EVALUATION OF DIRECT SERIES FILTRATION FOR THE TREATMENT OF SOUTH AFRICAN SURFACE WATERS

WRC Report

submitted to the Water Research Commission

by

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EXECUTIVE SUMMARY

The application of the direct series filtration process for the treatment of South-African surface waters therefore presents an economical option for the removal of algae, as a result of the low-cost and ease of constructing these filters. For low turbidity waters only coagulation and direct series filtration need to be used, while for high turbidity waters the filtration step can be preceded by flocculation and settling.

Apart from lower capital costs, direct series filtration also has the following benefits:

- easy and economical upgrading of existing treatment systems
- flexibility because of the use of modular sections
- high filtration rates can be achieved
- low coagulant dosages.

The aim of the project was to evaluate the process on pilot scale at a number of raw water sources throughout the country, representing the major types of surface waters in South Africa, to determine whether it presents a cost-efficient treatment option which could replace the more conventional technologies. If this was the case, then the further aim was to establish what further applied research is necessary to draw up design guidelines and further develop the process.

The pilot scale tests with a small direct series filtration unit were performed at a number of locations throughout the country so as to include the main categories of surface water qualities found in South Africa. These included tests at Hectorspruit, Mpumalanga (low turbidity water); Vaalkop Dam, North-West Province (high turbidity water); Roodeplaat Dam, Pretoria (eutrophic water); and Mossel Bay (coloured water). The tests were performed on each source with different coagulants (ferric chloride, aluminium sulphate and cationic polymer) and at different filtration rates (5 m/h; 10 m/h; and 20 m/h). The following results were obtained:

<u>Low turbidity water</u>

With turbidity of the raw water between 20 and 25 NTU, coagulant dosages of 15 mg/ℓ $FeCl_3$, or 1 mg/ℓ of a cationic polymer were used. With $FeCl_3$ as coagulant, final water quality in terms of turbidity was around 0,5 NTU. For filtration rates of 5, 10 and 20 m/h, the filter runs were 40, 17 and 7,5 h respectively. Runs were terminated when a pressure drop of 2 m was reached in the downflow filter.

When cationic polymer was used as coagulant, the filter running time was approximately four to five times longer than with the use of $FeCl_3$. The turbidity of the final water was however of a lower quality (1,2 to 1,5 NTU) compared to when $FeCl_3$ was used.

High turbidity water

Although the turbidity of the raw water varies considerably during the trial runs (20 to 120 NTU), the final product water had a turbidity of less than 1 NTU for all coagulants tested. This was achieved by using the various coagulants at their optimum coagulant dosages, namely $FeCl_3$ at 7,5 mg/ℓ, alum at 40 mg/ℓ and a combination of $FeCl_3$ and polymer at dosages of 8,0 mg/ℓ and 0,5 mg/ℓ respectively. The running times of the pilot filters were also of similar length, regardless of coagulant type. The 5 m/h run continues for approximately 21 to 25 h, the 10 m/h run for 7,0 to 8,5 h, and the 20 m/h run for only 1,5 to 2,7 h, to achieve the maximum pressure drop of 2 m in the downflow filter.

Eutrophic water

$FeCl_3$ and alum proved to be effective coagulants for removal of turbidity associated with algae. The final turbidity of the filtered water stayed below 1 NTU. The run times for $FeCl_3$ and alum were 18 to 20 h at 5 m/h, 8 to 10 h at 10 m/h, and 3 to 3,5 hours for 20 m/h. With polymer as coagulant, the final water had turbidities between 1 and 5 NTU. The improvement in run time was however significant at a rate of 5 m/h where a run time of 32 h was achieved. At filter rates of 10 and 20 m/h, the run times were comparable to the run times achieved with alum and $FeCl_3$.

In general, the use of $FeCl_3$ proved to be more effective for algae removal. The combination of polymer and alum was more effective than polymer or alum on their own for removal of algae. The pilot plant filter was not very effective for algae removal, with final product water chlorophyll *a* values of 1 - 4 μg/ℓ using the above mentioned coagulants (raw water chlorophyll *a* values between 2 and 80 μg/ℓ). Chlorophyll *a* values of less than 1 μg/ℓ were however frequently achieved.

Coloured water

Tests were performed on raw water which had apparent colour values of 520 mg/ℓ as Pt and true colour of 400 mg/ℓ as Pt. Lime was added to the raw water for pH adjustment whereafter alum was dosed at 100 mg/ℓ. The optimum pH range for flocculation was between pH 4,7 and pH 5,2. Run times of the filter at 5, 10 and 20 m/h filtration rates were 21, 11 and 3,5 h respectively. Removal efficiencies at the different filtration rates were comparable, with apparent colour values of around 50 mg/ℓ as Pt and true colour values of 5 mg/ℓ achieved in the final water.

The following conclusions can be drawn based on the pilot scale evaluation of the direct series filtration process on South African surface waters:

- The process is effective for the treatment of low turbidity waters, and can produce product water turbidities of 0,5 NTU on a consistent basis using a metal coagulant such as $FeCl_3$. At normal rapid sand filtration rates of 5 m/h, the run time of the series filtration process can be up to 40 hours or more. Even at a high filtration rate of 20 m/h, filter run times of almost 8 hours can be achieved.

- Cationic polymers can produce even longer filter runs when treating low turbidity water, but cannot achieve the same low turbidity levels of the filtered water as when metal coagulants are used.

- Effective coagulation of the raw water is required to ensure high quality final water after the upflow and downflow filtration process.

- The process can also effectively treat high turbidity water to produce a filtered water with turbidities of down to 1 NTU, but as expected will have much shorter filter run times. This does not present significant problems when treating highly turbid waters at low filtration rates (typically 5 m/h), but will be a limiting factor when attempting to treat these waters at a high filtration rate on full-scale.

- The process also produces low final water turbidities (1 NTU and less) when treating eutrophic waters, but is not very effective for removal of algal cells, as measured by the chlorophyll *a* content of the water.

- It is also not effective for the treatment of highly coloured waters, mainly as a result of the fragile nature of the flocs that are formed when the natural organic matter (mainly humic substances) in the water is coagulated. The strength of the floc seemed to be improved somewhat with the dosing of a cationic polymer, but can still not prevent floc breakthrough after relatively short filter run times. The effect of secondary flocculation in the downflow filter and shear forces in the upflow filter also appear to be more significant when treating these coloured waters, as evidenced by the more erratic results of the test runs.

The practical experience gained through implementation of the process at full-scale at the four locations in South Africa (cf. Section 2.2) indicates that:

- the system consistently provides water of acceptable quality and quantity for small, developing communities

- by exploiting modular design and the use of prefabricated concrete pipe sections, capital cost savings of 20% to 50% are attained compared to conventional treatment

- indirect evidence suggests that coagulant savings of 20% could be realised for series filtration

- with appropriate safety factors and degree of automation, the system can be successfully operated with limited operator skill, provided that competent technical back-up and guidance are provided at least monthly.

Two criteria are important for establishing the water quality limits within which series filtration can be applied. The first is whether the final water quality meets the required standard, and the second is whether the system can be operated at sufficiently long filtration cycles before terminal headloss or turbidity breakthrough is reached.

For all the cases investigated, both at pilot and at full-scale, final water turbidity below 1,0 NTU could be attained except when a cationic polymer was used as only coagulant. The performance in terms of colour removal is much more erratic, as pointed out above. In some cases, colour can be reduced from 500 mg/ℓ as Pt to 5 mg/ℓ as Pt; in others, colour of 500 mg/ℓ as Pt could not even be reduced to 50 mg/ℓ as Pt. For colour removal, the system therefore needs to be tested first.

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The most important limiting factor is the filter run time, which is limited by the clogging head available for the downflow filter. (If the upflow filter clogs beyond what it is designed for, it simply expands in order to maintain the required flow rate). With low raw water turbidity, low coagulant dosage and low filtration rate, the filter run times pose no problem, as expected. If any of these parameters increase, the filter run time will decrease. The worst practically encountered case was when filter run times were down to about 6 hours when the raw water turbidity was 400 NTU for a prolonged period at a filtration rate of 4,5 m/h. With raw water turbidity at an average of 100 NTU, run times of 12 hours or more could be maintained.

Chapter 2 gives an overview of the development of direct series filtration in South Africa, And in Chapter 5 some design aspects for series filtration systems are considered. Recommendations for further studies include the following:

- Investigate whether, and to what extent, filter production (of filter run times) can be increased by replacement of the single medium in the downflow filter with dual media (sand plus anthracite).

- To date the ratio between the number of upflow filters and the number of downflow filters has been taken as 2:1, *i.e.* the loadings on the downflow filters were double that on the upflow filters. In the case of Burgersfort an equal number of upflow and downflow filters have been provided, and it appears that filter production has been improved by this. This will naturally reduce the capital cost of a plant, and should therefore be further investigated.

NOMENCLATURE

In the report, a number of abbreviations, concepts and shortened forms for products or equipment are used in the text, tables and graphs. For easy reference, these abbreviations and shortened forms with their explanations are given below.

direct filtration	a filtration system which is not preceded by a separate flocculation or sedimentation stage
series filtration	a two-stage filtration system consisting of either an upflow or downflow filter as contact clarifier in the first stage, followed by a rapid gravity downflow filter as the second stage
polymer	a polyelectrolyte used either as primary coagulant or as flocculant (coagulant aid)
RUN V10.3 (for example)	identification of test run. The first alphanumeral indicated where the tests were performed, *viz.* HF = Hectorspruit full-scale plant H = Hectorspruit pilot plant V = Vaalkop Dam R = Roodeplaat Dam M = Mossel Bay's Sandhoogte Water Treatment Works The second alphanumeral denotes the filtration rate, *i.e.* either 5 m/h, 10 m/h or 20 m/h. The last alphanumeral after the decimal denotes the number of the test run.
5 m/h up (for example)	filtration rate of 5 m/h in the upflow filter
5 m/h down (for example)	filtration rate of 5 m/h in the downflow rapid gravity filter
mg/ℓ $FeC\ell_3$	dosage of ferric-chloride as the solution
LT 22	a cationic, high molecular weight polyelectrolyte

eutrophic water	algae laden water with chlorophyll *a* concentration of more than 25 $\mu g/\ell$
coloured water	surface water containing aquatic humus which gives rise to a yellow-brown colour found in the water
mg/ℓ alum	dosage of aluminium sulphate as $A\ell_2(SO_4)_3.18H_2O$
Ultrafloc	a cationic polyelectrolyte

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Apart from lower capital costs, direct series filtration also has the following benefits:

- easy and economical upgrading of existing treatment systems
- flexibility because of the use of modular sections
- high filtration rates can be achieved
- low coagulant dosages.

On a national level the successful utilisation of direct series filtration systems for the treatment of surface waters will have the following advantages:

- more appropriate technology for the removal of algae
- elimination of potential problems with the formation of by-products as well as certain tastes and odours
- applicable even in developing areas
- cheaper alternative to dissolved air flotation in the flocculation/settling/flotation/filtration process configuration.

1.2 OBJECTIVES

The objective of this project was to evaluate the direct series filtration process for the treatment of South-African surface waters, in order to

- provide an appropriate water treatment technology for small municipalities and water suppliers at considerably lower cost than conventional technologies
- provide an economical treatment option for eutrophied waters to upgrade existing conventional purification works
- replace dissolved air flotation in the flocculation/ settling/ flotation/ filtration process configuration.

CHAPTER 1

INTRODUCTION AND OBJECTIVES OF THE STUDY

1.1 INTRODUCTION

The quality of South-African surface waters is gradually deteriorating as a result of the population growth and increase in industrial activities in the country. It is evident that the technologies which are used for purifying these waters for human consumption will have to be improved in order to utilise the deteriorated sources to its full capacity. In addition the population explosion has placed increasing pressure on the authorities to supply safe and acceptable (wholesome) water to as large a part of the population as possible. Attention is therefore given to using more appropriate and affordable water treatment technologies.

A recent development in this area has been the evaluation of a two-stage treatment system, consisting of coagulation and direct filtration, at the Iowa University in the USA. The system comprises two filters in series (downflow-downflow) which replace the flocculation, sedimentation (or flotation) and filtration units. The system has already been applied successfully in America for the removal of turbidity, colour, algae, as well as organisms (Reid and Loewenthal, 1989).

In South Africa the Local Government Affairs Council has commissioned two test units on a semi-experimental basis, with a third that was completed in August 1990. Preliminary results indicated that good turbidity removal can be achieved, and that the capital cost of such a plant would only amount to about 50% of that of a conventional treatment plant. The direct series filtration system also occupies smaller land space and uses less chemicals than a conventional plant.

Both the systems mentioned above have, up to that time, only been evaluated for the removal of turbidity, and no evaluation of the process for the treatment of eutrophied or coloured water has been carried out. Design parameters for the treatment of local surface waters have not been determined.

The more specific aim was to evaluate the process on pilot scale at a number of raw water sources throughout the country, representing the major types of surface waters in South Africa, to determine whether it presents a cost-efficient treatment option which could replace the more conventional technologies. If this was the case, then the further aim was to establish what further applied research is necessary to draw up design guidelines and further develop the process.

CHAPTER 2

LITERATURE REVIEW ON DIRECT FILTRATION, AND OVERVIEW OF THE DEVELOPMENT OF DIRECT SERIES FILTRATION IN SOUTH AFRICA

2.1 DIRECT FILTRATION SYSTEMS

Direct filtration has been defined by the American Water Works Association as being a water treatment system in which filtration is not preceded by separate sedimentation of flocculated water (Logsdon, 1978). There are a variety of systems under this category (Odira, 1985):-

- <u>direct filtration using:</u>
  alum or ferric chloride / rapid mix / filter aid (non-ionic polymer or activated silica) / rapid filtration;

- <u>direct filtration using:</u>
  cationic polymer / rapid mix / flocculation / rapid filtration;

- <u>direct filtration using:</u>
  flocculant / rapid mix / contact basin (without sludge collector) / rapid filtration; or

- <u>direct filtration using:</u>
  metal salt / rapid mix / rapid filtration.

Series filtration requires two filtration stages, one after the other. The final stage is always a conventional downflow rapid gravity filter. The first stage could be either an upflow filter in which case the combination is also called the upflow - downflow system (Schulz & Okun, 1984), or a downflow filter in which case the combination is called the dual - stage filtration system (Brigano *et al*, 1994).

In all the reported cases, the first filter is functionally characterized as a *contact clarifier*, where flocculation takes place and a part of the sediment load is captured. Upflow filters in direct filtration offer the desirable coarse-to-fine grading feature, hence the higher capacity of suspended solids retention (Odira, 1985).

2.1.1 Rapid filtration mechanisms

The principle mechanisms are transport, attachment and detachment (Baumann, 1979). The role of transport mechanisms has been defined as the provision of forces that will cause the particles to leave their carrying streamlines and to approach the media grain surfaces where attachment forces can be effective (Ives, 1980).

The transport mechanisms in rapid filtration are (Ives, 1980):

- interception
- diffusion
- inertia
- sedimentation
- hydrodynamic action

Although interstitial straining is not a transport mechanism as such, it remains a physical removal factor (Odira, 1985). It relates to the entrapment of particles in the junctions of bed grains and in small pore openings. High suspension concentrations may influence this removal mechanism as pore sizes are reduced and continuously changing during filtration (Odira, 1985).

The attachment mechanism is a physical-chemical process involving the attachment of particles to the filter grains and to other particles. The filter grain can be viewed as including material that has been removed from the suspension and is attached to the filter grains (Odira, 1985). The added chemical determines the dominant attachment mechanism. It can be classified according to two models namely the classic *double-layer model* which is based on an interaction between the electrostatic repulsive forces and the van der Waal's forces; and the *bridging model* (Adin & Rebhun, 1975).

Detachment occurs when the hydrodynamic shear forces are greater than the attachment forces (Adin & Rebhun, 1975). As a filter gets clogged it is obvious that increased velocities and smaller pore sizes will cause greater shear stresses (Ives, 1980). Detachment is a necessary action in the backwashing process when flow velocities are several times higher than filtration velocities.

2.1.2 Raw water quality for direct filtration

The potential for direct filtration is mainly determined by the raw water quality and variability. Some of the parameters that affect adequate treatment are turbidity and colour, the nature of turbidity particles, algal types and counts, water temperature, and pH (Culp, 1977 and McCormick *et al*, 1980).

