Practical aspects of water treatment plant design for a hypertrophic impoundment[+]

J Haarhoff[1]*, O Langenegger[2] and PJ van der Merwe[3]
[1] *Energy Laboratory, Rand Afrikaans University, PO Box 524, Johannesburg 2000, South Africa*
[2] *Otto Langenegger and Partners, PO Box 72937, Lynnwood Ridge 0040, South Africa*
[3] *Local Government Affairs Council, PO Box 1341, Pretoria 0001, South Africa*

Abstract

The Hartbeespoort Dam is well known for its exceptionally high degree of eutrophication. It nevertheless has to serve as the drinking-water source of the communities in the vicinity. By the end of 1991, the 3 largest plants (Brits, Schoemansville and Kosmos) treating water from the impoundment had been extensively upgraded. This paper summarises the present state of knowledge on this often controversial impoundment, with specific focus on those parameters relevant to water treatment plant design. The history of water treatment at Hartbeespoort Dam is summarised, with a general discussion on the merits of and choice between the different phase separation processes. The choice of dissolved air flotation at all 3 plants, and the additional sedimentation at Brits are motivated. A detailed cost comparison between the different phase separation processes is presented. The removal of taste and odour compounds by granular activated carbon (GAC) and powdered activated carbon (PAC) is reviewed, and the choice of PAC on all 3 plants is economically and practically justified. Finally, a summary is presented on the assumptions on which the design parameters were based.

Introduction

Hartbeespoort Dam, constructed 66 years ago, offers an outstanding example of eutrophication by human activities and has consequently been the subject of intensive limnological investigation. It attracted popular attention in the mid 1970s when it became 60% overgrown with water hyacinth, and was subsequently cleared by a successful chemical control program (Scott et al., 1979). During the early 1980s the impoundment reached an incredible state of hypertrophy, giving rise to algal hyperscums (crusts of algal biomass), concentrated by wind action up to a metre thick at the dam wall (NIWR, 1985). This aroused renewed public and scientific interest in the impoundment. During 1985, a 1 mg P/ℓ phosphate limit was imposed on most of the sewage effluents discharging to the catchment area, which again led to intensive monitoring of the impoundment to determine the effects of the phosphate limit (Chutter, 1989).

While a wealth of limnological information has thus became available, relatively little is recorded on the treatment problems presented by the water from the impoundment. During the past few years, the authors have been independently involved with the extensive upgrading of the 3 largest water treatment plants treating water from the impoundment. The authors have combined this practical experience in order to address the following issues:

- to summarise the water quality parameters relevant to treatment plant design;
- to describe the problems encountered by earlier treatment processes;
- to identify the ideal process combinations;
- to analyse the costs involved with different process combinations; and
- to present the practical design constraints and solutions for each of the 3 plants.

Hartbeespoort Dam water quality characteristics

Hartbeespoort Dam is located immediately downstream of the confluence of the Magalies and Crocodile Rivers, and drains an area of 4 144 km². A map of the catchment area is shown in Fig. 1. The impoundment has a full supply level of 1 162 m above sea level, a full supply volume of 195 000 Mℓ, a mean depth of 9,6 m and offers a mean retention time of 0,87 years (NIWR, 1985). The water level fluctuation between 10% of full capacity (the minimum level assumed for pumping purposes) and 100% of full capacity is 16,5 m.

The bulk of the water consumed by the Pretoria-Witwatersrand-Vereeniging metropolitan area is pumped over a considerable distance from the Vaal River in the south. A substantial portion of this water is pumped over the watershed between the catchments of the Vaal River and the Crocodile River. This portion is eventually collected, treated and discharged into the catchment area of Hartbeespoort Dam. As urbanisation in the Hartbeespoort catchment increases, the import of sewage effluent into the impoundment follows suit. The result is that the virgin mean annual runoff of 154 000 Mℓ has increased to an average annual runoff of 224 000 Mℓ during the period 1964 to 1978 (Chutter, 1989).

The water quality deteriorated as the flow into the impoundment was augmented by sewage effluent. In 1932 the impoundment was described as "oligotrophic", in 1958 as an "oxidation pond", in 1961 as "very eutrophic" and finally in 1980 as "hypertrophic" (Robarts et al., 1982). From a water treatment point of view, the water quality temporarily improved during the excessive growth of the water hyacinth *Eichhornia crassipes* in 1976 to 77, when the algal growth was curtailed by the shade of the floating hyacinth mat, and the clarity of the water column

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*To whom all correspondence should be addressed.
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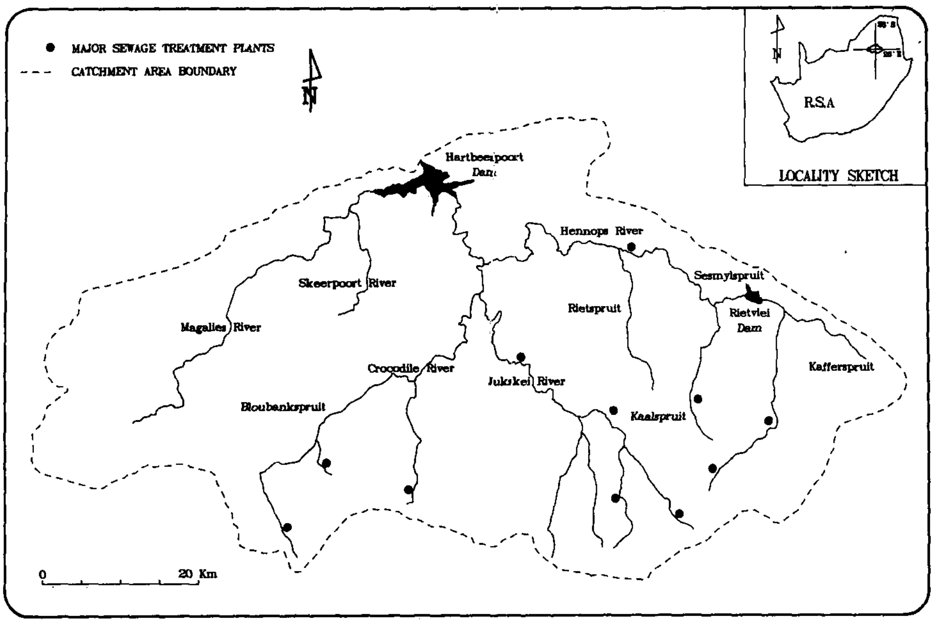

