GAC performance at three Southern African water treatment plants

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Abstract

The use of granular activated carbon (GAC) for the final treatment of eutrophic surface water is not common in South Africa. Except for two full-scale applications started in the 1960s and 1970s (of which one had been abandoned), the technology had not been used for bulk potable water treatment. During the 1990s, however, three independent pilot investigations into GAC filtration were made – at Umgeni Water (treating eutrophic water from Inanda Dam), at Windhoek (treating high-organic water from maturation ponds) and at Rietvlei (treating eutrophic water from Rietvlei Dam). The latter project led to the construction of a full-scale GAC filtration system.

The three pilot studies collectively investigated the following variables:

- Empty-bed contact time (at all three sites)
- Different types of GAC (at Umgeni and Windhoek)
- Effects of ozonation prior to GAC (at Umgeni and Windhoek).

The data sets from all these investigations were combined and analysed in a consistent way. From this meta-analysis, a clear picure emerged of which water quality parameters were significantly improved by GAC, and to what extent. The actual performance at each site was further quantified by using the international STIMELA simulation model to reduce the performance in each case to two modelling parameters. These modelling parameters are especially powerful, as they show where similarities existed amongst the different pilot studies, and providing further pilot studies elsewhere with a much narrower starting point than previously available. The final analysis shows that the GAC is spent much faster than originally anticipated, which is probably due to the high concentration and complex nature of the organic matter in South African surface water. On the other hand, there appears to be a strong residual adsorption potential after the initial breakthrough, probably due to biological activity which is stimulated during the warmer summer months. This aspect requires further study, as it could play a significantly role in determining future GAC reactivation strategies, with concomitant cost benefits.

Background

South African surface waters are generally characterised by high levels of organic carbon. A policy of indirect reuse since pioneering legislation in 1956 caused a gradual increase in organic carbon concentrations due to increasing return flows from upstream water users. In the coastal areas, natural humic and fulvic acids have always been high, leading to some of the highest recorded natural colour levels in the world. Despite these pressing reasons for using granular activated carbon (GAC) for municipal drinking water treatment, its application in Southern Africa is rare. A pioneering application was at the Windhoek water reclamation plant since 1968, followed by an application downstream of the Hartbeespoort Dam a few years later – a plant now abandoned. The use of powdered activated carbon (PAC) as an emergency measure during sporadic occurrences of intolerable taste and odour is much more common – a practice found at many treatment plants.

During the early 1990s, three independent GAC pilot studies were conducted at different sites in Southern Africa. In the absence of very little reliable data from Southern Africa, these studies made valuable contributions. At their conclusion, permission from all parties was obtained to conduct a metastudy, in an attempt to draw some generalised conclusions from these three studies. This paper provides a short summary of the most important conclusions, limited to the performance of GAC without ozone pretreatment. To differentiate between the contributions of ozone and GAC in a combined system, falls outside the scope of this paper.

Details of the pilot studies

The Windhoek study

At the start of the 1990s, a decision was reached to increase the reclamation plant capacity from 4.5 Mℓ/d to 21 Mℓ/d. At the same time, a number of new technologies were to be considered for possible inclusion in the future process train. To study the optimal application of GAC and ozone, a pilot plant was operated for over a year. After eight months of operation, some changes were made - only the first 240 d of operational data could therefore be considered.

Two carbon types were considered, both with and without ozone pretreatment, at different empty bed contact times (EBCTs).

The Wiggins study

The Wiggins water treatment plant draws raw water from the Inanda Dam and supplies potable water to the coastal region of the Umgeni Water supply area. The Inanda Dam is already eutrophied to some extent due to an increased contribution from wastewater effluent and growing human settlement in its catchment area. PAC had to be used on occasion to combat taste and odour problems. Should the level of eutrophication increase (as it is anticipated), the use of GAC

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TABLE 1
Operational parameters at the three pilot locations

Parameter	Windhoek	Wiggins	Rietvlei
Source water	Biologically treated wastewater, followed by full-scale DAF and filtration	Inanda Dam water, treated by settling and filtration in a pilot plant	Rietvlei Dam water, treated by DAF and filtration at full-scale
GAC tested	Wood-based Coal-based	Wood-based Coal-based	Coal-based
EBCT tested	7, 14, 21 min	10 min	3, 6, 9, 12 min
GAC column diameter	300 mm	400 mm	110 mm
GAC depth	1 000 mm	1 000 mm	250 mm
Hydraulic loading rate	5.7 m/h	6.0 m/h	5.0 m/h
Ozone tests	With and without	With and without	Without
# determinants tested	54	30	6
# data points	7 262	16 768	720

would probably be required. Umgeni Water therefore embarked on a pilot programme to determine some preliminary design and cost parameters.