Limiting raw water conditions as reported in the literature are as follows:

Table 2.1: Reporting limiting conditions of raw water for direct filtration

Author	Turbidity (Turbidity units)	Colour (Colour units)	Algae
Culp (1977)	25 average and 200 maximum	100	500-100 asu/mℓ
Baumann (1982)	50 - 60		
*Schulz & Okun (1984)	normally <50 and 160 maximum		
McCormick & King (1980)	0 - 10	0 - 15 (APHA units)	0 - 1000 units/mℓ (clump count)
**Odira (1985)	65		

* The only authors referring to upflow - downflow series filtration
** Single stage upflow filtration

The objection to high colour contents in raw water is usually the high solids-producing metal coagulant requirement (Odira, 1985). Colour removal is generally accomplished with alum or iron coagulation. Colour is often formed in low turbidity waters draining from forested catchment areas containing humic and fulvic acids (Logsdon, 1978).

Wagner and Hudson (1982) state that direct filtration will be feasible if the required metal salt coagulant does not exceed 15 mg/ℓ. Culp (1977) reports : "The limitation of direct filtration is the ability to handle high concentrations of suspended solids. At some point, the suspended solids will be too high for reasonable filter runs, and settling before filtration will be necessary."

Algal blooms most probably produce the greatest clogging potential for direct filtration (Hutchinson, 1976 and McCormick & King, 1980). The same authors also reported that a larger effective size in multi-media filters improved filtration of algae laden water. Foess and Borchardt (1969) reported that removal of algae could be improved by lowering the pH or coating the media with positively charged materials. They suspected that the relatively high concentrations of protein and cellulose in algae cells may control the surface properties of algae.

2.1.3 Coagulants in direct filtration

Alum flocs tend to be weaker than the flocs formed by polymers. The stronger polymer flocs result in longer filter runs but have a higher associated head loss (Adin & Rebhun, 1975). These researchers found that the polymer's rapid head loss development does not make it feasible for beds of conventional grain size.

Stamp & Novak (1979) state that molecular weight and charge are the most important characteristics of a polymer - the low molecular weight polymers have poor turbidity removal and large molecular weight polymers cause excessive head loss.

A typical range of 0,05 - 0,5 mg/ℓ for anionic and non-ionic polymers as filter aids, and a range of 0,1 - 5,0 mg/ℓ for cationic polymers as primary coagulants is suggested by Culp (1977).

According to Odira (1985), polymers are widely employed in direct filtration practice both to prevent early turbidity breakthrough and to reduce suspended solids loads. Stump and Novak (1979) reported that cationic polymers "consistently achieve superior turbidity removal", when compared to non-ionic or anionic polymers. Kawamura (1985) also discourages the use of anionic polymers as filter aids. Odira 91985) further states that "conventional metal salt coagulants, usually alum, in addition to a cationic or non-ionic polymer, are used at most full-scale direct filtration plants described in the literature."

Odira (1985) also reported that upflow direct filtration needs less than half the amount of coagulant as compared to a conventional system under similar conditions.

2.1.4 Media in direct filtration

Media for direct filtration is extensively described in the literature but unfortunately mostly for downflow rapid gravity systems and thus not quite applicable to the *contact clarifier* in the upflow-downflow system.

One of Odira's (1985) upflow pilot filters had the following media gradings and layer depths :

10 - 5 mm	: 300 mm deep (bottom layer)
2 - 3 mm	: 300 mm deep
1 - 2 mm	: 300 mm deep
0,8 - 1,2 mm	: 600 mm deep (top layer)

According to Schulz & Okun (1985) the total media depth of the upflow filter should be between 1,5 m and 3 m and "the medium of the upflow unit may range from coarse sand having an effective size of 0,7 mm to 2,0 mm up to graded gravel ranging in size from about 10 mm to 60 mm".

Design parameters for the downflow component of the system are analogous to those used for rapid gravity filters i.e. single-, double- or multi media.

2.1.5 Filtration rates

Baumann (1979) recommended that a filtration rate of 14,7 m/h (6 gpm/sq. ft.) should not be exceeded. Recently, however, higher rates have been applied in direct filtration on low turbidity raw waters. The range of filtration rates used in Odira's (1985) studies were 4 - 12 m/h. Schulz & Okun (1985) reported filtration rates of 12 - 16 m/h for coarse sand and 4 - 8 m/h for gravel beds.

2.1.6 Backwashing

Odira (1985) used several techniques in his backwashing investigation of upflow filters:

- bed expansion with water alone;
- washing with water and air

He further mentions that savings in backwash water consumption could be affected by filterbed drainage before commencing backwashing. (The S.A. experience learned that backwashing could not commence until the filterbed has been drained - excessive sand losses with the start of the water cycle occurred without prior drainage of the filterbed.)

Odira (1985) also reported a water backwash rate of 50 m/h and a backwash water consumption in the range of 4 - 12% of the total filter production per run. Odira (1985) states, however, that the hydraulics of backwashing has not been studied in his investigation.

2.2 DEVELOPMENT OF DIRECT SERIES FILTRATION IN SOUTH AFRICA

The Local Government Affairs Council has jurisdiction over some 50 Local Areas Committees in the old Transvaal province. These are smaller communities which have not yet achieved autonomous local authority status, and which are mostly remote communities. The provision of infrastructure for such communities with limited funds is a continuous challenge. Water supply to these communities has in the past being, and will continue to be, a high priority.

The establishment of direct series filtration plants for drinking water purification was solely the result of economic needs. Small treatment plants in these areas are invariably attended to by unskilled operators, and operations are controlled and supervised by trained and experienced personnel that visit these plants on a monthly basis (only). For the day to day operation, therefore, important process requirements are:

- simplicity
- reliability
- robustness
- a modular design approach.

Thusfar (with the exception of Burgersfort) the filter structures consist of prefabricated concrete pipe sections (1750 mm ID) of different heights (250, 500 and 1000 mm). The fabrications conform to SABS specifications and the jointing material can either be an epoxy resin or cement mortar to ensure water tightness.

The primary clarification stage entails a proportioned coagulated water inflow at the bottom of a battery of upflow filters (or contact clarifiers) operating in parallel. The filter medium ranges from graded gravel (6 - 12 mm) to coarse sand (0,9 - 1,5 mm) with a total depth of 2,5 m. A filtration rate of 4 to 7 m/h is applied. The choice of media was based on pilot filter studies with raw water turbidities ranging from 30 to 150 NTU.

A common header connects the overflows of the upflow filters with the inlet of the downflow filters of which the design is analogous to those used for rapid gravity filters. The operating mode is typically declining-rate filtration.

Backwashing of the upflow filter is done with raw water in six steps. The first step consists of scouring with air at a rate of about 25 $m.h^{-1}$ for approximately 1 minute. The second step, an innovation developed in South Africa, is a *rapid* draining step. By providing adequately sized scour valves at the bottom of the upflow filters, and by rapidly opening them, the downward surge of water will slough off a significant fraction of the deposits in the media. In the third step, the water level in the filter is restored to the overflow weir. The fourth step is again an air scour step as before while the fifth step consists of backwashing with water at a rate of 70 $m.h^{-1}$ for about 5 minutes or until the water is clear. During the sixth and final step, upflow filtration is resumed, but at least one bed volume is filtered to waste to displace the uncoagulated washwater in the bed. (The last step is only required when the upflow filter is washed with raw water. If washed with final water, it could be omitted.)

The downflow filters are backwashed conventionally with air at a rate of 25 $m.h^{-1}$ for about 3 minutes first, followed by backwash with final water at a rate of 28 $m.h^{-1}$ for 5 minutes.

Filter runs can vary between 12 and 50 hours depending on a combination of the following factors:

- raw water turbidity
- flocculant used and dosage rate
- filtration rate.

Table 2.2 lists full-scale direct-series filtration plants that have been built and are being operated in South Africa. Table 2.3 gives the typical media specifications for these plants.

The series filtration system requires substantial valve operation during a backwash cycle, and the correct manual operation asks for a level of skill and experience which is often not available in small, developing communities. Considerable effort has therefore gone into the development of a simple, robust electro-pneumatic sequencing and control system which will complete the entire backwashing operation once initiated by the operator.

Table 2.2: Full-scale application of series filtration in South Africa

Location	Source	Year of start-up	Upflow (m/h)	Downflow (m/h)	Capacity (Mℓ/d)
Magaliesburg	Blaauwbank River	1985	5	10	0,5
Marloth Park	Crocodile River	1987	5	7	0,8
Hectorspruit*	Crocodile River	1990	7	14	1,5
Burgersfort*	Spekboom River	1994	7	7	2,0

* Plant designed with backwash water recovery system

Table 2.3: Typical media specification for series filtration in South Africa

	Media depth (m)	Media size (mm)	Theoretical minimum fluidization velocity (mm/s)
UPFLOW FILTER			
Layer 1 (bottom)	0,15	6 - 12	± 84*
Layer 2	0,15	4,0 - 6,0	± 56*
Layer 3	1,50	3,0 - 4,5	± 46*
Layer 4	0,25	1,5 - 3,0	± 33*
Layer 5 (top)	0,25	1,0 - 1,5	± 15
DOWNFLOW FILTER			
Layer 1	1,20	0,5 - 1,0	± 8

* Fluidization cannot be achieved.

Table 2.4 Typical water losses due to backwashing, measured at Hectorspruit during October 1990 and March 1991

	Without recovery		With recovery	
	Upflow	Downflow	Upflow	Downflow
$FeCl_3$ coagulation	2,5%	1,5%	0,95%	0,5%
Polymer coagulation	1,1%	0,7%	0,4%	0,3%

The application of direct filtration technology in South Africa is restricted since surface water turbidities can exceed 80 NTU, which, according to several investigators, is the upper limit of raw water turbidity for this process.

Factors which can be considered as advantageous to the process are:

- cost-effectiveness - the capital cost can be up to 50% less than that for a conventional plant where provision has to be made for separate flocculation and settling facilities;
- considerable reduction in the amount of flocculant required; and
- extensions are modular and can also be incorporated in the augmentation of small conventional plants.

Semi-automatic backwash systems are installed to ensure predetermined and regular time intervals for the different stages of a backwash cycle. It is of assistance to unskilled operators but of more importance is the presentation of possible filterbed deterioration as a result of improper backwash procedures.

CHAPTER 3

PRELIMINARY TESTS

Before pilot scale tests commenced under this project, preliminary tests were carried out at the full-scale direct series filtration plant at Hectorspruit in the Eastern Transvaal. This 1 Mℓ/d plant was built by the Local Government Affairs Council as a semi-experimental unit to allow optimisation of the process, as no specific design criteria were available. A similar plant (with design flow of 0,8 Mℓ/d) was constructed by the Council at Marlothpark, some distance downstream of Hectorspruit on the banks of the Crocodile River.

3.1 CROCODILE RIVER WATER QUALITY

The turbidity of the water in the Crocodile River in the Hectorspruit-area normally ranges from about 5 to 30 NTU. However, a maximum of around 400 NTU was measured in the river in 1988 near Marlothpark.

Typical values of other determinants in the river water are given in table 3.1.

3.2 DESCRIPTION OF HECTORSPRUIT FULL-SCALE PLANT

The Hectorspruit Water Treatment Plant is a direct-series filtration plant situated adjacent to the town of Hectorspruit in the Eastern Transvaal. Water is withdrawn from the Crocodile River. The capacity of the plant is 1 Mℓ/d and it supplies Hectorspruit with potable water.

Water is pumped from a weir in the river to a holding dam next to the treatment plant (no turbidity reduction takes place in the holding dam). Coagulant ($FeCl_3$ or cationic polymer LT 22) is dosed to the raw water on it's entering the plant. Rapid mixing was originally obtained with an hydraulic jump, but this was later replaced by an in-line static mixer (due to air entrainment and subsequent release in the filters when using the hydraulic jump). The

Table 3.1: Typical analysis of Crocodile River water quality in the Hectorspruit-area.

DETERMINANT	TYPICAL VALUE
Turbidity (NTU)	5 - 30
Colour (Hazen)	26 - 60
pH	7,9
Electrical conductivity (mS/m)	15,4
Total Dissolved Solids (mg/ℓ)	99
Total Alkalinity (mg/ℓ as $CaCO_3$)	60
Total Hardness (mg/ℓ as $CaCO_3$)	63
Calcium (mg/ℓ as $CaCO_3$)	25
Magnesium (mg/ℓ as $CaCO_3$)	38
Chlorides (mg/ℓ as Cℓ)	10

in parallel and thereafter through two downflow rapid gravity filters. In this way filtration rates in vsb3T

3.3 FULL-SCALE TESTS

The results of three experimental filter runs that were done on the full-scale treatment plant at Hectorspruit is shown graphically in Figures 3.1 to 3.6. The filter runs are summarized in the table below.

Table 3.2: Hectorspruit full-scale plant tests

FILTER RUN ID	FILTRATION RATE (m/h)	CHEMICAL	DOSAGE (mg/ℓ)
HF5.1	Up 5; down 5	$FeCl_3$	10
HF18.1	Up 18; down 9	$FeCl_3$	14
HF18.2	Up 18; down 9	Poly	1,1

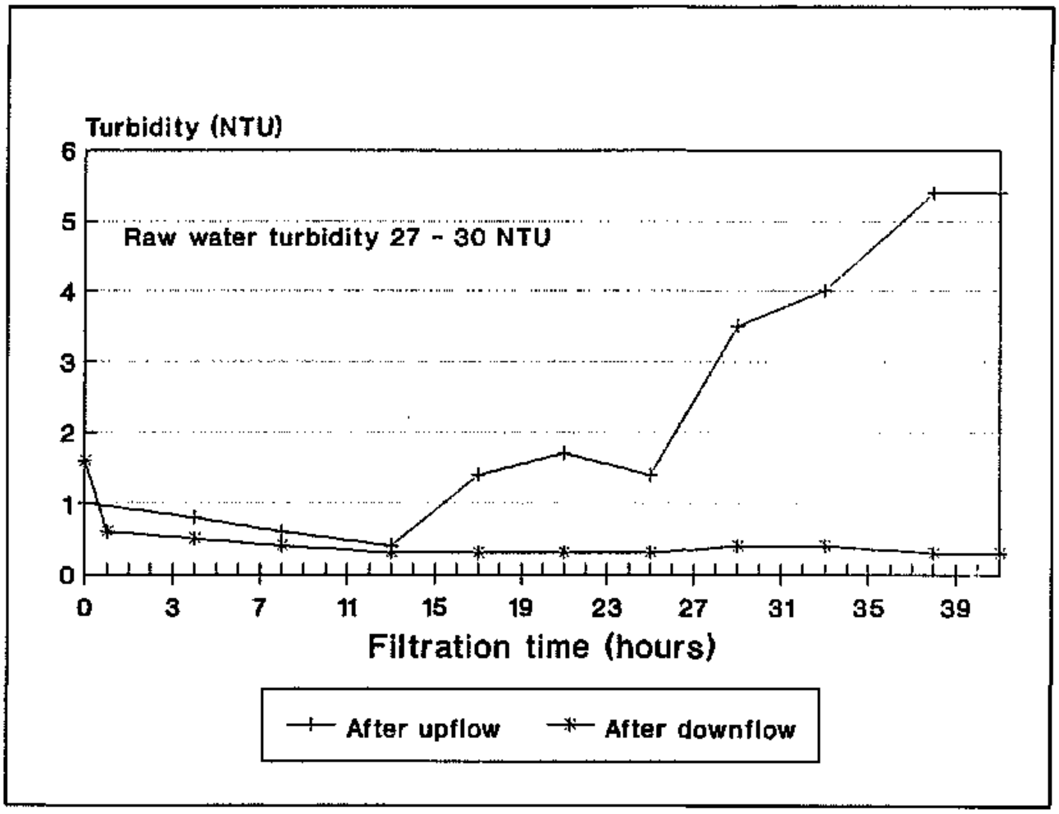


Figure 3.1 Turbidity removal at Hectorspruit plant for RUN HF 5.1: Filtration rate 5 m/h up; 5 m/h down and 10 mg/ℓ $FeCl_3$