Figure 1
Hartbeespoort Dam catchment

improved due to the collection of suspended particles within the root zone of the hyacinth plants. After the spraying of the herbicide terbutryn and a flood the following year, the water hyacinth disappeared and algal growth rebounded (Scott et al., 1979). During the 1980 to 1988 period the annual average orthophosphate concentration peaked at 750 μg/ℓ as P in 1983/84 and the nitrogen concentration at 5 027 mg/ℓ as N in 1986/87. Although no satisfactory relation between phosphate concentrations and chlorophyll *a* levels was evident, the chlorophyll *a* levels also reached an annual average high of 94 μg/ℓ during 1982/83. The dominant species was *Microcystis aeruginosa,* which comprised more than 80% of the biomass at the height of the hypertrophy. During the 1980s, taste and odour problems were continuously encountered during treatment; this was most proabably due to *Microcystis.*

Hartbeespoort Dam is a monomictic impoundment, which means that it is stratified and mixed once per year, with stratification breaking down in late summer/early winter. Due to the high level of algal activity, the anaerobic hypolimnion extends up to 8 m from the surface during stratification. During the annual overturn, large concentrations of reduced compounds are released and distributed which result in almost total lake anoxia. During the overturn of 1981, for example, the surface oxygen concentration dropped from 170% saturation to 5,7% saturation. After a week the value rose to 15,9% and it took 3 months before supersaturation was re-established. During the overturn the water colour changed from green to black, indicating particulate sulphides (Robarts et al., 1982). Although depth profiling was done extensively during the limnological surveys, no water treatment tests were done (to the authors' knowledge) to determine the most suitable depth of abstraction for treatment purposes.

The overall water quality of Hartbeespoort Dam was recently assessed by using a 1982 German technical standard (Thornton, 1987). This integrative water classification method makes use of 59 determinands, which are each rated on a scale from 1 (unimpaired) to 5 (impaired). The 59 determinanads are grouped in three categories, i.e. **hydrography, trophic state and hygiene**. The individual ratings within each category are averaged to obtain a representative rating for each category. The category with the poorest rating was trophic state (4,0) followed by hydrography (2,7) and hygiene (2,3). The latter category covers those determinands reflecting mineral, heavy metal, toxicant and microbiological status. Except for hardness and pH, the standard of the water was considered to be "of good quality" for drinking water purposes. This classification is in line with a finding of another study (Chutter, 1989) that heavy metal concentrations were acceptable and that organohalogen potential was not increased by the impoundment. The treatment effort therefore should be directed primarily at the ***aesthetic*** improvement of the water; the ***safety*** of the water is otherwise unimpaired

Since 1987, after a decade of hypertrophy, the water quality improved dramatically. Algal biomass declined drastically, the dominant species switched from blue-green to green, the N:P ratio increased from 4:1 in 1984/85 to 25:1 in 1988/89, and water treatment became much easier. Although the phosphate standard introduced in 1985 may have had some effect, it is suspected that the filling of the dam, from 38% in 1985/86 to 100% in 1987/88, may have been the main reason for the improvement (Chutter, 1989). If this turns out to be true, the present improvement is temporary and the dam will probably soon return to its previous state of hypertrophy.

History of the treatment of Hartbeespoort Dam water

Schoemansville

The Schoemansville treatment plant (see Fig. 2 for its location) was commissioned in 1961 and consisted of a settling tank and slow sand filters, the latter operated at a rate of 0,13 m/h and with an effective sand size of 0,27 mm. No coagulants were used. This plant was doubled in 1964, and once more in 1971. Prechlorination was introduced, up to 20 mg/ℓ at times, to improve the settling of the algae. (This occurred long before the implications of trihalomethanes were known). Around 1980, the treated water quality was adequate, but growth in demand necessitated extensions. After a pioneering investigation into the feasibility of dissolved air flotation (NIWR, 1981), the plant capacity was increased by converting one settling tank into a flocculation tank, and the other two settling tanks into flotation tanks (Williams et al., 1985). Coagulant dosing was also introduced at that time. At first, it was thought that this alteration would comfortably allow an increased filtration rate of about 0,40 m/h through the slow sand filters because the turbidity after chemical dosing and flotation was **less** (consistently < 1,0 NTU) than what was previously achieved with settling alone. It turned out that the filter run lengths **decreased** drastically instead, from the previous 20 to 30 days to a totally impractical 2 to 3 days. A follow-up investigation (NIWR, 1984) revealed that the ferric hydroxide floc particles (10 to 15 µm in diameter) were carried over from flotation to block the surface of the fine filter sand. The slow sand filters were then abolished and replaced by high-rate pressure filtration. During the mid-1980s, it became necessary to add powdered activated carbon (PAC) for taste and odour control. This treatment arrangement continued until June 1991, when it was replaced with a new treatment plant. The new plant provides for activated carbon, pH correction, flotation, filtration and chlorination and will be discussed further on.