The experimental design was similar to that in Windhoek. Two different carbons were tested, with and without pre-ozonation. The runs ran for about 800 d in total, but some changes were introduced after 440 d. Only the first 440 d of the trials could therefore be included in this metastudy.

The Rietvlei study

The Rietvlei water treatment plant supplies potable water to the eastern parts of Pretoria. Its raw water source is the Rietvlei Dam, an impoundment which is also increasingly eutrophied by the upstream discharge of treated sewage effluent. Moreover, the wetlands immediately before the impoundment, which acted as a nitrogen trap in the past, lost its efficiency during the beginning of the 1990s and the algal dominance in the impoundment switched from green to bluegreen. For these reasons, laboratory investigations into the use of GAC started in 1994, and eventually culminated in a pilot study conducted during 1995 and 1996.

The experimental plant was very simple, testing only one carbon at four different EBCTs. At regular intervals, water was taken to the laboratory where batch ozone studies were conducted. The plant ran for 196 continuous days, unchanged, and all the data could be used for this study. The water for the pilot plant was drawn off the final production pipeline, just before the chlorine addition point.

Data preparation

A significant part of the study was devoted to manipulate the data to a format which would allow valid comparisons. Each study measured different sets of parameters at different intervals, so direct comparisons were not possible. The data preparation steps are briefly described below.

Collection and initial inspection

Site visits were conducted and the complete data sets were lifted from the original databases. It turned out that, viewed together, 64 different water quality determinants were measured in total at intervals ranging from 1 measurement/day to 2 measurements/month. The determinants could be grouped as the physical determinants (4), the chemical micro-determinants (14), the chemical macro-determinants (16), the organic chemicals (13), the microbiological determinants (8) and the toxicological determinants (9). The microbiological determinants (measured mostly at Wiggins) and toxicological determinants (measured exclusively at Windhoek) were sketchy and erratic and were therefore summarily excluded from the rest of the analysis.

Removal of outliers

As a second step, the obvious outliers (indicating experimental or data entry errors) were removed. The mean and standard deviations of each determinant, at each sampling point, were determined. Assuming a normal distribution of values about the mean, all values further than 3.7 standard deviations from the mean were removed. In statistical terms, this indicates a 99.98% probability that the rejected values are outliers. Of the 24 450 data points considered in this study, only 288 (slightly more than 1%) were rejected in this way. For the individual locations the rejection rates were Windhoek (40 out of 7 262), Wiggins (247 out of 16 768) and Rietvlei (1 out of 720).

Selection of determinants significantly affected by GAC

Every determinant was next analysed to determine whether the GAC had a significant effect. Each data point was divided by the corresponding value of the influent to obtain a value for C/C_0. All the values of C/C_0 of every sampling point could then be averaged and further analysed. Two criteria had to be met before a determinant was considered to be significantly affected by GAC:

- The null hypothesis was that there was no significant removal (in other words H_0 being $C/C_0 = 1$). The null hypothesis had to be rejected at $\alpha = 0.02$.
- The average C/C_0 (even if it were statistically significant different from 1) had to be less than 0.95 or larger than 1.05.

Only those determinants which were significantly affected by GAC, were subjected to the next steps of the analysis.

Data smoothing

Due to the different sampling frequencies, and missing data points due to rejected data points on weekends or practical problems, it was next necessary to interpolate data points for every day. This was done by simple linear interpolation.

To enable easier visual spotting of trends, and to facilitate the fitting of theoretical models (discussed further on) a moving 7 d average trend line line was calculated and plotted. These smoothed lines were used for the rest of the study.

Analysis of average removal values

Table 2 provides a summary of the average C/C_0 values at five sampling points. The following should be noted:

- The table is confined to GAC performance only. All sampling points where ozone was dosed upstream, are excluded.
- Only the sampling point with the longest EBCT at each location is shown. For Windhoek, the EBCT for the coal-based GAC was 21 min, and the EBCT for the wood-based GAC 14 min. At Wiggins, the EBCT for both carbons was 10 min and at Rietvlei the EBCT was 12 min.
- The table provides a comprehensive list of the determinants tested at all the locations, excluding the microbiological and toxicological determinants. Also, it indicates which determinants were measured at each location.