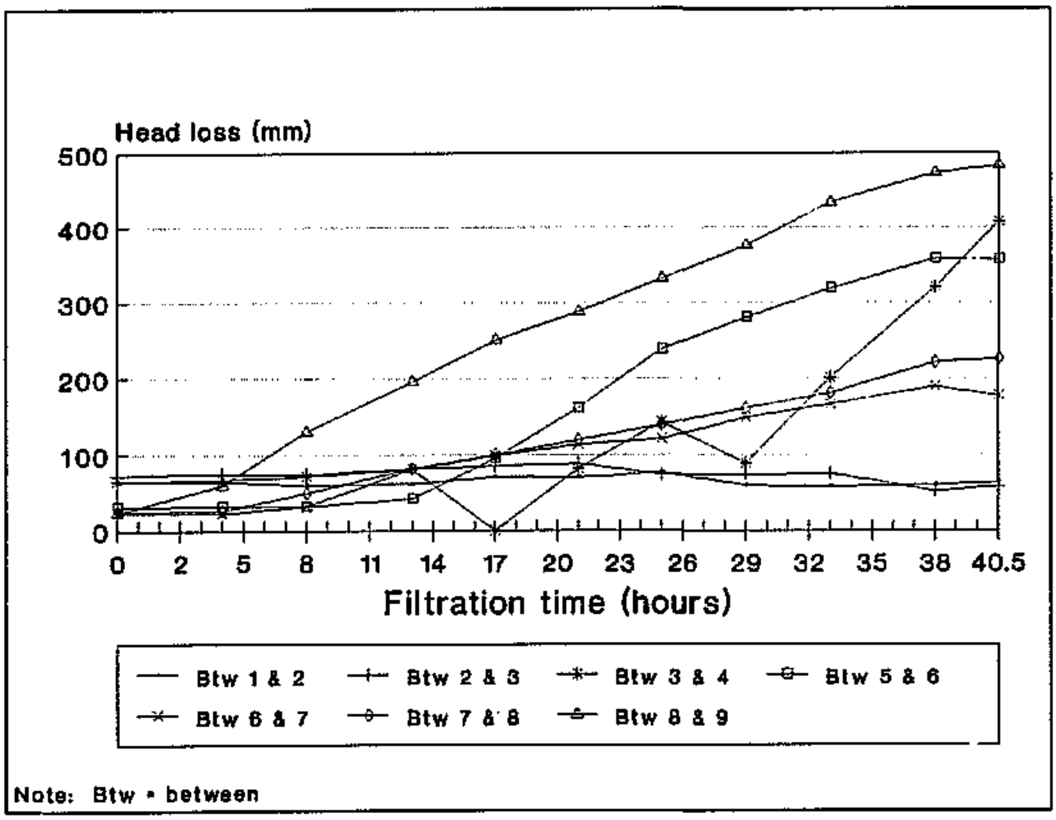


Figure 3.2 Head loss development in the filter for RUN HF 5.1 Filtration rate 5 m/h up; 5 M/H down and 10 mg/ℓ $FeCl_3$

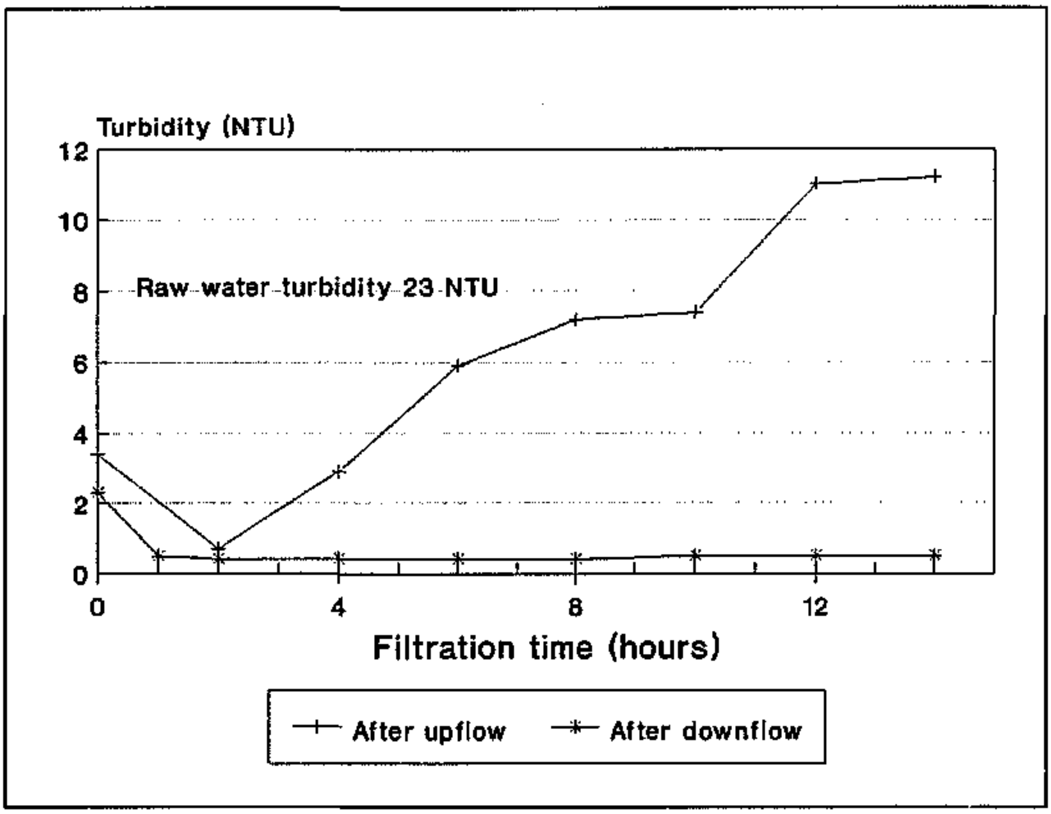


Figure 3.3 **Turbidity removal at Hectorspruit plant for RUN HF 18.1: Filtration rate 18 m/h up; 9 m/h down and 14 mg/ℓ $FeCl_3$**

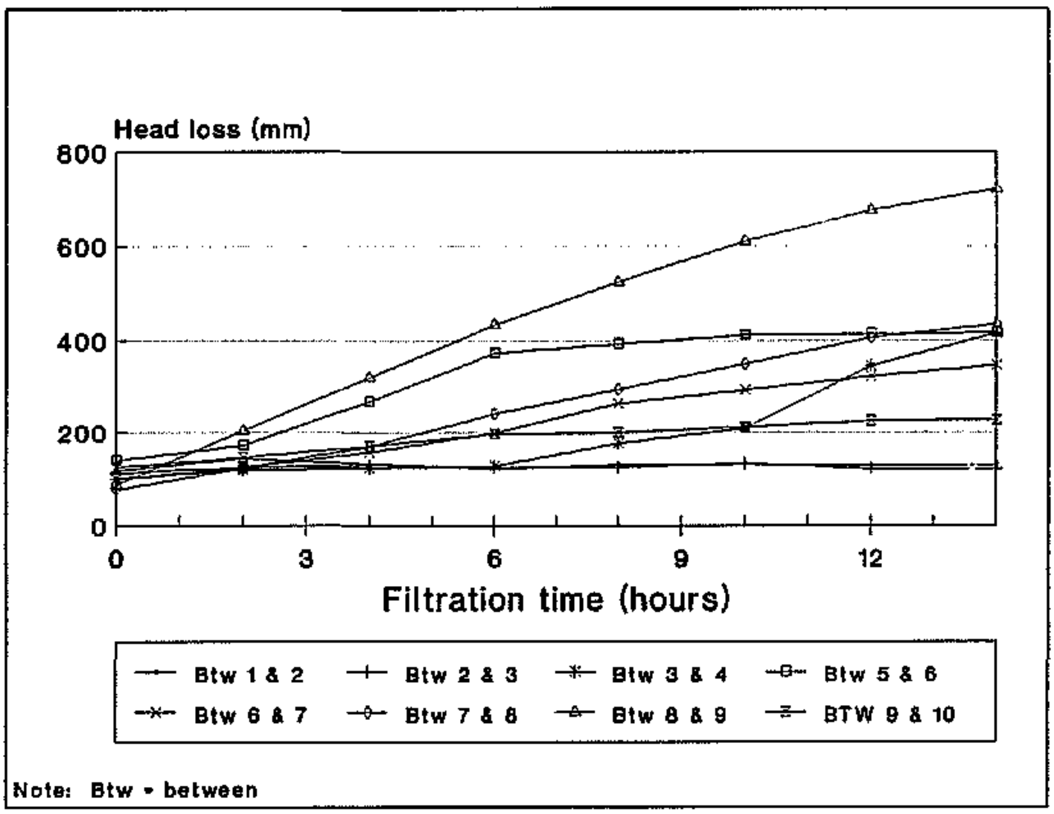


Figure 3.4 **Head loss development in the filter for RUN HF 18.1: Filtration rate 18 m/h up; 9 m/h down and 14 mg/ℓ $FeCl_3$**

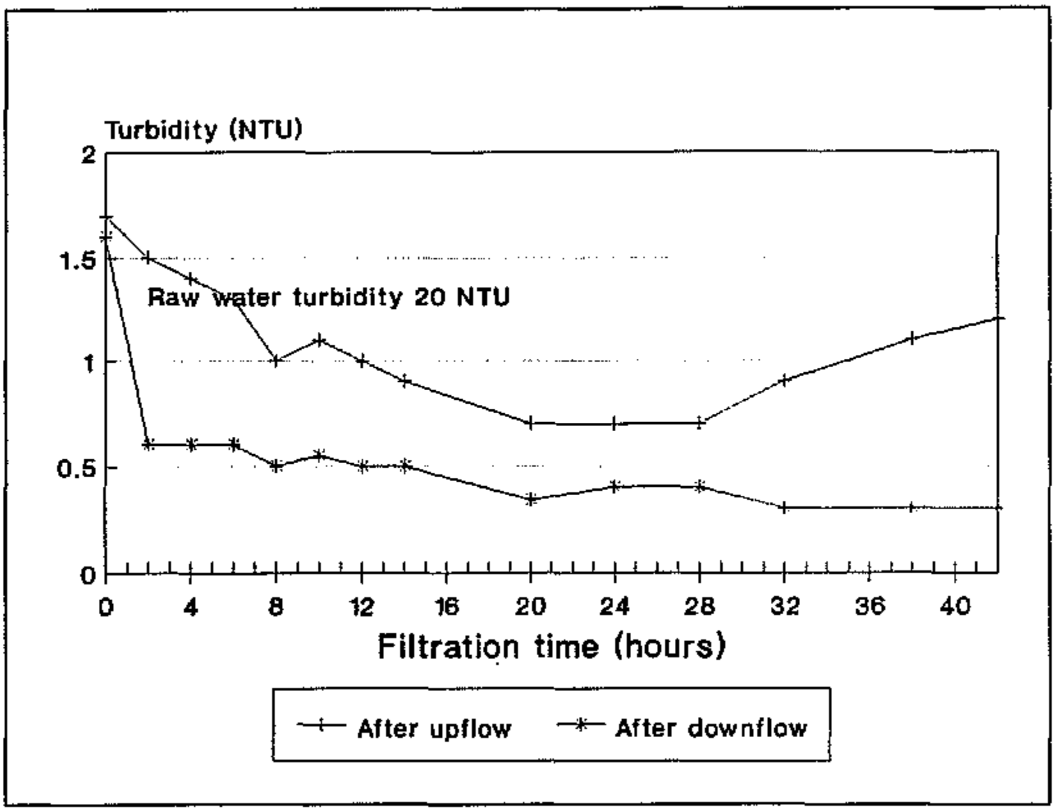


Figure 3.5 **Turbidity removal at Hectorspruit plant for RUN HF 18.2: Filtration rate 18 m/h up; 9 m/h down and 1,1 mg/ℓ LT 22**

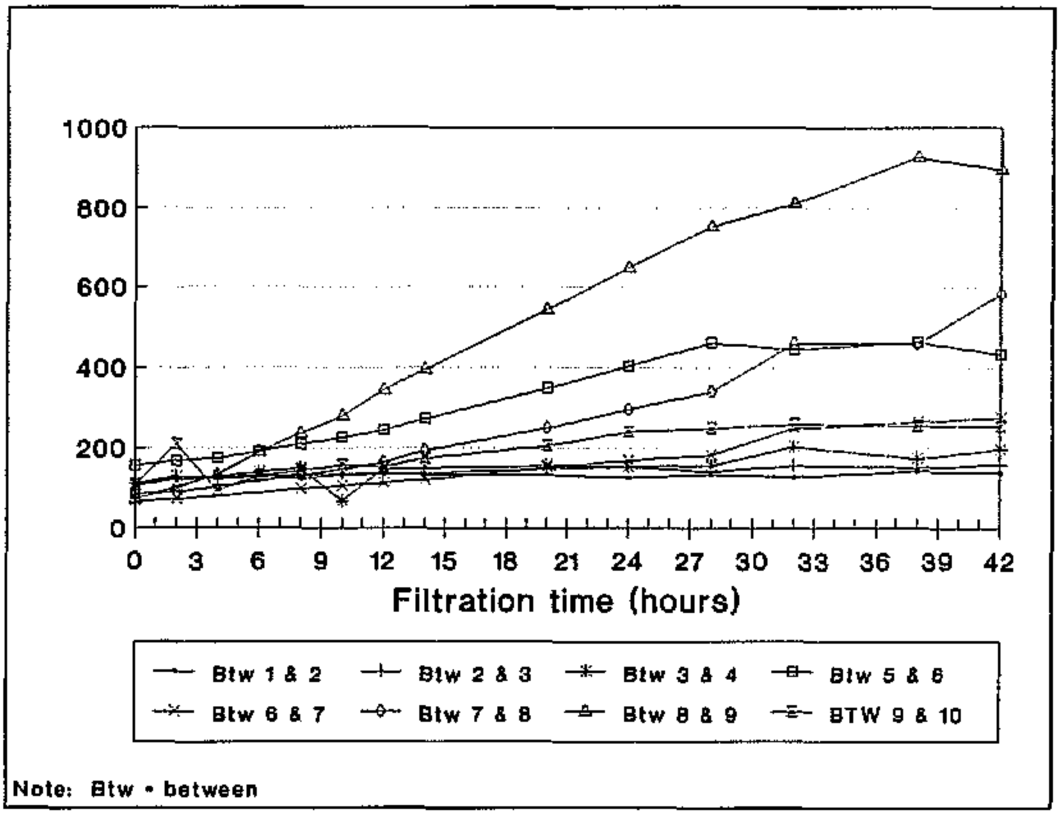


Figure 3.6 **Head loss development in the filter for RUN HF 18.2: Filtration rate 18 m/h up; 9 m/h down and 1,1 mg/ℓ LT 22**

CHAPTER 4

PILOT SCALE TESTS

4.1 INTRODUCTION

Pilot scale tests with a small direct series filtration unit were performed at a number of locations throughout the country so as to include the main categories of surface water qualities found in South Africa. These categories and the site where the pilot scale tests were performed are given below:

- Turbid Waters
  - Low turbidity (0 - 50 NTU)
    Hectorspruit, Crocodile River, Mpumalanga
  - High Turbidity (> 50 NTU)
    Vaalkop Dam, Magalies Water, North-West Province

- Eutrophic Water (defined as having chlorophyll a values in excess of 25 $\mu g/\ell$)

  Roodeplaat Dam, Pretoria

- Coloured Water (organic colour with values in excess of 200 mg/ℓ Pt considered as highly coloured)

  Mossel Bay, South-Cape

4.2 DESCRIPTION OF PILOT PLANT

The direct series filtration pilot scale system that was set up for this project is shown diagrammatically in Figure 4.1. The system comprised the following units:

- a feed pump that pumped raw water from the source to the filter unit
- chemical make-up tanks from where the coagulant and/or flocculant was pumped to the feed pump inlet (for tests on coloured water, lime for pH correction was dosed some distance upstream of the coagulant dosing point)
- a two-stage direct series filter, consisting of an upflow stage placed on top of the downflow stage.