Kosmos

The treatment plant at Kosmos developed along roughly parallel lines as that at Schoemansville. During the early 1980s the treatment process also consisted of prechlorination, settling and slow sand filtration. The redesign of the Kosmos treatment plant in 1986 was, however, not necessitated by an increase in demand, but by the decreasing quality of the source, which deemed the treatment process inadequate. The final effluent, according to a typical set of analyses of that period, still had ammonia of 0,45 mg/ℓ, phenols of 29 µg/ℓ, turbidity of 2,7 NTU and chlorophyll *a* of 3,5 µg/ℓ. Unpleasant tastes and odours were continually characteristic of the water, and the sand beds were organically contaminated throughout their depth. At the same time the filter run length gradually declined to 7 to 10 d, which translated into a sand loss rate of 480 mm/a. This sand replacement cost alone, excluding labour, amounted to a unit cost of 7,1 c/m^3 of water treated at current prices. The redesigned plant was commissioned during January 1987, and provides for activated carbon, pH correction, flotation, filtration and chlorination and will be discussed later on.

Brits

The treatment plant at Brits, which is presently being upgraded and extended, was commissioned between 1972 and 1974. This treatment plant is located 15 km downstream of the dam wall, between the Crocodile River and an irrigation canal leading from the dam wall on the north-eastern bank of the river (Fig. 2). The water release point for both the river and the canal abstracts water about 20 m below the full supply level, which means that water is almost constantly withdrawn from the anaerobic hypolimnion. Although the treatment plant can also be supplied from the canal, the turbulence and residence time in the canal are insufficient for complete oxidation of the reduced compounds released from the dam. As a result, there is no other option but to convey the water along the river bed to the treatment plant to ensure adequate oxidation. This aspect poses an important design constraint which will be discussed later in the paper. The existing treatment plant provides for prechlorination, settling, rapid sand filtration and finally activated carbon columns. The new treatment plant will be commissioned during 1992.

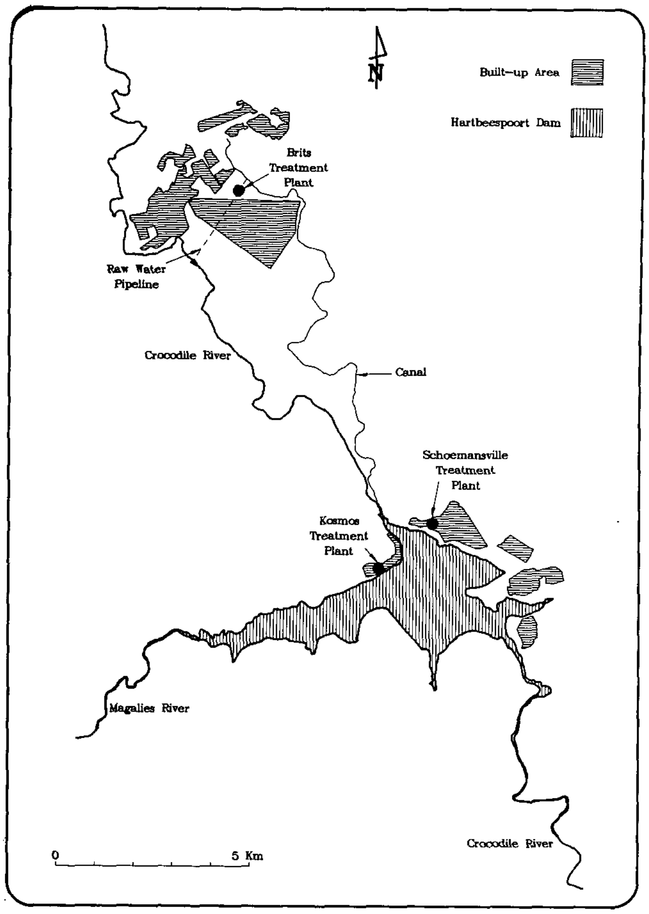

Figure 2
Location of treatment plants

Phase separation - water quality considerations

Traditionally, the treatment plant designer had little choice in selecting a phase separation process; **slow sand filtration** or **direct filtration** if the water had a low concentration of suspended material, with the option of using **settling** as pretreatment if substantial turbidity was expected. During the past 10 years, **dissolved air flotation** has become generally accepted as a viable treatment method for euthrophic waters. During the past 3 years, there has also been limited local experience with the **series filtration** process. The latter 2 processes are less known and design parameters are not as well established. Currently there are 2 projects underway, sponsored by the Water Research Commission, to evaluate both these processes. The following discussion is based on the authors' own experience.

Figure 3 is a generalised process selection diagram to indicate the regions of raw water quality where different processes or process combinations may be applicable. The classification is based on the raw water **turbidity** and the raw water **algal concentration.** The diagram boundaries are uncertain with our

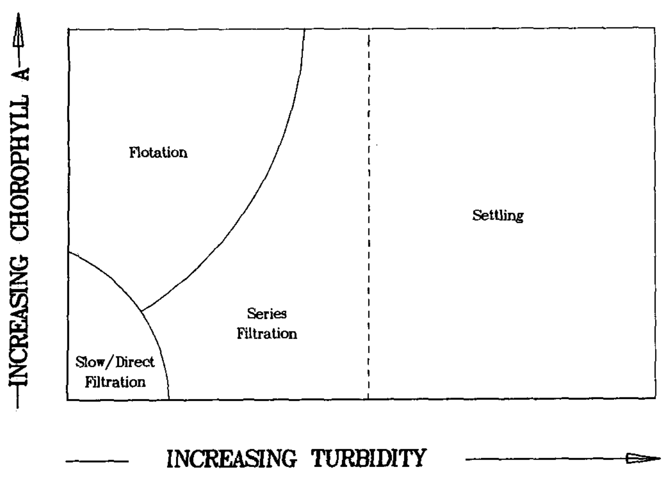

Figure 3
Process selection diagram

present state of knowledge, and areas will probably overlap to some extent once such a diagram is fully developed.