The average values in Table 2 do not fully reflect the complex breakthrough behaviour of the adsorption process, but nevertheless allows some conclusions:

- The physical determinants were reduced as expected. The secondary filtration effect of the GAC (measured by turbidity) was larger than one would have expected.
- The inorganic microdeterminants were not affected at all, as one would expext. The only organic micro-determinant was the pesticides, which was effectively reduced as would be expected.
- The macro-determinants were also not affected, with the exception of the nitrogenous determinants. The pathways between nitrite, nitrate, ammonia and TKN are complex and a stoichiometric analysis was not attempted. It is, however, obvious that some oxidation processes were at work, very probably biologically induced.
- GAC really came into play with the removal of the organic determinants. Only the phenols and geosmin were not significantly removed at any of the sampling points.
- The Wiggins study allows a direct comparison between wood-based and coal-based GAC, as the EBCT and pretreatment were identical. It is clear that the wood-based GAC performed markedly poorer than the coal-based GAC.
- The Windhoek study does not allow direct comparison between the two carbon types, as the EBCT of the wood-based GAC (14 min) was not the same as the EBCT of the coal-based GAC (21 min). Even making a qualitative allowance for this, it still seems as if the wood-based GAC was less effective than its competitor.

As the coal-based GAC performed the best throughout, the rest of this paper is limited to the modelling of the coal-based GAC only.

A GAC adsorption model

The study could now move to the more detailed consideration of the kinetic behaviour of the GAC at the different locations. It was firstly necessary to use a mathematical model to allow a sensible comparison amongst the different locations. Once the model is calibrated at each site, the model parameters can be directly compared as they are not limited to specific loading rates, EBCTs, and GAC bed depths.

The following model was used (full derivation given by Olivier (2001)):

$$\frac{\partial C}{\partial z} = -\frac{1}{u}.\frac{\partial C}{\partial t} - M.\left(C - \sqrt[n]{\frac{q}{K}}\right)$$

where:

C is the concentration of a determinant
z the bed depth, u the pore velocity
t the time
q the flow rate.
The parameters M, n and K are constants that need to be adjusted as calibration factors to match the model to actual performance.

These parameters have the following qualitative effects on the breakthrough curve:

- The parameter M is a mass-transfer coefficient, and therefore determines the initial removal efficiency. In terms of model calibration, this is the parameter that is adjusted first until the initial removal efficiency is matched.
- The Freundlich parameter n determines the shape of the breakthrough curve. A high value for n implies that breakthrough begins soon after new GAC is put into operation, whereas a low value implies a period of constant removal before breakthrough is detected. This is normally the parameter that would be adjusted next until the shape of the actual breakthrough is matched.
- The Freundlich parameter K is a capacity factor and determines the total mass of the determinant that can be adsorbed. Graphically, it simply "stretches" the graph in a horizontal direction. This parameter is normally adjusted as the last step to obtain the best match between model and practice.

Modelling of measured data

To model the performance of an actual GAC bed, the bed needs to be mathematically discretised into an arbitrary numbers of layers, which are then treated as reactors in series. The number of layers were first treated as a variable, ranging from one layer to seven layers. Satisfactory results were obtained when five layers were used, which was then adopted for the rest of the modelling.

During the pilot studies, there were large and continuous changes in the influent concentrations of almost all the determinants, induced by seasonal and other environmental changes. The model was therefore set up as a dynamic model, which could deal with continuous changes in the influent concentration.