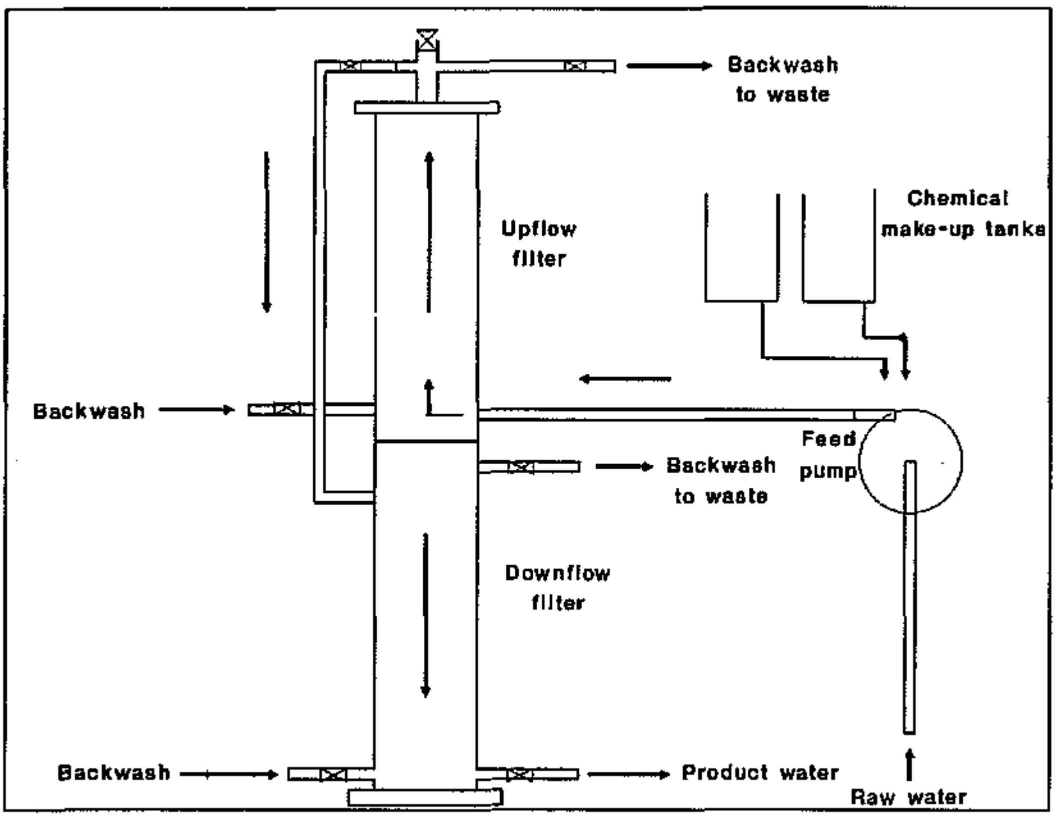


Figure 4.1 Direct series filtration pilot scale system

The filtration pilot plant itself is shown in Figure 4.2. It consists of 5 sections of 150 mm ϕ perspex columns, attached to each other with flanges in the configurations shown in the diagram. One backwash nozzle of 28 mm ϕ was provided in each of the two filtration stages. Connection points for head loss measurement were provided at 100 mm intervals along the length of the column to allow measurement of head loss (in manometer pipes mounted onto a measuring board) in the various sand gradings in the filter.

A flow meter is provided at the inlet to the upflow section of the filter, and connection points are also provided for backwashing each of the filters. The flowmeter was used to obtain filtration rates of 5,10 and 20 m/h through the two filtration stages.

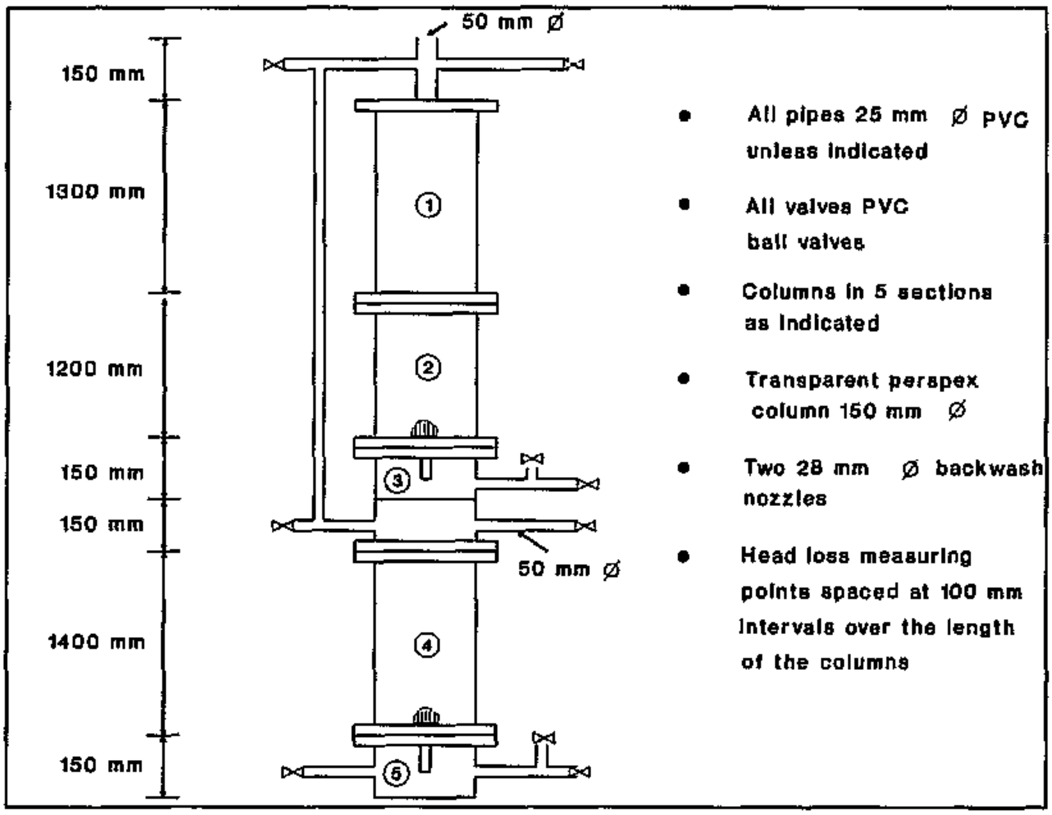


Figure 4.2 Lay-out and dimensions of the direct series filtration pilot plant

Head losses that developed in the various sand gradings of the filter were noted periodically after commencement of each run, and at the same time samples were taken of the raw water, after the upflow filtration stage and the final water after the downflow filtration stage.

The upflow filter contained various sand gradings, with the course medium at the bottom and the finest sand on top. The downflow filter contained only a single fine sand. The sand gradings in the two filtration stages are shown in Figure 4.3. The positions of the manometer points from which the head loss over the different sand gradings were determined are also shown, with points 1, 2 and 3 in the downflow filter and points 4 to 9 in the upflow filter.

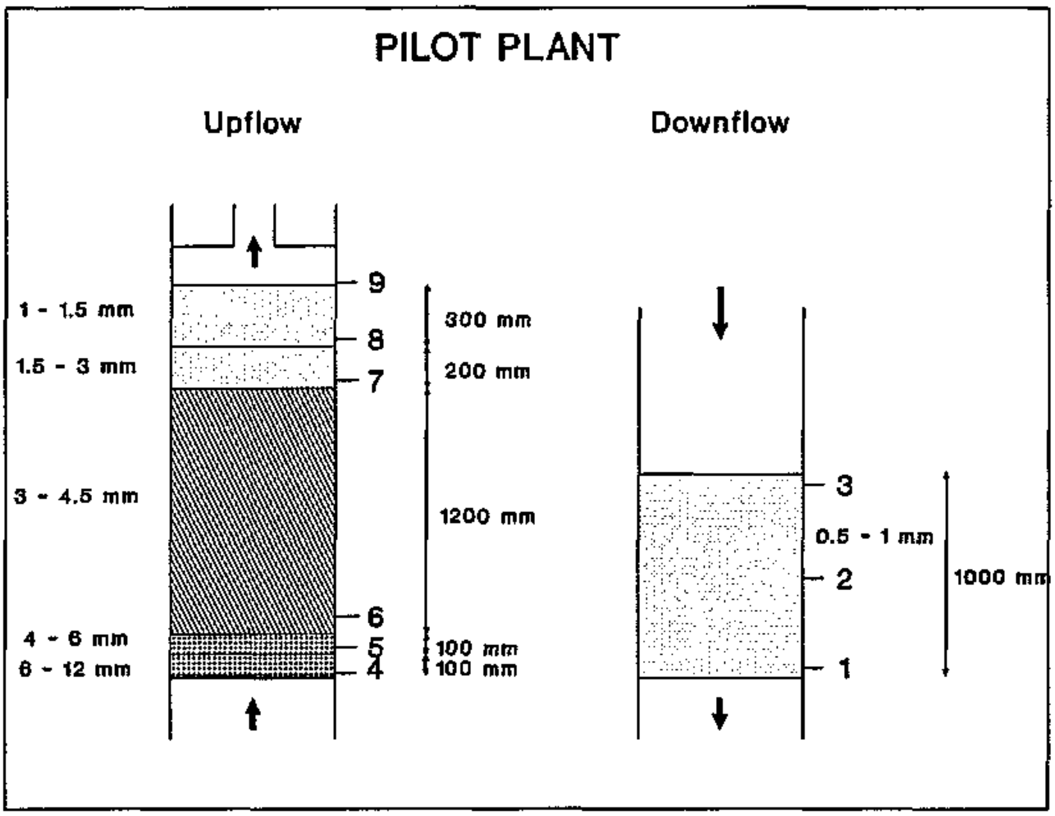


Figure 4.3 Sand-gradings and manometer positions in the pilot plant

The pilot plant is shown in more detail in Figures 4.4 through 4.7.

4.3 EXPERIMENTAL PROTOCOL

The series filtration pilot plant was evaluated at different filtration rates to determine the maximum flow rate that could be achieved still giving practical filter run times. Three filtration rates were selected, *viz.* 5 m/h (representing that of conventional filtration), 10 m/h and 20 m/h. During initial tests, the filtration rate was also increased to 30 m/h, but it soon became evident that only short filter runs could be attained at this high rate, which was considered impractical for use on full-scale plants. Consequently, no further tests were done at filtration rates of 30 m/h.

Various coagulants, polyelectrolytes and combinations thereof were used in the evaluation of the filter to determine which present the most cost-effective option for treating that specific surface water. The chemicals were added at dosages determined in beaker tests to be optimum for turbidity/chlorophyll *a*/colour removal by flocculation and settling for that day's raw water.

The effect of filter media grading or media depth was not investigated, and neither was the backwash requirements for the different types of raw waters treated.

4.4 TURBID WATER

4.4.1 Low Turbidity Water

For purposes of this project low turbidity waters were defined as those with turbidities of less than 50 NTU, and not containing algae or organic colour.