Direct filtration/slow sand filtration

This process is confined to water where the turbidity and algal concentration are both very low. There are not many raw water sources in South Africa that satisfy these requirements, and pretreatment methods such as part-stream clarification (Marx and Johannes, 1988) and horizontal roughing filtration (Williams, 1988) are sometimes used ahead of slow sand filtration. For slow sand filtration, the limits are set at about 10 NTU and less than 10 µg chlorophyll *a/ℓ* for filter cycles of 1 to 2 months (Cleasby, 1991). For direct filtration, the limits are in the same region.

Settling

Settling works well if the particles to be removed have a specific gravity (SG) substantially higher than 1,0. Inorganic silt particles (SG > 2,0), once flocculated, are therefore effectively removed; algae (SG~1,0) are normally not. If a mix of inorganic turbidity and algae is present, the resultant flocs will still have an adequate SG for settling. For this reason, settling can remove very high concentrations of algae, provided that enough inorganic turbidity is present.

Series filtration

This process consists of 2 sand filters in series with relatively coarse media in the first and relatively fine media in the second. The first filter operates in upflow mode and the second in downflow mode. The first filter has a dual purpose; it acts as a fixed bed flocculator **and** traps a substantial portion of the solids. The second filter then takes care of the rest of solids. The local application of this process is described elsewhere (Van der Merwe and Van Vuuren, 1990). This process has application in those cases where the turbidity is too high for direct filtration, but not higher than say 50 NTU. Limited local experience has shown that it works well up to this level, and that turbidities of up to 400 NTU were even tolerated for short periods, but then resulting in very short filter runs. This experience has been gained on water containing mainly inorganic turbidity, but a study recently initiated also systematically looks at the removal of algal turbidity.

Dissolved air flotation

Dissolved air flotation has proved to be a most effective process for waters with high algal concentration, but with low inorganic turbidity. The process does not work well if inorganic turbidity of say 100 NTU or higher is present, because the heavier, less cohesive float layer cannot be sustained at the top of the tank. Where high algal concentration is encountered during certain periods, and high inorganic turbidity during others, a combination of settling and dissolved air flotation has been used with great success (Botes and Van Vuuren, 1990). The threshold level at which inorganic turbidity starts to inhibit the flotation of eutrophic waters has not been fully established yet.

Phase separation - cost considerations

An attempt was made to quantify the costs of the different phase separation processes, and to express them in terms of the water tariff. The capital costs of 3 recently constructed treatment plants (currently under planning or construction) were analysed, with maximum treatment capacities ranging from 10 Mℓ/d to 90 Mℓ/d. The objective was to separate the cost effects of **individual processes** - overhead items such as offices, laboratory, chemical storage and dosage equipment, postchlorination, roads, site works, etc. were deliberately omitted. To these capital costs, the operating costs of electricity and raw water were added. The reader should bear in mind that the costs at any 2 treatment plants will obviously differ to some extent due to unique site conditions, and that these costs therefore cannot be blindly extrapolated to all other conditions. Generalised cost analyses, however, are useful for guiding the designer towards the optimal solution.

The generalised treatment costs are presented in Tables 1 and 2. In Table 1, the raw water and electricity costs were taken as the average for the 3 plants at Hartbeespoort Dam; smaller differences exist amongst the 3 plants. In general, these costs are characterised by relatively low raw water costs and high electricity costs. Many other treatment plants are subject to an opposite cost structure, namely high raw water costs (such as in the Vaal River system) and low electricity costs (for bulk consumers). For this reasons, the costs in Table 1 were recalculated for other raw water and electricity costs and are reflected in Table 2.

From an analysis of Tables 1 and 2, a number of points are evident:

- The influence of electricity and raw water costs is relatively small. Note that these costs only relate to the **phase separation** and do not include the bulk **raw water tariff.** The raw water tariff only enters this calculation to estimate the **losses** from the different phase separation processes.
- There is a significant variation between the treatment costs of different treatment plants. This is due to a difference in scale, design and hydraulic loadings.
- The unit cost increases significantly as phase separation processes are added. The cost is almost doubled if settling and flotation are added to filtration.
- The eutrophic state of the source adds the incremental cost of additional flotation to the conventional process of sedimentation and filtration. This cost is less than 3 c/kℓ, which is becoming insignificant compared to the projected costs of raw water in South Africa.