TABLE 2
Average C/C_0 for selected sampling points

Determinant	Windhoek		Wiggins		Rietvlei
	Wood-based	Coal-based	Wood-based	Coal-based	Coal-based
PHYSICAL					
Colour	0.65	0.36	n/e	0.79	0.61
Conductivity	n/e	n/e	n/m	n/m	n/m
pH	n/e	n/e	n/e	n/e	n/e
Turbidity	0.61	0.55	0.57	0.50	0.63
MICRO-DETERMINANTS					
Aluminium	n/m	n/e	n/e	n/e	n/m
Boron	n/m	n/e	n/m	n/m	n/m
Bromide	n/e	n/e	n/m	n/m	n/m
Cadmium	n/m	n/e	n/m	n/m	n/m
Chromium	n/m	n/e	n/m	n/m	n/m
Copper	n/m	n/e	n/m	n/m	n/m
Gold	n/m	n/e	n/m	n/m	n/m
Iron	n/m	n/e	n/m	n/m	n/m
Lead	n/m	n/e	n/m	n/m	n/m
Manganese	n/m	n/e	n/m	n/m	n/m
Mercury	n/m	n/e	n/m	n/m	n/m
Nickel	n/m	n/e	n/m	n/m	n/m
Pesticides	n/m	n/m	0.50	0.19	n/m
Selenium	n/m	n/e	n/m	n/m	n/m
Silver	n/m	n/e	n/m	n/m	n/m
MACRO-DETERMINANTS					
Alkalinity	n/m	n/m	n/e	n/e	n/m
Ammonia	n/e	n/e	n/e	n/e	n/m
Calcium	n/m	n/e	n/e	n/e	n/m
Chloride	n/e	n/e	n/e	n/e	n/m
Fluoride	n/e	n/e	n/m	n/m	n/m
Potassium	n/e	n/e	n/m	n/m	n/m
Magnesium	n/e	n/e	n/e	n/e	n/m
Nitrite	1.84	3.15	n/e	n/e	n/m
Nitrate	n/e	n/e	1.36	n/e	n/m
Ortho-phosphate	n/e	n/e	n/m	n/m	n/m
Silica	n/e	0.94	n/m	n/e	n/m
Sulphate	n/e	n/e	n/e	n/e	n/m
TKN	n/e	0.71	n/m	n/m	n/m
Total phosphate	n/e	n/e	n/m	n/m	n/m
Zinc	n/m	n/e	n/m	n/m	n/m
ORGANIC					
2-MIB	n/m	n/m	0.85	0.83	n/m
$CHBr_3$ FP	n/e	n/e	1.18	1.46	n/m
$CHCl_3$ FP	0.85	0.53	0.74	0.50	n/m
$CHCl_2Br$ FP	n/e	0.74	0.91	0.80	n/m
$CHClBr_2$ FP	n/e	n/e	n/e	1.06	n/m
COD	0.86	0.65	n/m	n/m	n/m
DOC	0.94	0.87	n/e	0.90	0.55
Geosmin	n/m	n/m	n/e	n/e	n/m
Phenol	n/e	n/e	n/e	n/e	n/m
TTHM FP	0.87	0.64	0.88	0.78	n/m
UV	0.80	0.50	0.87	0.67	0.44

n/e = no effect; n/m = no measurement

The model was first implemented at the RAU Water Research Group in a Matlab environment to test the model and to perform some sensitivity checks. Once the model could be used with confidence, the bulk of the modelling was done after collaboration with the Technological University Delft, using their STIMELA model, also running in a Matlab environment using the SIMULINK module.

Figure 1 demonstrates a typical modelling run, in this case for the removal of DOC at Rietvlei after an EBCT of 12 minutes. An indirect check on the validity of the model was obtained by comparing the performance at the same plant for the same EBCTs. In other words, the model parameters for Windhoek was approximately the same, irrespective of whether the model was calibrated with the 7-minute EBCT or 21-minute EBCT data.

Only the first part of each data set could be used. It was normally an easy matter to fit the model to the first 50 to 100 d of data. In almost all cases, an improvement in performance was noticed after this initial period, not accounted for by the model. This could only be ascribed to biological activity, which only really starts after the adsorption capacity of the carbon had been exhausted. The results in this paper will be based on the initial breakthrough part of the curves only, without consideration of the biological activity.

Comparison of adsorption performance

The model parameters for different determinants at the different location are summarised in Table 3.

These values reflect deep and significant differences in adsorption behaviour amongst the different locations, despite the fact that almost identical GACs were used in the three cases. To demonstrate these differences, the model was finally used to calculate the performance at the three locations for the cases of constant influent concentration of UV absorbance of 20/m. The results are shown in Fig. 2.