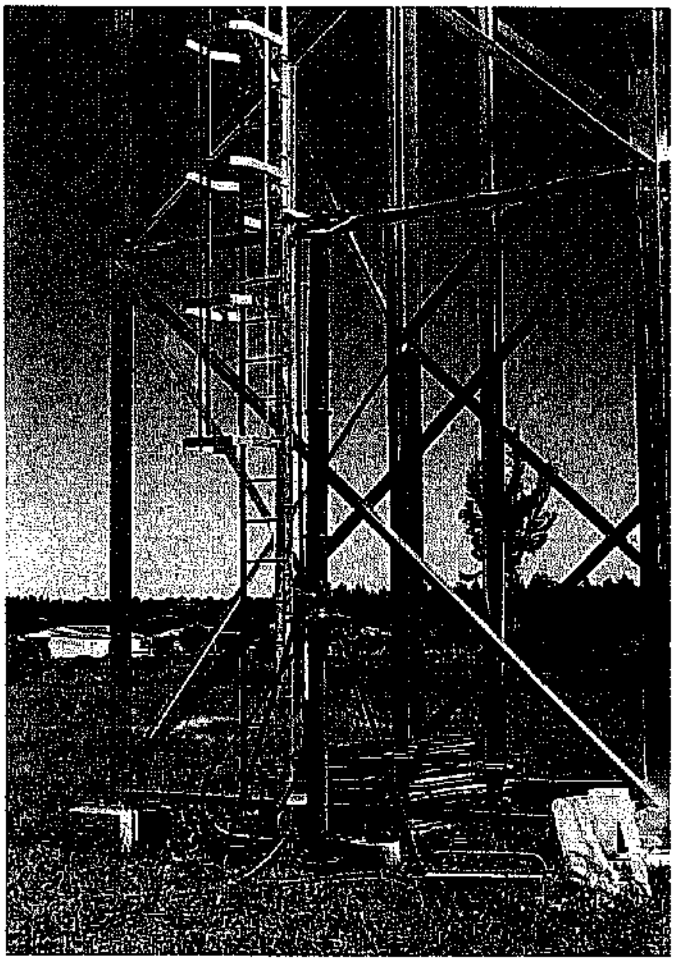


Figure 4.4 Direct series filtration pilot plant

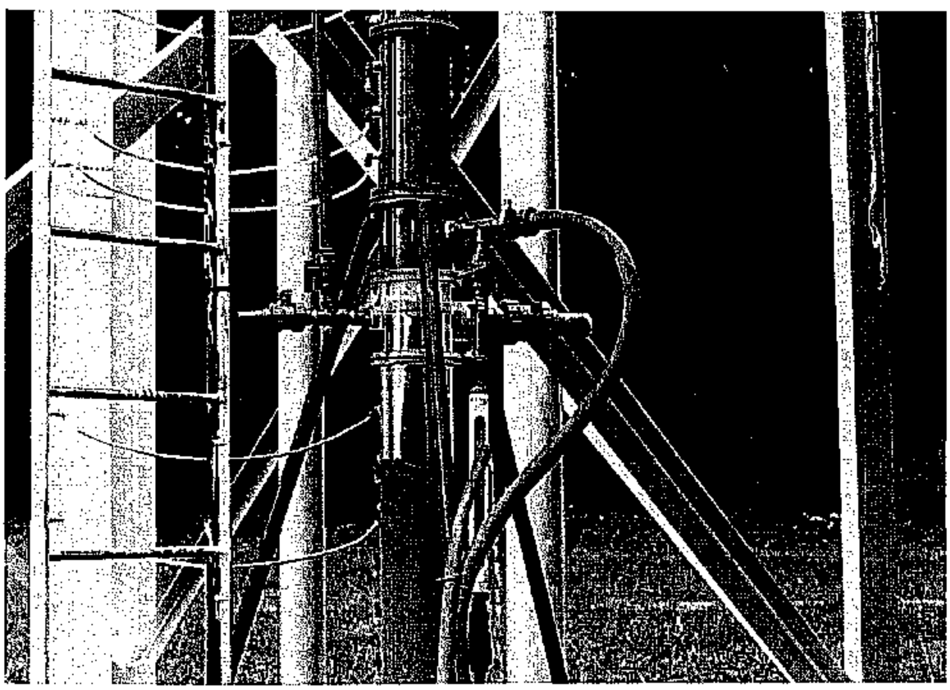


Figure 4.5 Inlet and outlet arrangement of the pilot plant

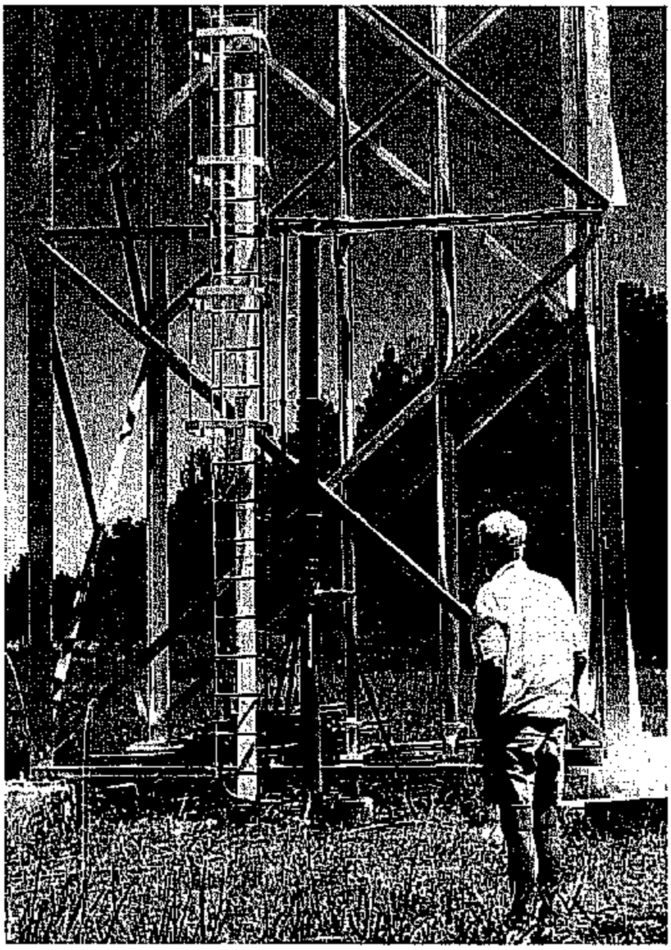


Figure 4.6 Pilot plant in operation at Lottering

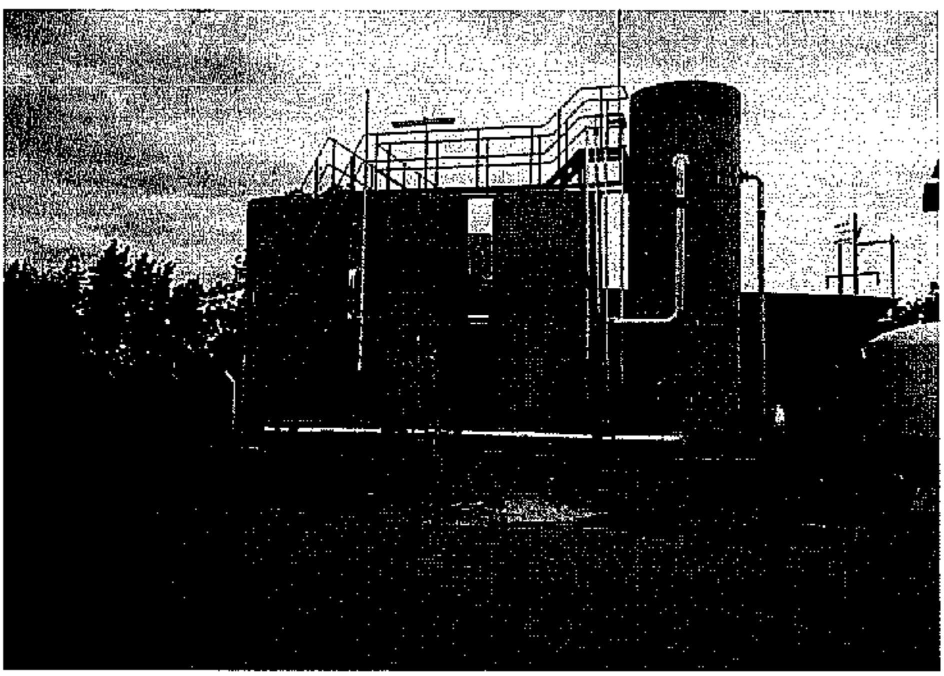


Figure 4.7 Full-scale direct series filtration plant at Hectorspruit

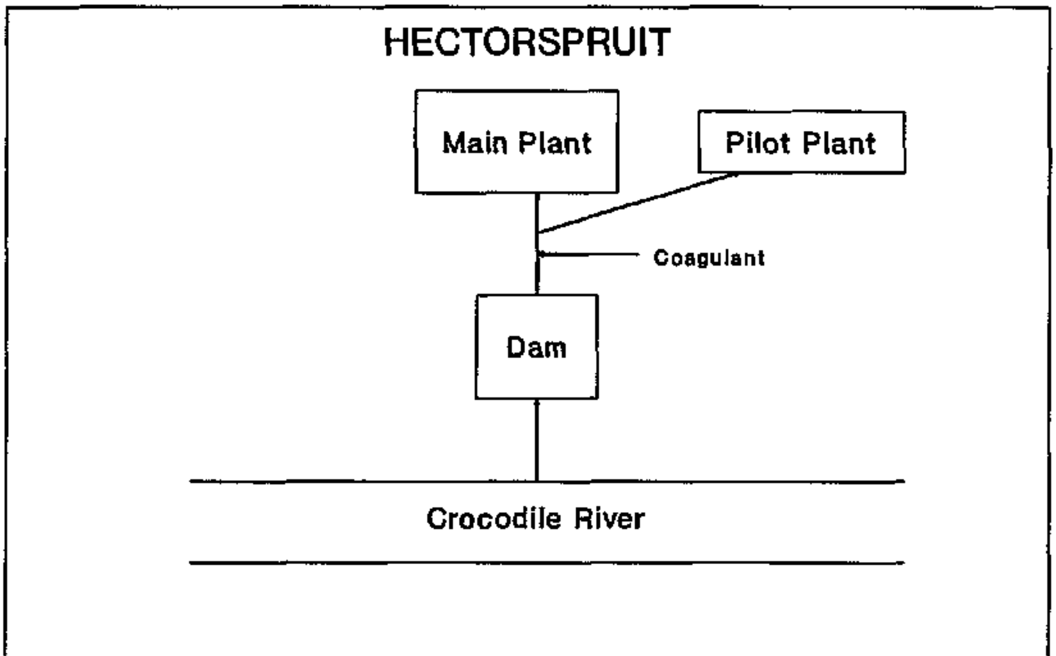
4.4.1.1 Introduction

The Crocodile River in Mpumalanga was used as source for evaluating the filter for the treatment of low turbidity water. The pilot plant was set-up at the Hectorspruit Water Treatment Works and operated in parallel with the full-scale plant, whereby the performance of the pilot and full-scale plants could be compared.

The water quality in the Crocodile River is given in Section 3.1 of the report.

4.4.1.2 Pilot plant setup and test methodology

The pilot plant was set up in parallel with the Hectorspruit full-scale plant as shown in Figure 4.8. (A description of the full-scale plant appears in Section 3.2).



Chemicals	Dosages	Filtration rate (m/h)
$FeCl_3$	15 mg/l	5, 10, 20, 30
Poly	1 mg/l	5, 10, 20, 30

Figure 4.8 Pilot plant setup at Hectorspruit Water Treatment Works

Raw water is pumped from the Crocodile River to a holding dam adjacent to the Hectorspruit plant (no turbidity is removed in the dam). From the dam the raw water is pumped through the filtration plant, and the purified water fed to a reservoir. Ferric chloride and/or cationic polymer is dosed at the inlet to the works and flash mixing established by means of an hydraulic jump. The coagulated water is then fed into the upflow filters of the full-scale plant, while a side-stream of the coagulated water was diverted to the pilot plant.

Runs were done on the pilot plant and the full-scale plant in parallel at filtration rates of 5,10 and 20 m/h. A run at 30 m/h was also done on the pilot plant, but the full-scale plant could not achieve this high flowrate. Ferric chloride was dosed at 15 mg/ℓ while the polymer dosage was 1 mg/ℓ.

Test runs were continued until breakthrough of turbidity was observed or until excessive head loss in the filter had developed. Samples were taken periodically (every 30 minutes/one hour/two hours) after the beginning of the run, of the raw water, after upflow filtration and after downflow filtration, and analysed for pH and turbidity. At the same time intervals the head losses that had developed in the different sand gradings were also noted.

4.4.1.3 Results

The filter runs done on the pilot plant and Hectorspruit full-scale plant are summarized in table 4.1. The results are given in table form and graphically in Appendix B.

Table 4.1 Summary of Hectorspruit pilot plant filter runs

FILTER RUN ID	FILTRATION RATE * (UP AND DOWN) (m/h)	CHEMICAL	DOSAGE (mg/ℓ)	FIGURE NUMBERS IN APP. B
H5.1	5	$FeCl_3$	15	B1 - B2
H10.1	10	$FeCl_3$	15	B3 - B4
H20.1	20	$FeCl_3$	15	B5 - B6
H30.1	30	$FeCl_3$	15	B7 - B8
H20.2	20	LT 22	1,0	B9 - B10
H30.2	30	LT 22	1,0	B11 - B12

Note: *Filtration rates for the upflow and downflow sections of the pilot filter are always equal, and consequently only one filtration rate is given in the tables and graphs with pilot plant results

4.4.1.4 Discussion of results

For this set of tests, the quality of water achieved from the main plant and the pilot plant running at the same filtration rate were compared. At filtration rates of 5 and 10 m/h, both plants delivered water with a final turbidity of around 0.5 NTU. Running time for these filter runs were 40 and 17 hours for 5 and 10 m/h respectively. These runs were aborted when maximum pressure drop in the main plant was reached (around 2 metres).

The main plant was also operated at 20 m/h which took 13 hours to reach maximum pressure drop. The quality of the product water with respect to turbidity was slightly better than what was achieved in the pilot plant. A 30 m/h run on the pilot plant lasted 6 hours during which product water turbidities of 0.5 NTU was achieved for the first four hours.

When polyelectrolyte was used as coagulant, the filter running time was approximately 5 times longer than when $FeCl_3$ was used. The turbidity of the final water was however of a lower quality (1.2 - 1.5 NTU) than the runs where $FeCl_3$ were used.

4.4.2 High Turbidity Water

High turbidity waters were considered as those with turbidities higher than 50 NTU.

4.4.2.1 Introduction

The Vaalkop Dam in the North-Western Transvaal was used as source of high turbidity water because of the high turbidity peaks found in the dam water from time to time. The pilot plant was set up at the Vaalkop Water Treatment Works which is owned and managed by Magalies Water. The quality of the raw water found in the dam ranges as indicated in Table 4.2 below.

Table 4.2: Vaalkop Dam raw water quality

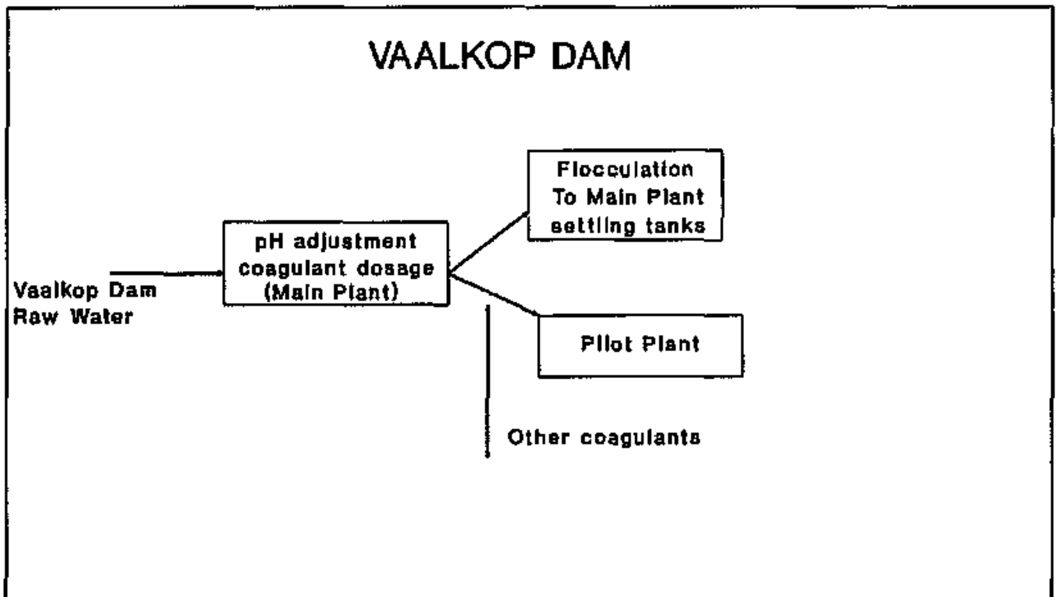
Determinant	Minimum	Maximum	Long-term average
Turbidity (NTU)	21	120	29
pH	8,1	8,6	8,4
Alkalinity (mg/ℓ as $CaCO_3$)	108	188	141
Total hardness (mg/ℓ as $CaCO_3$)	90	170	143
Conductivity (mS/m)	34	56	45
Temp (°C)	13	27	21
Iron (mg/ℓ as Fe)	< 0,005	0,91	0,057
Manganese (mg/ℓ as Mn)	0,005	0,136	0,060
Nitrite (mg/ℓ as NO_2)	< 0,02	< 0,02	< 0,02
Nitrate (mg/ℓ as NO_3)	0,41	0,72	0,52
Chlorides (mg/ℓ as Cℓ)	17	41	25
Sulphate (mg/ℓ as SO_4)	24	27	26
Sodium (mg/ℓ as Na)	37	45	40

4.4.2.2 Pilot plant setup and test methodology

The pilot plant was set up at Vaalkop as shown in Figure 4.9.

A sidestream of coagulated water was diverted from the Main Plant to the pilot plant. In additional test runs, chemicals were dosed directly to the feed pump feeding the pilot plant.

Chemicals that were dosed consisted of ferric-chloride at 7,5 mg/ℓ, alum at 40-45 mg/ℓ, Ultrafloc at 6 - 10 mg/ℓ and a combination of ferric-chloride and Ultrafloc at 8 mg/ℓ and 0,5 mg/ℓ, respectively.



Chemicals	Dosages (mg/l)	Filtration rate (m/h)
$FeCl_3$	7.5	5, 10, 20
Alum	40 - 45	5, 10, 20
Ultrafloc	6 - 10	5, 10, 20
$FeCl_3$/Ultrafloc	8 / 0.5	5, 10, 20

Figure 4.9 Pilot plant setup at Vaalkop Water Treatment Works

Test runs were done at filtration rates of 5, 10 and 20 m/h, and as before were terminated when turbidity breakthrough or excessive head loss development occurred. Samples taken were analysed for pH, turbidity and iron.

For each of the three filtration rates, a test run which gave good turbidity removal was selected and particle size distribution analysis done on the raw water, on the water after upflow section and on the final filtered water after downflow.

4.4.2.3 Results

The test runs done on the pilot plant at Vaalkop Dam are summarized in the table below. The results are given both in tables and graphically in Appendix C.

Table 4.3 Summary of Vaalkop filter runs

FILTER RUN ID	FILTRATION RATE (m/h)	CHEMICAL	DOSAGE (mg/ℓ)	FIGURE NUMBERS IN APP. C
V5.1	5	$FeCl_3$ Lime	7,5 15	C1 - C2
V10.1	10	$FeCl_3$ Lime	7,5 15	C3 - C4
V20.1	20	$FeCl_3$ Lime	7,5 15	C5 - C6
V5.2	5	Alum	40	C7 - C8
V10.2	10	Alum	40	C9 - C10
V20.2	20	Alum	45	C11 - C12
V5.3	5	Ultrafloc	6	C13 - C14
V10.3	10	Ultrafloc	10	-
V20.2	20	Ultrafloc	10	-
V5.4	5	$FeCl_3$ LT 22	10,5 0,5	C15 - C16
V10.4	10	$FeCl_3$ LT 22	7,8 0,5	C17 - C18
V20.4	20	$FeCl_3$ LT 22	7,6 0,5	C19 - C20

4.4.2.4 Discussion of results

Although the turbidity of the raw water varied considerably during the trial run (see table 4.2 for Vaalkop dam water characteristics), the final product water had a turbidity of less than 1 NTU. This was achieved using various coagulants at optimum coagulation dosages. The running time of the pilot plant filter runs using the different coagulants was also of similar length. The 5 m/h run took approximately 25 - 29 hours, the 10 m/h run 7,5 - 9 hours and the 20 m/h run between 1,7 and 3,3 hours to achieve maximum pressure drop.

Where $FeCl_3$ was used as coagulant, the iron in the product water never exceeded 0,02 mg/ℓ as Fe (zero for most of the time). The iron content of the raw water varied between 0,12 and 0,67 mg/ℓ. In the case of alum as coagulant, the concentration of aluminium in the product water remained around the 0,2 mg/ℓ level, which is equivalent to the aluminium content of the raw water.

Analyses of the particle size distribution (see figure C21) shows that particles larger than 91 μm are effectively removed by the filtration process. It can also be seen that better removal takes place in the upflow filter than in the downflow filter. This might be due to secondary flocculation taking place in the downflow filter with the result that larger particles than the incoming particles are formed. It can be seen that more particles pass through the upflow filter when the filtration rate is increased. This is due to an increase in shear velocity which loosens attached particles and washes it out. The higher linear velocity will also have a negative effect on flocculation effectiveness, resulting in less flocs being filtered out at the top of the upflow filter. For the downflow filter, it is seen that better removal of particles takes place at higher filtration rates. This might be due to the fact that the higher velocities minimises the tendency for secondary flocculation.

4.5 EUTROPHIC WATER

4.5.1 Introduction

The Roodeplaat Dam was selected as raw water source for evaluating the filter for algae removal. The dam was eutrophied during the time of performing the test runs, with chlorophyll *a* values ranging from 2 to 35 μg/ℓ. The long-term raw water quality of the dam is given in Table 4.4.