TABLE 1
UNIT COST (c/kℓ) FOR PHASE SEPARATION PROCESSES - CASE 1

Process combination	min$^+$	max$^+$	ave$^+$
Direct filtration	4,4	7,5	6,0
Settling and filtration	6,7	12,7	9,7
Flotation and filtration	6,6	11,9	9,3
Flotation/filtration (DAFF)	5,9	10,4	8,2
Settling and flotation and filtration	8,4	16,7	12,6

Assumptions

Interest rate	15%/a
Economic life civils	40 years
Economic life mechanical	15 years
Economic life pipework	25 years
Maintenance civils	1,5% of capital/a
Maintenance mechanical	5,0% of capital/a
Maintenance pipework	0,75% of cpital/a
Raw water tariff	2,5 c/kℓ
Coagulant unit cost	3,0 c/kℓ
Electricity tariff incl. kVA	20 c/kW·h
Electricity for flotation	6 000 kW·h/a
Electricity for filtration	300 kW·h/a
Losses for settling	1,0% of raw water
Losses for flotation*	0,5% of raw water
Losses for filtration	2,5% of raw water
Production per Mℓ/d capacity	200 Mℓ/a

$^+$min, max, ave refer to the plant costs which were analysed
*only if float layer is removed by flushing

TABLE 2
UNIT COST (c/kℓ) FOR PHASE SEPARATION PROCESSES - CASE 2

Process	min	max	ave
Direct filtration	4,8	7,9	6,4
Settling and filtration	7,3	13,3	10,3
Flotation and filtration	6,8	12,1	9,5
Flotation/filtration (DAFF)	6,2	10,6	8,4
Settling and flotation and filtration	8,8	17,1	13,0

Assumptions
Same as Table 1, with the exception of:

Raw water tariff	20 c/kℓ
Electricity tariff incl. kVA	10 c/kW·h

Taste and odour control - practical considerations

Taste and odour are most commonly removed with activated carbon. There are two practical alternatives in this case, namely the use of granular activated carbon (GAC) or powdered activated carbon (PAC). The main advantages of PAC over GAC are (Le Roux, 1989; Sontheimer et al., 1988):

- PAC does not require the substantial capital investment that GAC columns do.
- PAC reaches adsorption equilibrium more rapidly.
- PAC can be applied intermittently and at varying dosages in accordance with fluctuating treatment requirements.
- PAC has an important secondary advantage when the land disposal of the flotation float layer is contemplated. The PAC provides a gritty texture to the float which makes it less slimy and easier to handle. Moreover, the residual adsorption capacity of the PAC effectively removes odours emanating from the decaying float layer.
- PAC has a lower unit cost.
- PAC will adsorb a spike of say pesticides, and the adsorbed material will be removed with the PAC. In the case of GAC, the material will be gradually desorbed once the spike has passed.

GAC and PAC had been compared for three different classes of compounds (Huber et al., 1989). For **taste and odour,** PAC is by far the most commonly used. For **organohalogens,** GAC is more effective than PAC, especially at high influent levels of volatile chlorinated hydrocarbons. For **pesticides,** PAC is vastly superior to GAC.

Historically, all South African activated carbon requirements were imported. Some grades of PAC are now locally available, but most PAC and all GAC are still imported. The higher cost of GAC can be largely offset by regeneration when the GAC is exhausted. Unfortunately, local GAC regeneration facilities are not yet firmly established, which puts them at a considerable practical disadvantage.

The common dosage of PAC for taste and odour removal is 5 to 10 mg/ℓ (Sontheimer et al., 1988). This figure is borne out by a recent study on the removal of geosmin and 2-methylisoborneol (2 principal taste- and odour-producing compounds) which found that PAC can effectively remove them at levels between 5 and 10 mg/ℓ (Lalezary-Craig et al., 1988). At Schoemansville and Kosmos, PAC is dosed to a maximum of 10 mg/ℓ, which has resulted up to now in a total absence of consumer complaints. Complaints that are received, are usually traceable to periods of under-dosage or no dosage.

There are no definitive guidelines on the required PAC **contact time** for taste and odour removal. Overseas practice allows for long contact times of up to one hour, but such a long contact time requires an expensive contact tank. A second related issue is whether PAC should be contacted during flocculation; in other words, whether the adsorption by PAC is inhibited in the presence of flocs which may coat the PAC particles. According to a laboratory study (Le Roux and Van der Walt, 1991), the adsorption capacity of PAC is **not** impaired by ferric chloride flocs, but is adversely affected if cationic polymer is used as flocculant. In a recent review on PAC usage Najm et al. (1991) cite 2 contradictory reports on trichlorophenol adsorption; in the one case, adsorption was impaired in the presence of floc, in the other case not. If it does impair adsorption, the impact can only be nominal, because the practical experience at Schoemansville and Kosmos shows effective taste and odour removal at reasonably low PAC dosage, although the PAC contact is largely (Kosmos and the new Schoemansville plant) or totally (the old Schoemansville plant) in the presence of ferric hydroxide flocs.

The PAC **grade** is not critical for taste and odour removal. A leading standard for PAC (AWWA, 1991) specifies a minimum iodine number of 500; a specification which practically all products on the local market comply with. In addition, the **particle size** of the PAC also has no effect on the adsorption ability. Only if the PAC is to be removed by settling, does the particle size become important; a size larger than 75 µm is required for effective settling without coagulation (Le Roux, 1989a). In the case where PAC is removed after flocculation and/or by flotation, the cheapest PAC will probably suffice, regardless of grade or size.

The position of PAC dosing should theoretically be delayed until after phase separation. Most efficient is the counter-current use of PAC where fresh PAC is added after primary phase separation. After removal of this semi-spent PAC, it is recycled back to the inlet and removed with primary phase separation. Where the treatment process has 2 phase separation stages before filtration, this option should be incorporated. It will be shown further on that it is not economical to introduce a special phase separation process just for two-stage PAC usage. Previous full-scale experience by the authors also indicated that PAC introduced immediately ahead of rapid sand filtration led to consistent breakthrough of the PAC.