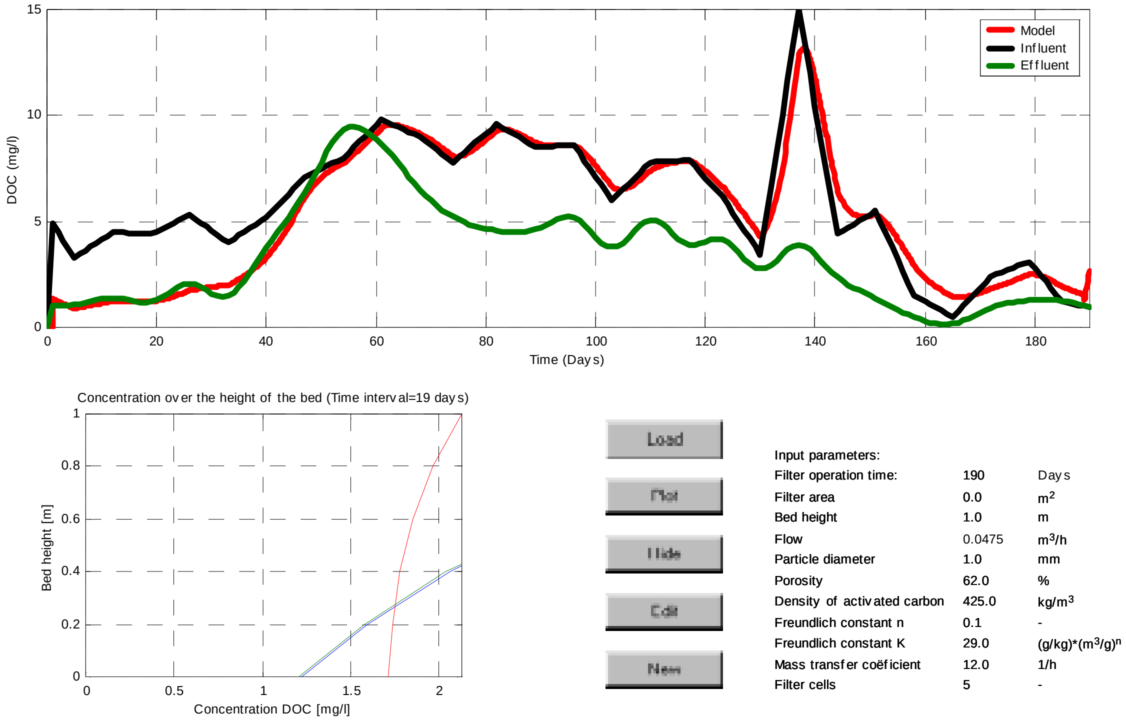

Figure 1
Modelling of DOC removal at Rietvlei for an EBCT of 12 min (screenshot from a simulation by the STIMELA package)

TABLE 3
Comparison of model parameters

Model parameters	Windhoek	Wiggins	Rietvlei
DOC			
n	0.35	0.10	0.10
K	8.5	30	29
M	2.5	8.5	12
POE	50 d	125 d	50 d
UV ABSORBANCE			
n	0.80	0.35	0.80
K	6.9	15	4.5
M	7.5	11	18
POE	125 d	-	65 d

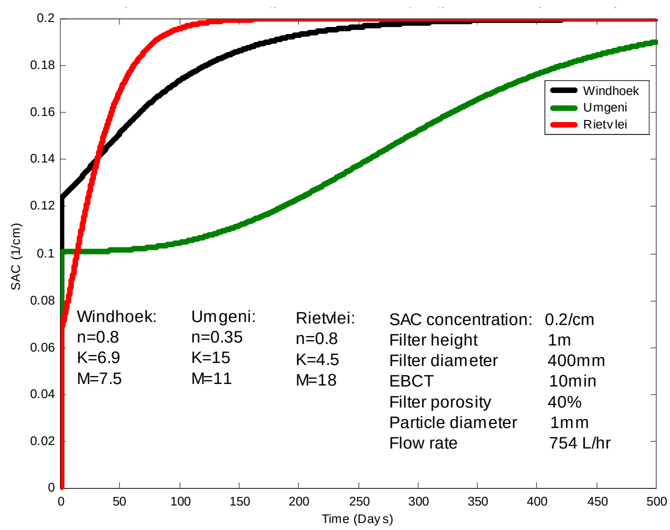

Figure 2
UV absorbance at the three locations

Conclusions

The simultaneous analysis of the three valuable pilot studies conducted at Windhoek, Wiggins and Rietvlei provided some useful pointers to others wanting to perform pilot studies in Southern Africa, as well as illuminating some aspects of GAC adsorption which require further systematic analysis:

- In all cases, satisfactory information could be obtained from the first 100 d of data, indicating that pilot studies of about six months should suffice to obtain reliable design parameters, unless the nature of the organic material is expected to show wide seasonal swings.
- The data obtained from the small pilot filters of 50 mm diameter at Rietvlei appeared to have produced data comparable with much larger pilot filters, indicating that smaller filters may be used with good effect if larger systems are beyond the reach of a specific location.
- For the studies examined, the physical adsorption performance of coal-based GAC was markedly better than wood-based GAC.
- There are large differences in adsorption behaviour amongst the different sites, even for identical GACs, indicating large differences in the composition and nature of the organic determinants, indicating that pilot studies are vital to develop design guidelines for a specific location.
- There is indisputable evidence of significant biological activity in the GAC, becoming evident after about 50 to 100 d after

commissioning of new GAC. This is apparent from nitrogen transformations within the GAC bed, as well as improved performance after the initial 50 to 100 d. Much further work is required to fully understand and model these mechanisms.

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References

OLIVIER J (2001) Granular Activated Carbon Performance at Three Southern African Water Treatment Plants. M.Eng. dissertation submitted to the Rand Afrikaans University.