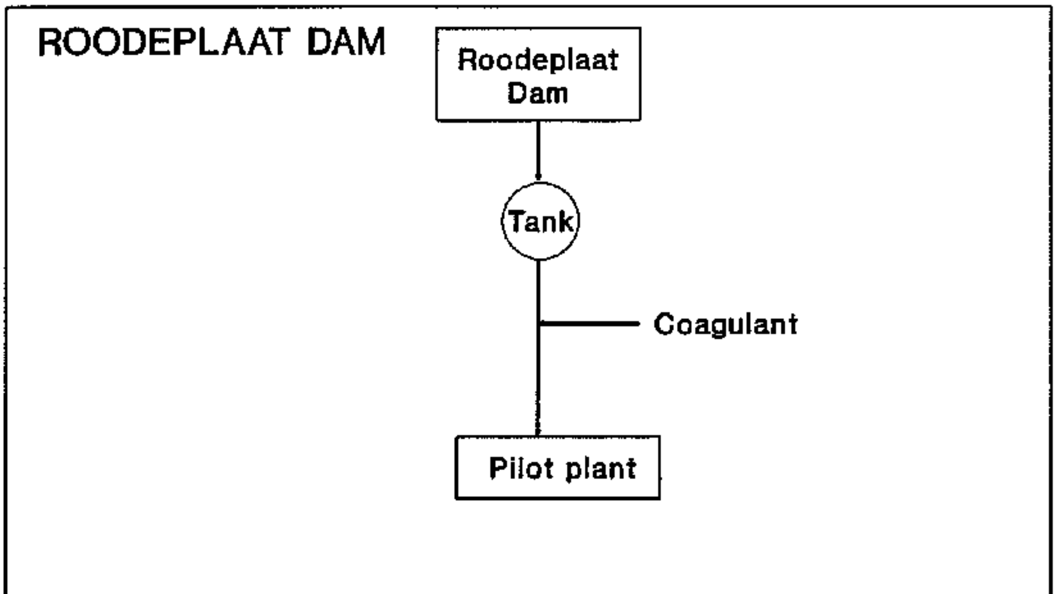
Table 4.4 Roodeplaat Dam raw water quality

Determinant	Minimum	Maximum	Long-term average
pH	5,8	10,1	8,2
Chlorophyll *a* (μg/ℓ)	1	911	27
Turbidity (NTU)(*)	1,1	24	7,8
Alkalinity (mg/ℓ as $CaCO_3$)	66	168	119
Conductivity (mS/m)	11,0	77,0	41,3
Chlorides (mg/ℓ as Cl)	4	68	33
Sodium (mg/ℓ as Na)	5	68	30
Magnesium (mg/ℓ as Mg)	8	31	18
Calcium (mg/ℓ as Ca)	5	49	24
Sulphate (mg/ℓ as SO_4)	5	162	29

(*) Measured during pilot scale tests

4.5.2 Pilot plant setup and test methodology

The pilot plant was set up at Roodevallei Country Lodge on the southern banks of the Roodeplaat Dam. The setup is shown in Figure 4.10.



Chemicals	Dosages (mg/l)	Filtration rate (m/h)
$FeCl_3$	30 - 35	5, 10, 20
Alum	30 - 35	5, 10, 20
LT 22	0.5 - 1	5, 10, 20
Alum/Poly	65/0.5	10, 20

Figure 4.10 Pilot plant setup at Roodeplaat Dam

4.5.3 Results

The filter runs done on the pilot plant at Roodeplaat Dam are summarized in table 4.5. The results are given in tabular and graphical form in Appendix D.

Table 4.5 Summary of Roodeplaat filter runs

FILTER RUN ID	FILTRATION RATE (m/h)	CHEMICAL	DOSAGE (mg/ℓ)	FIGURE NUMBERS IN APP. D
R5.1	5	Alum	35	D1 - D3
R10.1	10	Alum	30	D4 - D6
R20.1	20	Alum	30	D7 - D9
R5.2	5	$FeCl_3$	35	D10 - D12
R10.2	10	$FeCl_3$	30	D13 - D15
R20.2	20	$FeCl_3$	30	D16 - D19
R5.3	5	LT 22	0,5-1,0	D19 - D21
R10.3	10	LT 22	0,5-1,0	D22 - D24
R20.3	20	LT 22	0,5	D25 - D27
R10.4	10	Alum LT 22	60 0,5	D28 - D30
R20.4	20	Alum LT 22	70 0,75	D31 - D33

4.5.4 Discussion of results

$FeCl_3$ and alum proved to be effective coagulants for removal of turbidity associated with algae. The final turbidity of the filtered water remained below 1 NTU. Similar running times for the filter were achieved using these two coagulants: 18 - 20 hours for 5 m/h; 8 - 10 hours for 10 m/h and 4 - 5 hours for 20 m/h. Polyelectrolyte as coagulant produced a product water with turbidity between 1 and 5 NTU. The improvement in filter running time was significant at a filtration rate of 5 m/h, where a filter time of 36 hours was achieved. At filter rates of 10 and 20 m/h, the filter time was comparable to the running time achieved with alum in $FeCl_3$.

In general, the use of $FeCl_3$ proved to be the more effective coagulant for algae removal. The combination of polyelectrolyte and alum were more effective than either polyelectrolyte or alum on its own for removal of algae. The pilot plant filter was not very effective for algae removal, with final product water chlorophyll *a* values of 1 - 4 $\mu g/\ell$ when using the metal coagulants. Chlorophyll *a* values of less than 1 $\mu g/\ell$ were however achieved at certain times during the runs.

Analysis of particle size distribution of the Roodeplaat Dam raw and treated water showed a similar tendency to that which observed for the Vaalkop Dam water, namely better particle removal in the upflow filter than in the downflow filter, reduced filtration efficiency in the upflow filter when filtration rates are increased, and an improvement in particle removal in the downflow filter with increase in filtration rate. The reasons for the above can again be ascribed to secondary flocculation in the upflow filter resulting in particle growth, and also loosening of these particles by shear forces when the filtration rate is increased.

However, particle removal is not as good from the eutrophic water as was found with the oligotrophic water of Vaalkop Dam, which is in conformation with the results of chlorophyll *a* analyses during pilot study tests runs.

The process, as tested with the pilot scale series filtration plant, is therefore not very effective for algae removal.

4.6 COLOURED WATER

4.6.1 Introduction

The coloured water that was used as water source for evaluating the filter's ability to remove organic colour was that which is treated by the Sandhoogte Water Treatment Works at Mossel Bay. It is a typical carbonate species deficient mountain water found in the Southern-Cape, and has a yellow to dark-brown colour caused by dissolved humic substances in the water. These waters have a low pH, alkalinity and hardness and are therefore highly aggressive and corrosive.

The conventional method for treating organically coloured waters consists of pH adjustment, dosing of coagulant (mostly alum but also ferric chloride or ferric sulphate), rapid mixing, flocculation in channels with baffle plates (horizontal or vertical), settling in horizontal settling tanks, rapid sand filtration, stabilization with lime, and chlorination.

The quality of the raw water at the Sandhoogte Treatment Plant is given in Table 4.6

4.6.2 Pilot plant set up and test methodology

The pilot plant was set up at the Sandhoogte Water Treatment Works near Mossel Bay, and the setup is shown in Figure 4.11.

Raw water was pumped from the inlet works of the main plant to the pilot plant. Lime was dosed to the raw water for pH adjustment and some distance further alum was dosed as coagulant.

The optimum alum dosage and pH for good flocculation (formation of large flocs) was determined in beaker tests at the start of each new filter run. The lime dosage on the pilot plant was adjusted to give the optimum pH that was determined for that filter run's raw water feed. The optimum alum dosage was found to be 100 mg/ℓ and the optimum pH in the range 4,7 to 5,2.

Table 4.6 Sandhoogte long-term raw water quality

Determinant	Minimum	Maximum
Colour (apparent)(mg/ℓ Pt)	490	960
Colour (true)(mg/ℓ Pt)	150	886
Turbidity (NTU)	0,2	1,3
pH	3,7	5,2
Alkalinity (mg/ℓ as $CaCO_3$)	0	0,8
Total hardness (mg/ℓ as $CaCO_3$)	9	25
Conductivity (mS/m)	7,0	13,9
Iron (mg/ℓ as Fe)	0,35	0,85
Chlorides (mg/ℓ as Cℓ)	12	40

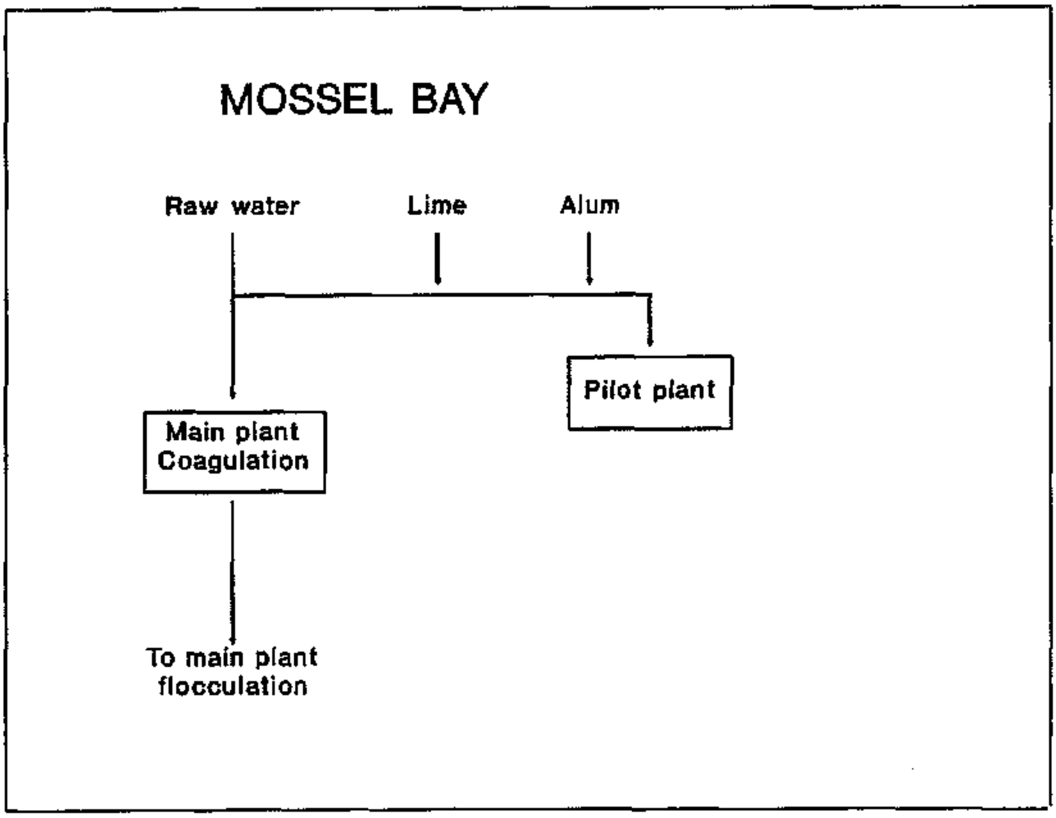


Figure 4.11 Pilot plant set-up at Mossel Bay

Test runs were done at filtration rates of 5,10 and 20 m/h. The runs were terminated when colour breakthrough or excessive head loss development of around 2 m occurred. Samples taken were analysed for pH, apparent colour, true colour, turbidity, and aluminium.

4.6.3 Results

The filter runs done on the pilot plant at Mossel Bay are summarized in the table below. The results are given in tabular and graphical form in Appendix E.

Table 4.7 Summary of Mossel Bay filter runs

FILTER RUN ID	FILTRATION RATE (m/h)	CHEMICAL	DOSAGE (mg/ℓ)	FIGURE NUMBERS IN APP. E
M5.1	5	Alum	100	E1 - E2
M10.1	10	Alum	100	E3 - E4
M20.1	20	Alum	100	E5 - E6
M5.2	5	Alum LT 22	140 1,0	E7 - E8
M10.2	10	Alum LT 22	140 1,0	E9 - E10
M20.2	20	Alum LT 22	140 1,0	E11 - E12

4.6.4 Discussion of results

Colour removal with the direct series filtration system was erratic, with reasonable colour removal being achieved at times, but with breakthrough of humic flocs and resulting poor final water quality taking place during early stages of most of the filter runs. Penetration and resultant shear of the flocs in the filter media appears to take place after some time during the filter runs, even at low filtration rates. This can be ascribed to the fragile nature of the humic flocs that are formed during coagulation of the coloured water.

The apparent colour of the product water after the downflow filtration stage varied between 16 and 65 mg/ℓ as Pt for the 5 m/h filter run, and between 9 and 154 mg/ℓ as Pt during the 10 m/h run. The shear force during the higher filtration rates results in floc breakup in the downflow filter, with resulting colour breakthrough. In most of the cases, the colour levels obtained after upflow filtration were lower than that of the final water, which indicate that the downflow filter could not achieve good floc removal on a consistent basis, even at the low filtration rate.

The run times of the filter were 20 hours for the 5 m/h filter run, 10,5 hours for the 10 m/h run and 3,5 hours for the 20 m/h run, before the maximum pressure drop accross the filter was reached. High turbidities were measured in the water after the upflow filtration stage, which was subsequently reduced by the downflow filter to values of only 1 to 15 NTU, showing the inefficiency of the downflow filter to produce a high quality water under these conditions.

The use of a cationic polyelectrolyte together with alum did not result in any improvement of the quality of the product water, as was expected (by providing more "strength" to the floc. The filter run times were, however, of similar duration as when only was used.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

Summary

The following results were obtained during pilot scale tests that were performed with the direct series filtration pilot plant on the different raw water sources, using different coagulants and employing different filtration rates:

Low turbidity water

With turbidity of the raw water between 20 and 25 NTU, coagulant dosages of 15 mg/ℓ $FeCl_3$, or 1 mg/ℓ of a cationic polymer were used. With $FeCl_3$ as coagulant, final water quality in terms of turbidity was around 0,5 NTU. For filtration rates of 5, 10 and 20 m/h, the filter runs were 40, 17 and 7,5 h respectively. Runs were terminated when a pressure drop of 2 m was reached in the downflow filter.

When cationic polymer was used as coagulant, the filter running time was approximately four to five times longer than with the use of $FeCl_3$. The turbidity of the final water was however of a lower quality (1,2 to 1,5 NTU) compared to when $FeCl_3$ was used.

High turbidity water

Although the turbidity of the raw water varies considerably during the trial runs (20 to 120 NTU), the final product water had a turbidity of less than 1 NTU for all coagulants tested. This was achieved by using the various coagulants at their optimum coagulant dosages, namely $FeCl_3$ at 7,5 mg/ℓ, alum at 40 mg/ℓ and a combination of $FeCl_3$ and polymer at dosages of 8,0 mg/ℓ and 0,5 mg/ℓ respectively. The running times of the pilot filters were also of similar length, regardless of coagulant type. The 5 m/h run continues for approximately 21 to 25 h, the 10 m/h run for 7,0 to 8,5 h, and the 20 m/h run for only 1,5 to 2,7 h, to achieve the maximum pressure drop of 2 m in the downflow filter.

Eutrophic water

$FeCl_3$ and alum proved to be effective coagulants for removal of turbidity associated with algae. The final turbidity of the filtered water stayed below 1 NTU. The run times for $FeCl_3$ and alum were 18 to 20 h at 5 m/h, 8 to 10 h at 10 m/h, and 3 to 3,5 hours for 20 m/h. With polymer as coagulant, the final water had turbidities between 1 and 5 NTU. The improvement in run time was however significant at a rate of 5 m/h where a run time of 32 h was achieved. At filter rates of 10 and 20 m/h, the run times were comparable to the run times achieved with alum and $FeCl_3$.

In general, the use of $FeCl_3$ proved to be more effective for algae removal. The combination of polymer and alum was more effective than polymer or alum on their own for removal of algae. The pilot plant filter was not very effective for algae removal, with final product water chlorophyll *a* values of 1 - 4 $\mu g/\ell$ using the above mentioned coagulants (raw water chlorophyll *a* values between 2 and 80 $\mu g/\ell$). Chlorophyll *a* values of less than 1 $\mu g/\ell$ were however frequently achieved.

Coloured water

Tests were performed on raw water which had apparent colour values of 520 mg/ℓ as Pt and true colour of 400 mg/ℓ as Pt. Lime was added to the raw water for pH adjustment whereafter alum was dosed at 100 mg/ℓ. The optimum pH range for flocculation was between pH 4,7 and pH 5,2. Run times of the filter at 5, 10 and 20 m/h filtration rates were 21, 11 and 3,5 h respectively. Removal efficiencies at the different filtration rates were comparable, with apparent colour values of around 50 mg/ℓ as Pt and true colour values of 5 mg/ℓ achieved in the final water.

Conclusions

The following conclusions can be drawn based on the pilot scale evaluation of the direct series filtration process on South African surface waters:

- The process is effective for the treatment of low turbidity waters, and can produce product water turbidities of 0,5 NTU on a consistent basis using a metal coagulant such as $FeCl_3$. At normal rapid sand filtration rates of 5 m/h, the run time of the series filtration process can be up to 40 hours or more. Even at a high filtration rate of 20 m/h, filter run times of almost 8 hours can be achieved.

- Cationic polymers can produce even longer filter runs when treating low turbidity water, but cannot achieve the same low turbidity levels of the filtered water as when metal coagulants are used.

- Effective coagulation of the raw water is required to ensure high quality final water after the upflow and downflow filtration process.

- The process can also effectively treat high turbidity water to produce a filtered water with turbidities of down to 1 NTU, but as expected will have much shorter filter run times. This does not present significant problems when treating highly turbid waters at low filtration rates (typically 5 m/h), but will be a limiting factor when attempting to treat these waters at a high filtration rate on full-scale.

- The process also produces low final water turbidities (1 NTU and less) when treating eutrophic waters, but is not very effective for removal of algal cells, as measured by the chlorophyll *a* content of the water.