The reader should be reminded that the discussion in this paragraph is solely concerned about the removal of taste and odour by activated carbon. There are other problems which may also be addressed by activated carbon, such as organic precursors, the removal of previously formed THMs, cyanotoxins, et cetera. Totally different dosage levels and contact times, or even alternative oxidants may be required for these applications, and the economy of PAC versus GAC, which is discussed in the following paragraph, may be reversed.

Taste and odour control - cost considerations

A thorough cost comparison between GAC and PAC was made for the Brits treatment plant, for a maximum treatment capacity of 60 Mℓ/d. The unit cost of PAC treatment is shown in Fig. 4. The comparison was conducted for different dosage levels, as well as the number of months in the year during which PAC dosage is necessary. Table 3 presents the calculation of the unit cost for GAC.

The following is evident after an analysis of Fig. 4 and Table 3:

- The cost of GAC treatment is relatively constant, while the cost of PAC treatment varies almost in linear proportion with the period of dosage and dosage concentration.
- The cost of PAC treatment is significantly less than the cost of GAC treatment. Even a **continuous** dosage of PAC at the current maximum of 10 mg/ℓ, the cost of PAC is about a third of the cost of GAC.
- The cost of GAC is more than the total cost of flotation, settling and filtration.

Design assumptions for Kosmos, Brits and Schoemansville

Up to this point in the paper, some of the constraints posed by water quality, experience, practical considerations and costs were presented. The treatment plant designer has to balance these considerations and ultimately decide on the optimum process combination. In the case of the 3 treatment plants under discussion, a number of assumptions could be made on the basis of the information presented earlier:

- The water from the Hartbeespoort impoundment is safe for human consumption and does not require special treatment measures. Aesthetically the water is poor and has to be treated extensively to remove algae, taste and odour.
- The rapid improvement in quality during the past 2 years appears to be a temporary phenomenon. The quality could revert to the worst conditions experienced during previous years.
- Water abstraction should be limited to the upper layers (not deeper than say 5 m) to avoid the anaerobic hypolimnion; even then anoxic conditions may be encountered during lake

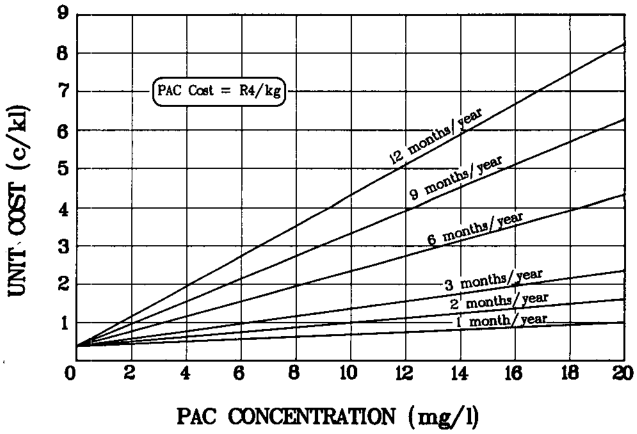

Figure 4
Cost of PAC dosage

TABLE 3
CALCULATION OF GAC UNIT COST

Assumptions
(based on a design capacity of 60 Mℓ/d)

Capital cost of columns (GAC excluded)	R/Mℓ·d	87 500
Economic life of columns	years	20
Interest rate	per annum	15 %
Annual cost of columns (over 20 years)	R/Mℓ·d	13 979
Maintenance (GAC excluded)	of capital	0,75 %
Annual maintenance cost	R/Mℓ·d	656
Required volume of GAC	m^3/Mℓ·d	10
Bulk density of GAC	kg/m^3	300
Unit cost of new GAC	R/kg	8
Capital cost of new GAC	R/Mℓ·d	24 000
Annual cost of GAC (over 20 years)	R/Mℓ·d	3 834
GAc life before exhaustion	months	24
Regeneration loss	per cycle	20 %
Regeneration unit cost	R/kg	2
Annual regeneration cost, incl. makeup	R/Mℓ·d	4 800
Head loss through columns	m	2
Electricity tariff incl. kVA	c/kℓ	20
Pump efficiency	-	70 %
Annual energy cost	R/Mℓ·d	311

Unit costs for GAC
(based on production of 200 Mℓ/a for every Mℓ/d treatment capacity)

	R/Mℓ·d	**c/kℓ**	**percentage**
Repayment of columns	13 979	6,99	59 %
Maintenance	656	0,33	3 %
Repayment of GAC	3 834	1,92	16 %
Regeneration of GAC	4 800	2,40	21 %
Energy cost	311	0,16	1 %
Total	23 581	11,79	100%

overturn. In the case of Kosmos and Schoemansville, this affects the design of the raw water intakes. In the case of Brits, where the raw water is abstracted from a fixed point at the bottom of the anaerobic hypolimnion, this leaves no option butto release the raw water into the natural watercourse for aeration and oxidation before it reaches the treatment plant.

