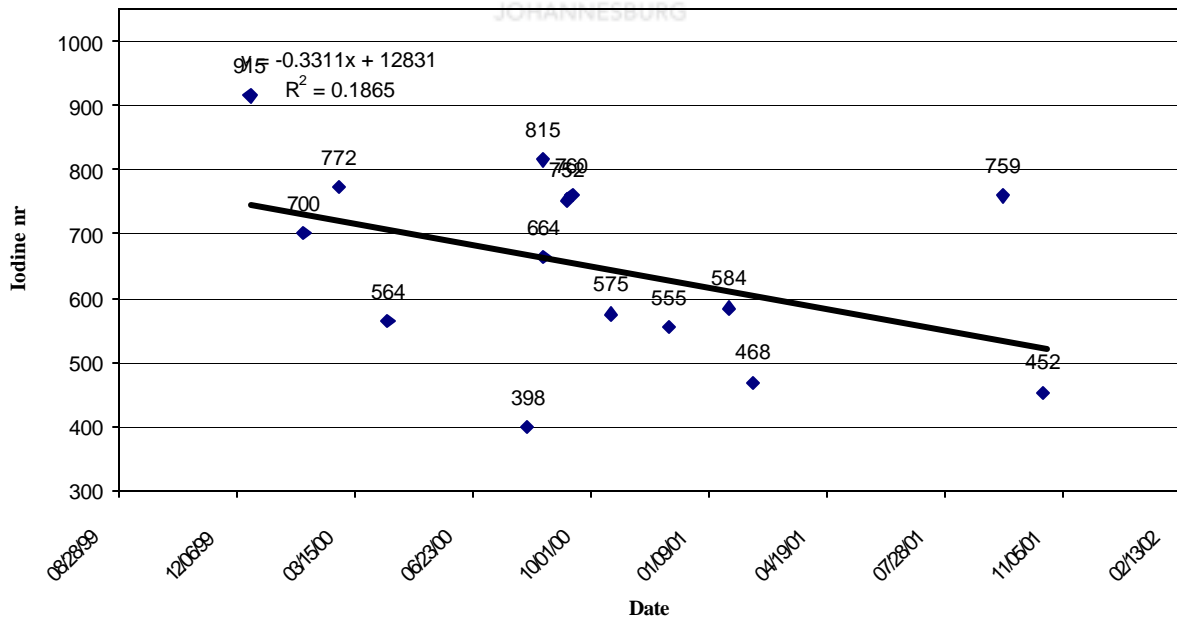
Iodine nr History (Filter 14)



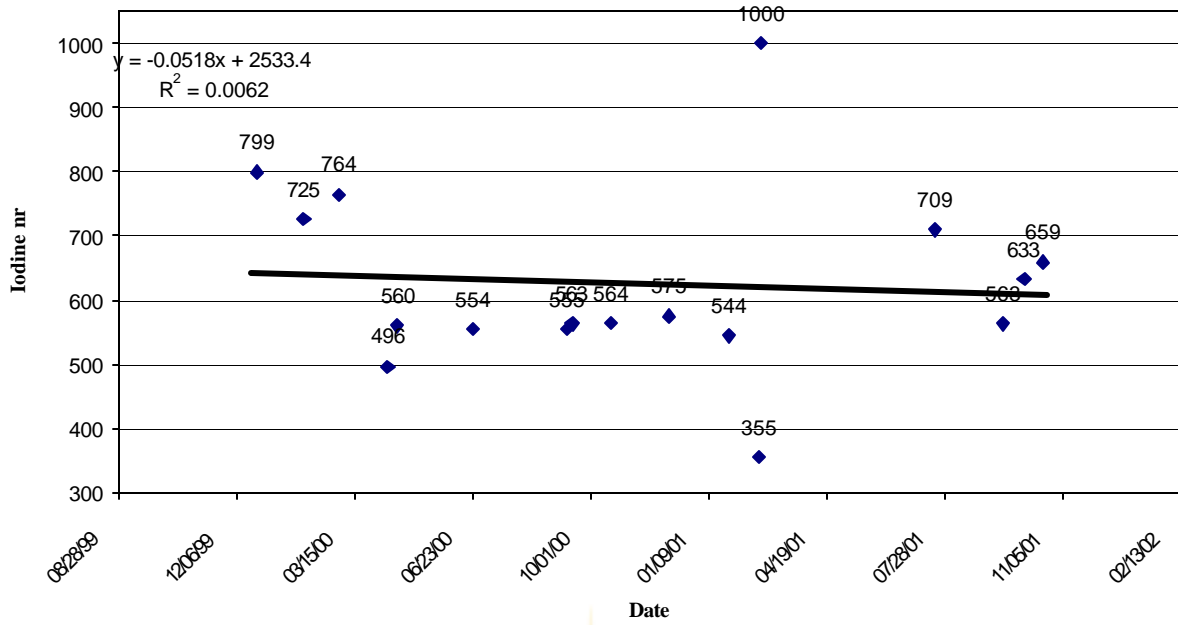
Iodine nr History (Filter 15)