- It is also not effective for the treatment of highly coloured waters, mainly as a result of the fragile nature of the flocs that are formed when the natural organic matter (mainly humic substances) in the water is coagulated. The strength of the floc seemed to be improved somewhat with the dosing of a cationic polymer, but can still not prevent floc breakthrough after relatively short filter run times. The effect of secondary flocculation in the downflow filter and shear forces in the upflow filter also appear to be more significant when treating these coloured waters, as evidenced by the more erratic results of the test runs.

The practical experience gained through implementation of the process at full-scale at the four locations in South Africa (cf. Section 2.2) indicates that:

- the system consistently provides water of acceptable quality and quantity for small, developing communities

- by exploiting modular design and the use of prefabricated concrete pipe sections, capital cost savings of 20% to 50% are attained compared to conventional treatment

- indirect evidence suggests that coagulant savings of 20% could be realised for series filtration

- with appropriate safety factors and degree of automation, the system can be successfully operated with limited operator skill, provided that competent technical back-up and guidance are provided at least monthly.

Limits of application

Two criteria are important for establishing the water quality limits within which series filtration can be applied. The first is whether the final water quality meets the required standard, and the second is whether the system can be operated at sufficiently long filtration cycles before terminal headloss or turbidity breakthrough is reached.

For all the cases investigated, both at pilot and at full-scale, final water turbidity below 1,0 NTU could be attained except when a cationic polymer was used as only coagulant. The performance in terms of colour removal is much more erratic, as pointed out above. In some cases, colour can be reduced from 500 mg/ℓ as Pt to 5 mg/ℓ as Pt; in others, colour of 500 mg/ℓ as Pt could not even be reduced to 50 mg/ℓ as Pt. For colour removal, the system therefore needs to be tested first.

The most important limiting factor is the filter run time, which is limited by the clogging head available for the downflow filter. (If the upflow filter clogs beyond what it is designed for, it simply expands in order to maintain the required flow rate). With low raw water turbidity, low coagulant dosage and low filtration rate, the filter run times pose no problem, as expected. If any of these parameters increase, the filter run time will decrease. The worst practically encountered case was when filter run times were down to about 6 hours when the raw water turbidity was 400 NTU for a prolonged period at a filtration rate of 4,5 m/h. With raw water turbidity at an average of 100 NTU, run times of 12 hours or more could be maintained.

Design aspects for upflow filter

Because the media in the upflow filter is to coarse for fluidisation or bed expansion to take place during backwashing, the backwash rate should not be less than 70 m/h. This means that the backwash pump should have a high flow rate, and which could be limiting in determining the size of an upflow filter, *e.g.*

- in the case of prefabricated concrete pipe sections the effective filtration area is 2,41 m^2 and thus requires a backwash pump with a capacity of 170 m^3/h (Marloth Park; Hectorspruit; Magaliesburg); or
- in the case of Burgersfort, the filter area is 12 m^2 requiring a backwash pump with capacity of 840 m^3/h.

At all the plants that have been built to date, provision has been made for a raw water storage facility to use raw water for backwashing. It is then important to bear in mind that the first bed volume after backwashing, and when coagulant is again dosed, should be discharged to waste before the filtrate is directed to the downflow filters.

An upflow filter can not be backwashed effectively unless the filter is not drained totally after the first air scour cycle. This is an important consideration which should be provided for in the backwash program. Filter draining prior to backwash prevents loss of media, *i.e.* the finer graded media on top of the filter. It also results in considerably less backwash water being required because most of the residual solids (silt) have already being removed during draining of the filter.

It is becoming increasingly important that residuals and backwash water should not discharged directly to a public water course as a result of the impact on the environment. Settling of this residuals and backwash water and recycling of the supernatant to the head of the works not only saves water on the long term, but also reduces the production losses. At Hectorspruit and Burgersfort this reuse of discharge water from the plant is already practised, and provision has been made to also employ this in the extension of the Marloth Park treatment plant.

The problems with using polymers as primary coagulant in direct filtration are well known. These include:

- the formation of mud-balls; and
- progressive fouling of the filter because the backwashing is not able to clean the filter completely during each cycle (it forms stronger bonds between media grains and floc particles than in the case of a metal salt flocculant).

If a polyelectrolyte then has to be used as primary coagulant, it is recommended that the filter be "treated" periodically with a strong chlorine solution, for example by leaving an HTH solution in the filter for a number of hours and then backwashing the filter. In this way a substantial amount of the organic material in the filter bed will be oxidised.

The stabilisation reaction of water is prolonged. It can therefore be found that if lime is dosed before filtration and too high dosage is applied for whatever reason, that grain or media growth occurs in the filter (because of to high calcium carbonate precipitation potential). For this reason sodium carbonate (soda ash) is dosed after filtration to stabilise the treated water.

Further studies

An aspect which requires further investigation is whether, and to what extent, filter production (of filter run times) can be increased by replacement of the single medium in the downflow filter with dual media (sand plus anthracite).

To date the ratio between the number of upflow filters and the number of downflow filters has been taken as 2:1, *i.e.* the loading on the downflow filters was double that on the upflow filter. In the case of Burgersfort an equal number of upflow and downflow filters have been provided, and it appears that filter production has been improved by this. This will naturally reduce the capital cost of a plant, and should therefore be further investigated.

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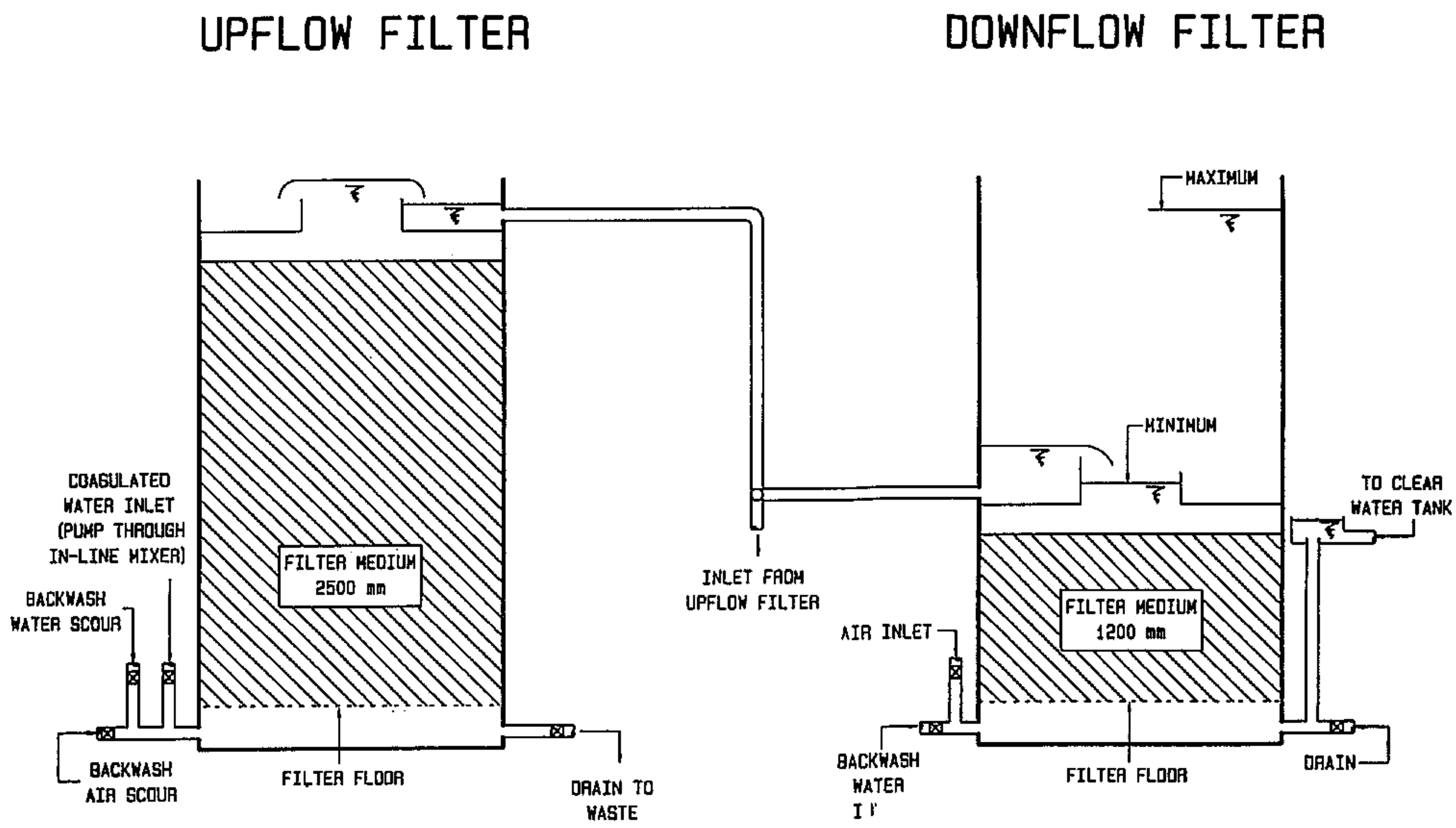
APPENDICES

APPENDIX A

SCHEMATIC SECTION OF THE DIRECT SERIES FILTRATION SYSTEM AS IMPLEMENTED ON FULL-SCALE IN SOUTH AFRICA


UPFLOW FILTER
DOWNFLOW FILTER
COAGULATED WATER INLET (PUMP THROUGH IN-LINE MIXER)
BACKWASH WATER SCOUR
BACKWASH AIR SCOUR
FILTER MEDIUM 2500 mm
FILTER FLOOR
DRAIN TO WASTE
INLET FROM UPFLOW FILTER
MAXIMUM
MINIMUM
FILTER MEDIUM 1200 mm
AIR INLET
BACKWASH WATER
FILTER FLOOR
TO CLEAR WATER TANK
DRAIN

APPENDIX B

RESULTS OF PILOT-SCALE TESTS ON LOW TO MEDIUM TURBIDITY WATER AT HECTORSPRUIT WATER TREATMENT WORKS

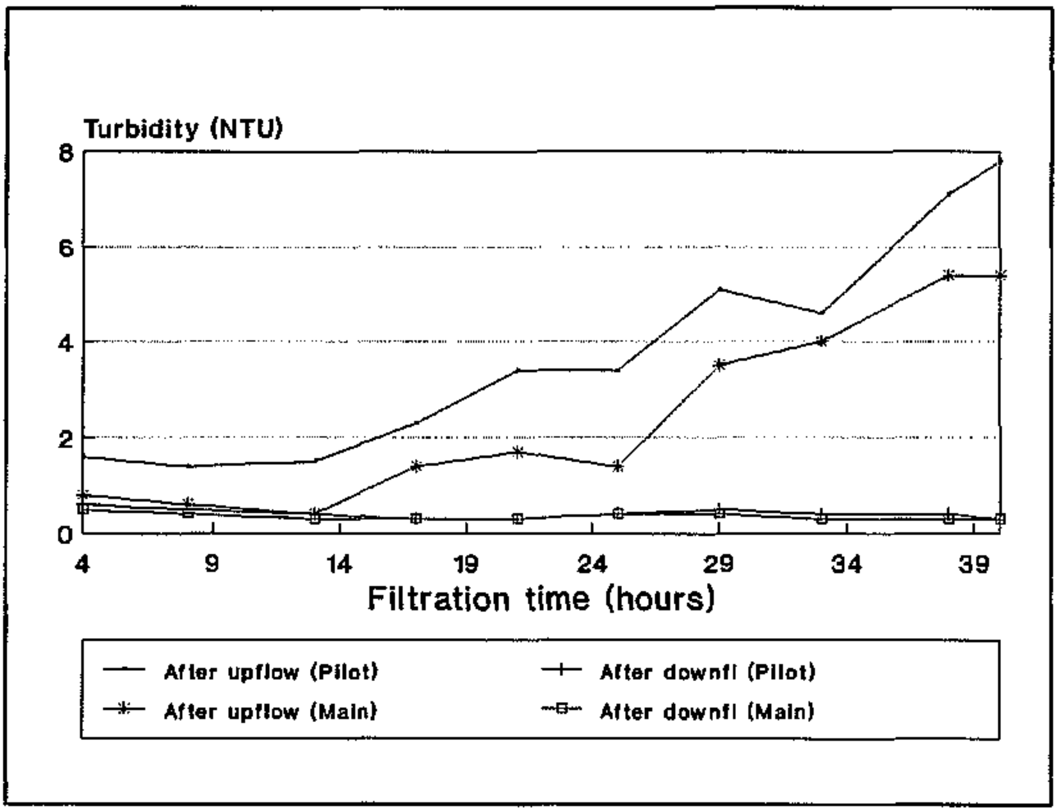


Figure B1 Turbidity removal at Hectorspruit for RUN H5.1: Filtration rate 5 m/h and 15 mg/ℓ $FeCℓ_3$

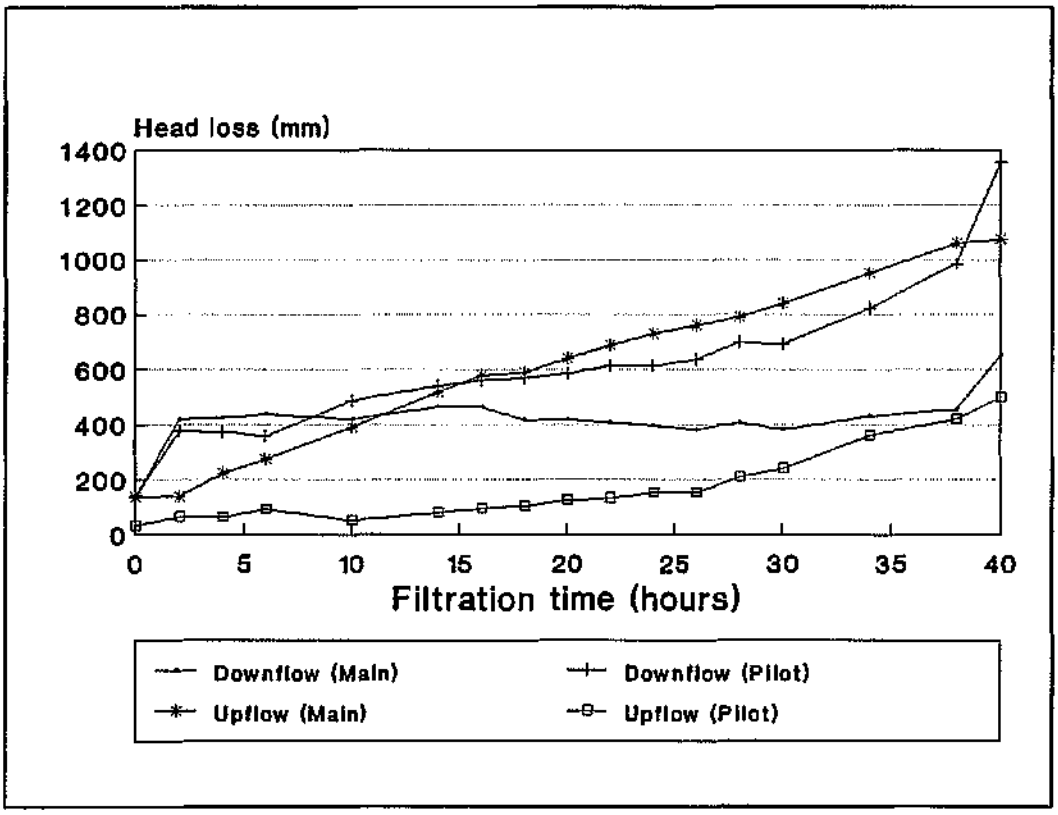


Figure B2 Head loss development in the filter for RUN H5.1: Filtration rate 5 m/h and 15 mg/ℓ $FeCℓ_3$