- During times of high algal activity, the use of dissolvedair flotation iimperative for adequate phase separation. This adds 3 to 5 c/kℓ to the unit cost of water (1991 costs).
- During times of flood discharge into the impoundment, the raw water turbidity remains low, which means that settling is not required in the case of Kosmos and Schoemansville. In the case of Brits, where the raw water is routed through a stretch of the natural river after impoundment, turbidity pick-up is considerable and a settling step is inevitable. This adds between 3 to 4 c/kℓ to the unit cost of the water (1991 costs).
- Activated carbon has to be used for the control of taste and odour.
- PAC is considerably cheaper than GAC, and grades with iodine number larger than 500 are adequate for the removal of taste and odour. At a projected average dosage of 5 mg/ℓ over a full year (say 10 mg/ℓ for about 3 months and 3 mg/ℓ for the rest), the unit cost of PAC dosage is between 2 and 3 c/kℓ. GAC dosage, at about 12 c/kℓ, is about the same as the total cost for settling, flotation and filtration.
- PAC can be more effectively utilised if it is used counter-currently in two stages. In the case of Brits, where both settling and flotation steps are used anyway, this option is included. In the case of Schoemansville and Kosmos, where only flotation is used, the counter-current use of PAC would necessitate an extra settling step, which costs between 3 to 4 c/kℓ. The total cost of PAC is between 2 and 3 c/kℓ and counter-current usage would save only a fraction of this - extra settling just to enable PAC counter-current usage is not economically justified.
- PAC has a secondary benefit for Kosmos and Schoemansville, where there is no room for lagoons and the sludge has to be landfilled. The float layer is compacted by means of a grid on top of the flotation tank and the PAC improves the handling and curtails the odour from the solids that are scraped off. In the case of Brits, the float layer on the flotation tank is flushed away and the waste sludge is processed in the sewage treatment plant during low-flow periods.

TABLE 4
DESIGN PARAMETERS FOR BRITS, KOSMOS AND SCHOEMANSVILLE

		Brits	Kosmos	Schoemansville
Hydraulic loading (without flotation recycle)				
Design capacity	Mℓ/d	60,0	1,2	10,0
Sedimentation	m/h	5,2	n/a	n/a
Flotation	m/h	6,3	5,0	8,3
Filtration	m/h	5,2	4,7	4,3
Primary chemical dosing				
Coagulant	-	$FeCl_3$	$FeCl_3$	$FeCl_3$
Mixer	-	in-line	weir	in-line
Flocculator	-	channel	pipe	channel
Flocculation time	min	10	16	5
Velocity gradient	s^{-1}	60-40	72-20	70
Secondary chemical dosing				
Coagulant	-	$FeCl_3$/poly	n/a	n/a
Mixer	-	in-line	n/a	n/a
Flocculator	-	floc blanket	n/a	n/a
Primary PAC contact				
Feed mode	-	slurry	dry	slurry
Time alone	min	3,5	3,0	4,9
Time with coagulant	min	25	16	10
Separation time	min	40	18	11
Secondary PAC contact				
Time with coagulant	min	20	n/a	n/a
Separation time	min	14	n/a	n/a

Final design solutions

The process flow diagrams for the 3 plants under discussion are shown as Fig. 5 (Kosmos), Fig. 6 (Schoemansville) and Fig. 7 (Brits). The most important design parameters are compared in Table 4.

Discussion

There has been much recent press coverage on the alleged inadequacy of SA water quality standards, as well as alleged outdated treatment technologies. While the water treatment industry would jump at the opportunity to introduce additional, sophisticated treatment processes, it also has a responsibility to put public money to the best possible use. Moreover, it should base its decisions on a solid scientific foundation rather than on speculative fears. In accordance with current legislation and the data presented in this paper, the water from the Hartbeespoort impoundment at present does not warrant treatment beyond that indicated in the process diagrams. This leaves 3 important questions:

- Firstly, to what extend should provision be made for "inadequate" standards? The authors believe that the designer would overstep his authority by individually deciding which standards are inadequate, and by how much they fall short. If every designer could randomly set his own more (and less?) stringent standards, this would expose the consumer to uncontrolled costs (or risks).
- Secondly, to what extent should provision be made for a deteriorating water source? Where there is definite evidencethat a source will deteriorate within a foreseeable period, it is prudent to include, or design for the eventual inclusion of an extra treatment process. In the case of Hartbeespoort Dam, where the future of water quality is clouded with uncertainty, the authors believe it is best to assume the worst historical conditions.
- Thirdly, how can the individual consumer protect himself if he believes that current water quality guidelines are inadequate? These consumers do have the option of adding one or more point-of-use treatment devices to their home supply system, which are readily available on the local market. Such devices could incorporate additional activated carbon adsorption for organohalogen removal, ion exchange for softening, microfiltration, et cetera.

Not much practically useful information was found in the extensive limnological studies performed on the Hartbeespoort impoundment. Although it is realised that the main thrust of these studies was not towards water treatment, it would have been helpful to have had data on the best position for raw water