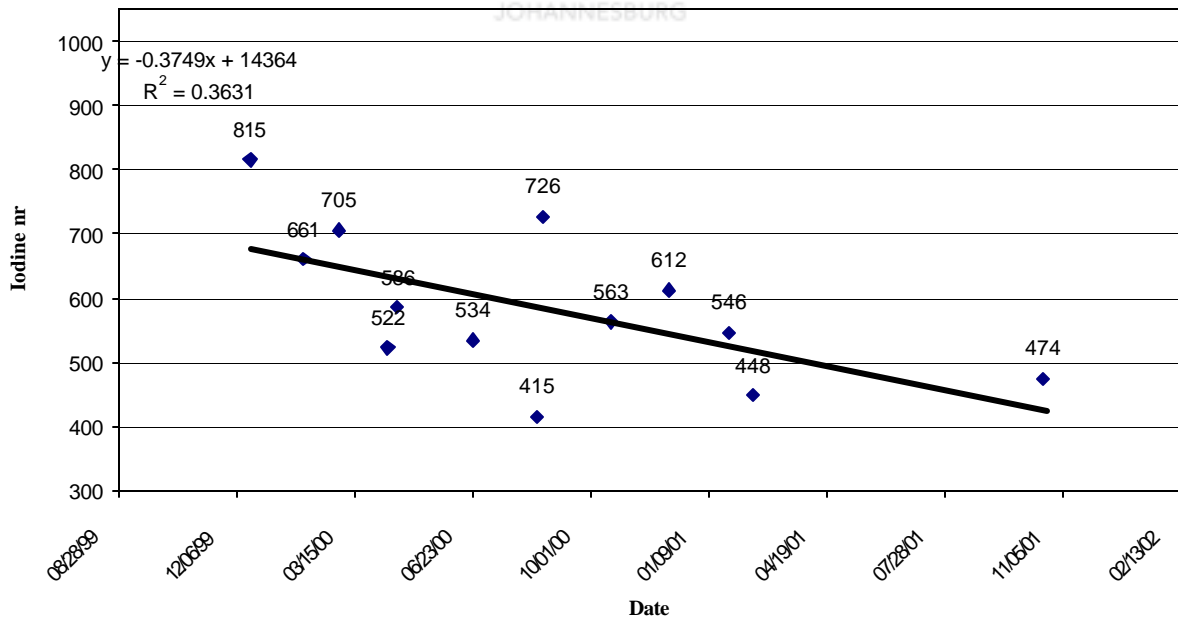
Iodine nr History (Filter 16)



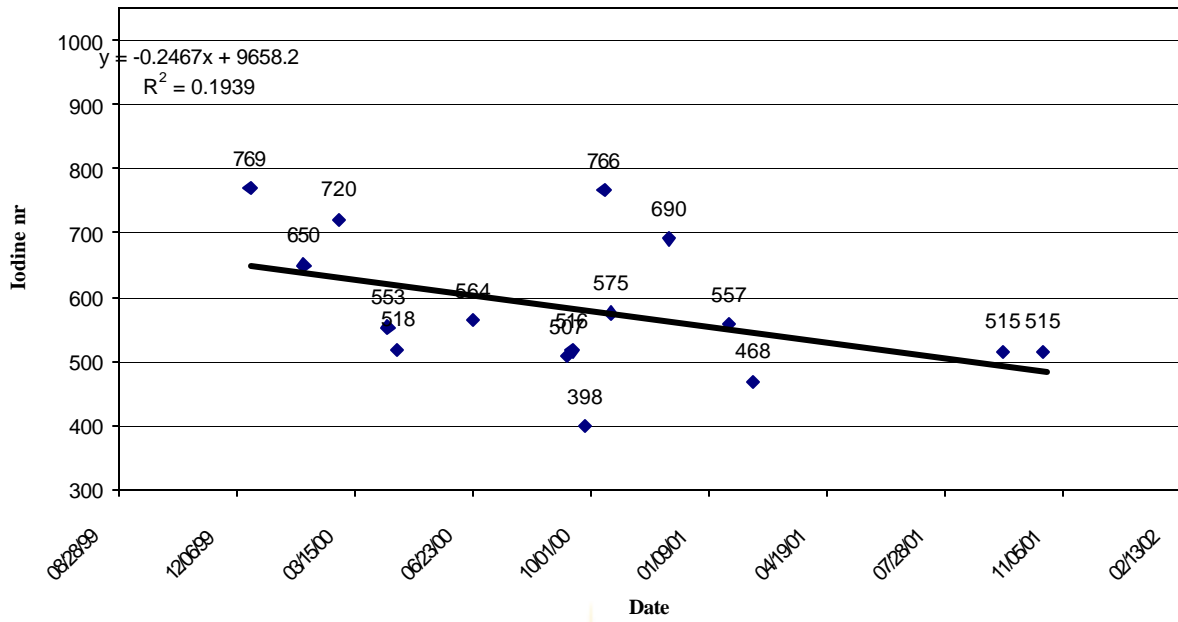
Iodine nr History (Filter 17)



Iodine nr History (Filter 18)



Iodine nr History (Filter 19)



Iodine nr History (Filter 20)