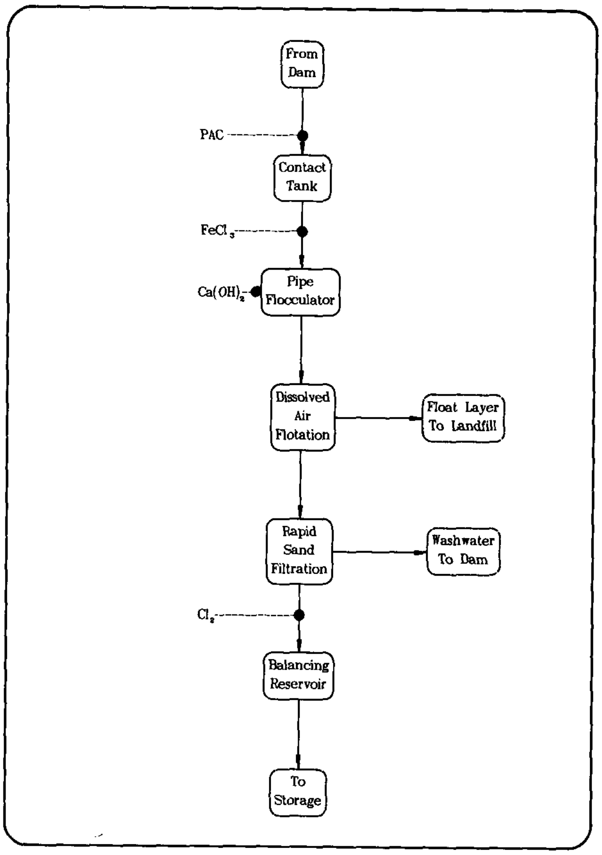

Figure 5
Process diagram for Kosmos Treatment Plant

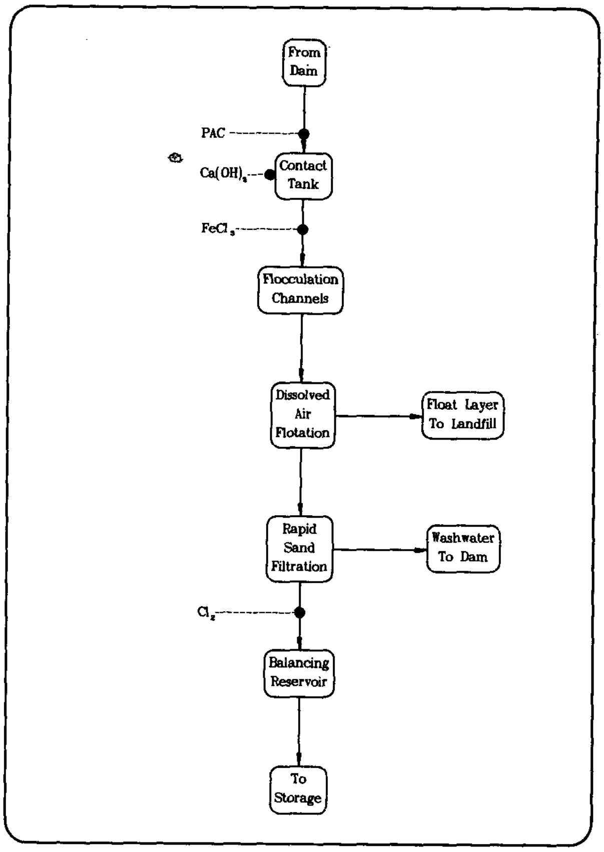

Figure 6
Process diagram for Schoemansville Treatment Plant

abstraction, the best abstraction depth during different seasons, the concentration and nature of suspended solids, et cetera. Future monitoring of the impoundment could include some of these parameters.

The dosage control of PAC for taste and odour removal poses a practical problem. PAC is an expensive chemical and should be dosed to the minimum. In the absence of taste panels, the best guidance can be obtained from consumer complaints. In the case of Schoemansville and Kosmos, practical experience has shown that consumer complaints on taste and odour are generally very reliable. If the dosage is adequate, almost no complaints are received, but after a day or two of underdosage a spate of calls is experienced. Care should be taken to record these complaints systematically and diligently and to convey them immediately to the treatment plant personnel.

The practical process design of a water treatment plant has to strike a balance between the best available knowledge and technology on the one hand, and the very important practical and cost constraints on the other. It was indicated that, while working from the same scientific basis, 3 substantially different designs were developed. The 2 underlying reasons appear relatively trivial; a poorly positioned withdrawal point and the most practical method of sludge disposal.

The importance of treatment cost is often overlooked when treatment options are considered in scientific publications. For example; the option of removing trihalomethane precursors by GAC adsorption is often mooted in discussions on the treatment of eutrophic waters. It was indicated that, while such an option may be desirable and technically straight forward, it will double

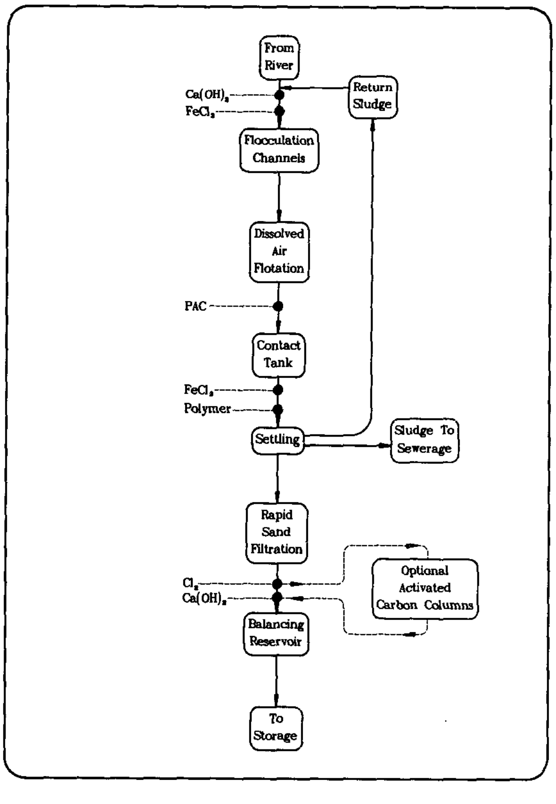

Figure 7
Process diagram for Brits Treatment Plant

the treatment cost of water, even when settling, flotation and filtration are used. Likewise, however elegant the counter-current use of PAC may be, it remains cheaper to design a new plant for the once-through use of PAC, unless a second phase separation process is already available as at Brits. Similarly, one may, at first glance, question the wisdom of conveying the raw water for Brits through the river, which necessitates an extra sedimentation step. When weighed against the cost of a new raw water pump station and pipeline, it is by far the most economical decision. New and novel process options should, wherever possible, be economically validated before they are blindly advocated.

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