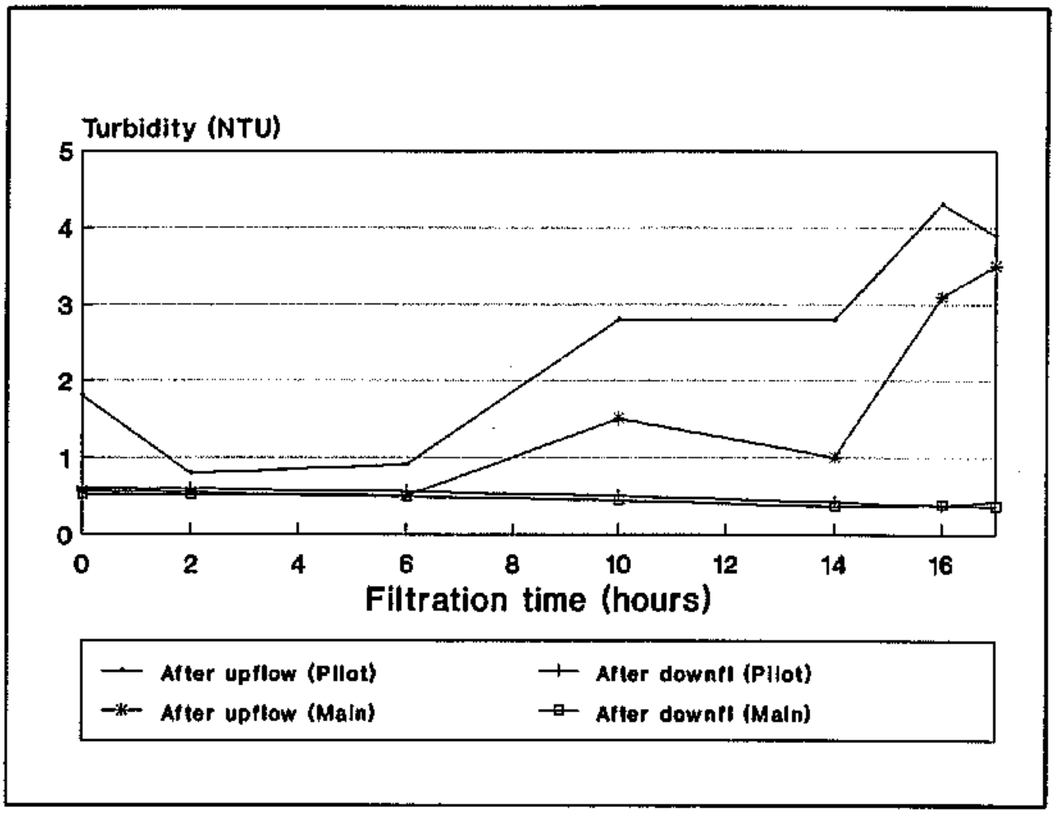


Figure B3 Turbidity removal at Hectorspruit for RUN H10.1: Filtration rate 10 m/h and 15 mg/ℓ $FeC\ell_3$

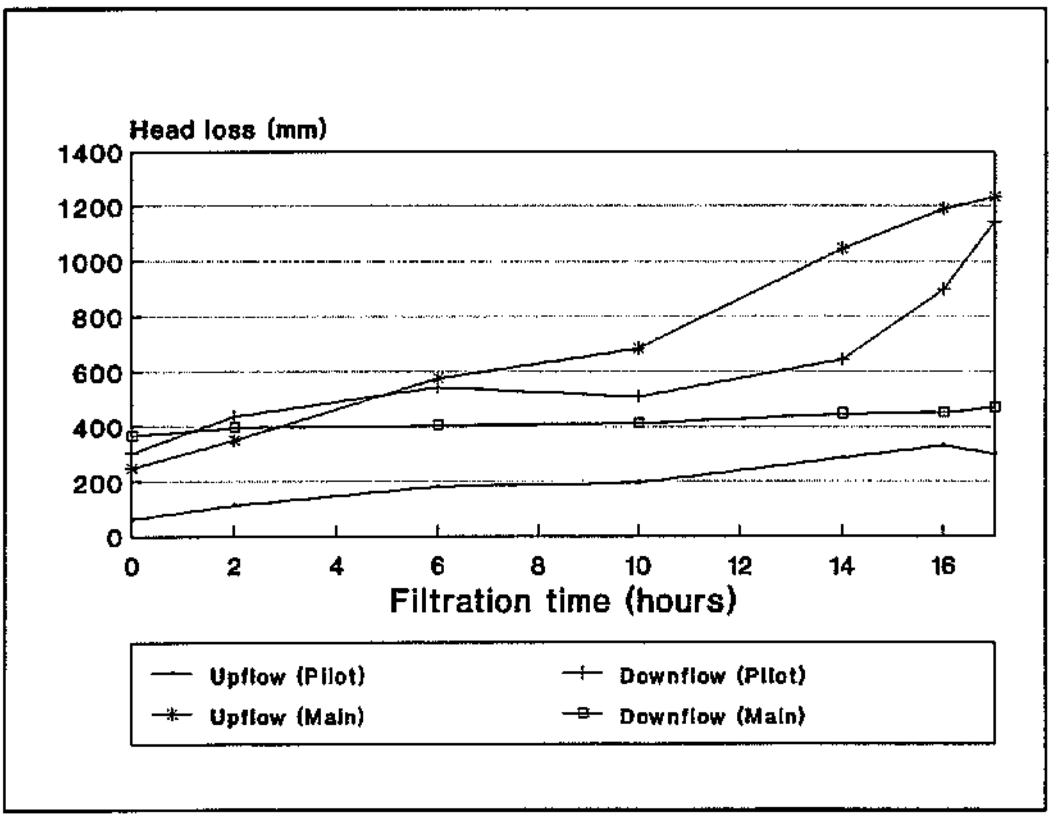


Figure B4 Head loss development in the filter for RUN H10.1: Filtration rate 10 m/h and 15 mg/ℓ $FeC\ell_3$

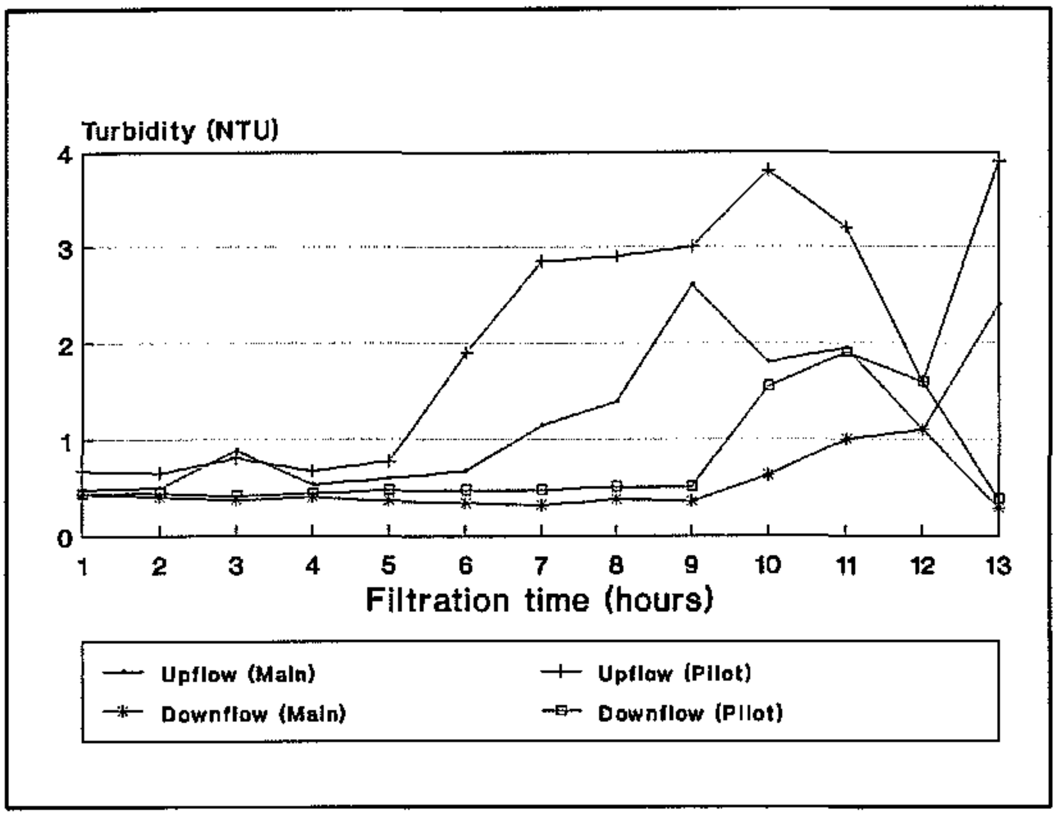


Figure B5 Turbidity removal at Hectorspruit for RUN H20.1: Filtration rate 20 m/h and 15 mg/ℓ $FeC\ell_3$

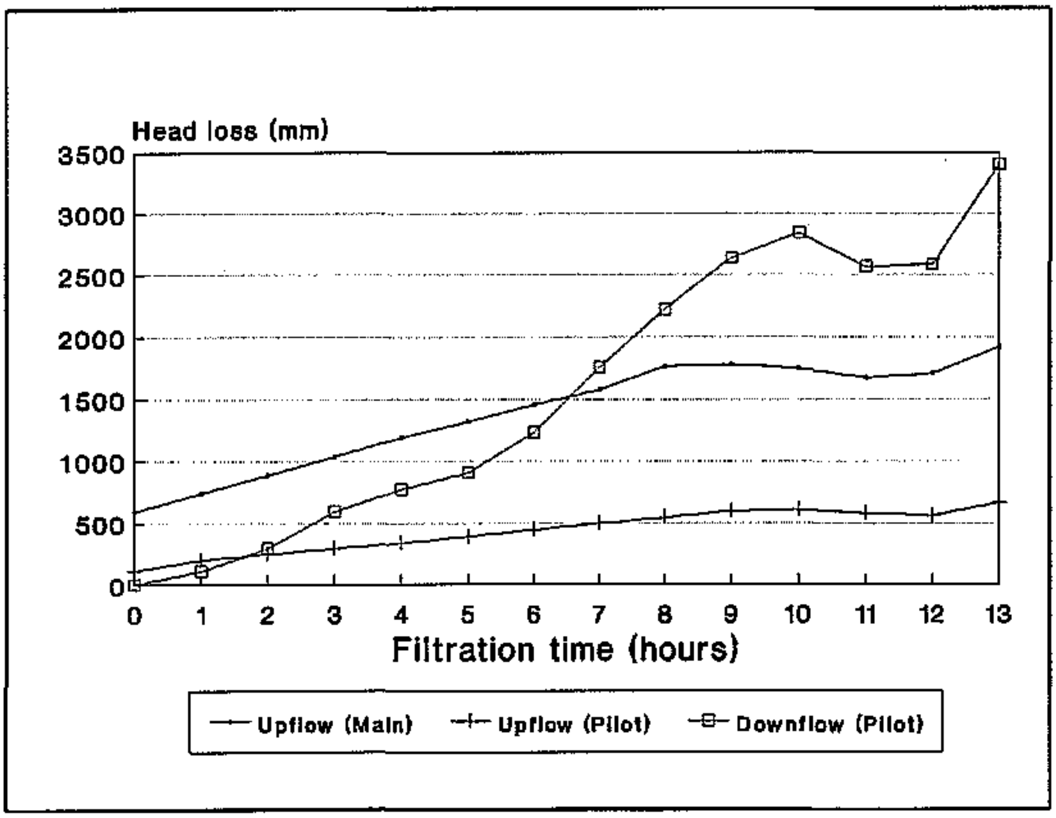


Figure B6 Head loss development in the filter for RUN H20.1: Filtration rate 20 m/h and 15 mg/ℓ $FeC\ell_3$

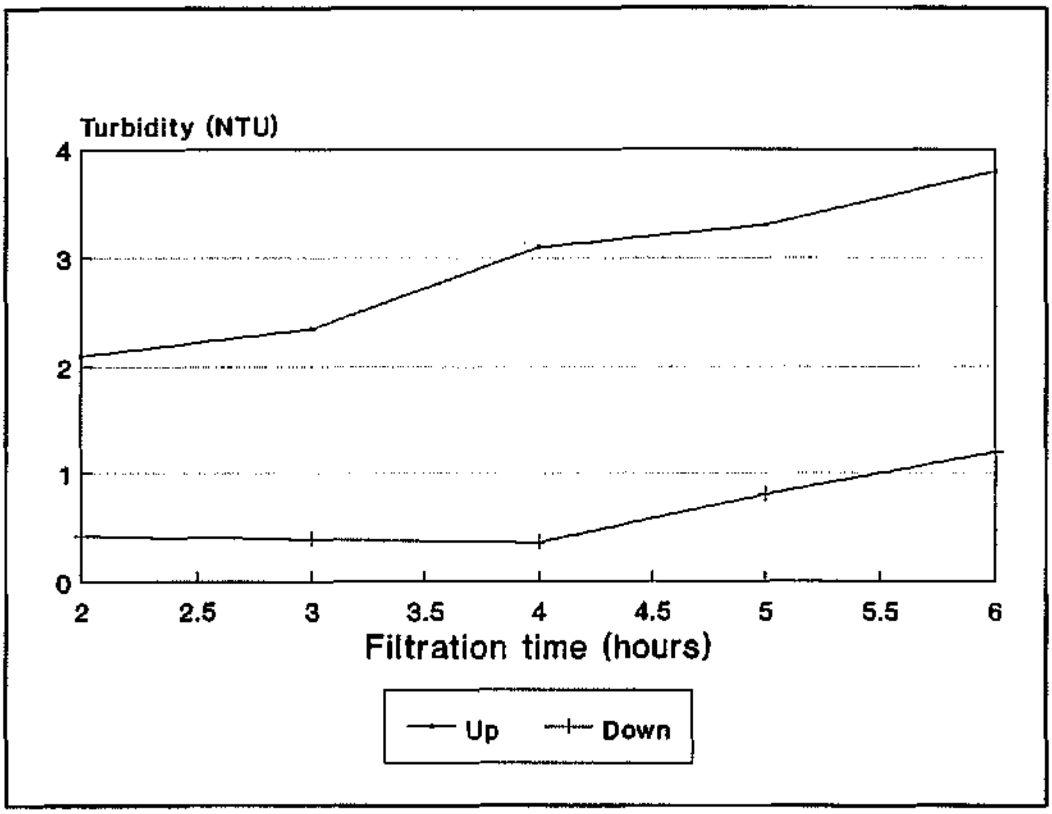


Figure B7 Turbidity removal at Hectorspruit for RUN H30.1: Filtration rate 30 m/h and 15 mg/ℓ $FeC\ell_3$

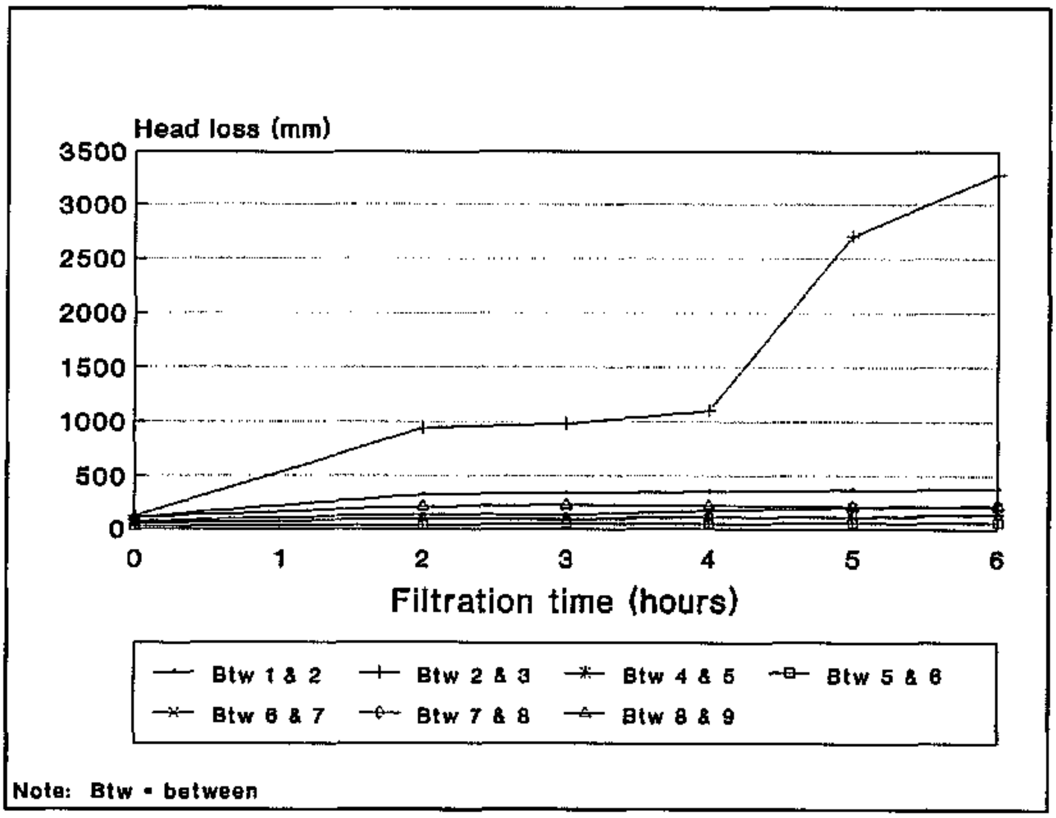


Figure B8 Head loss development in the filter for RUN H30.1: Filtration rate 30 m/h and 15 mg/ℓ $FeC\ell_3$

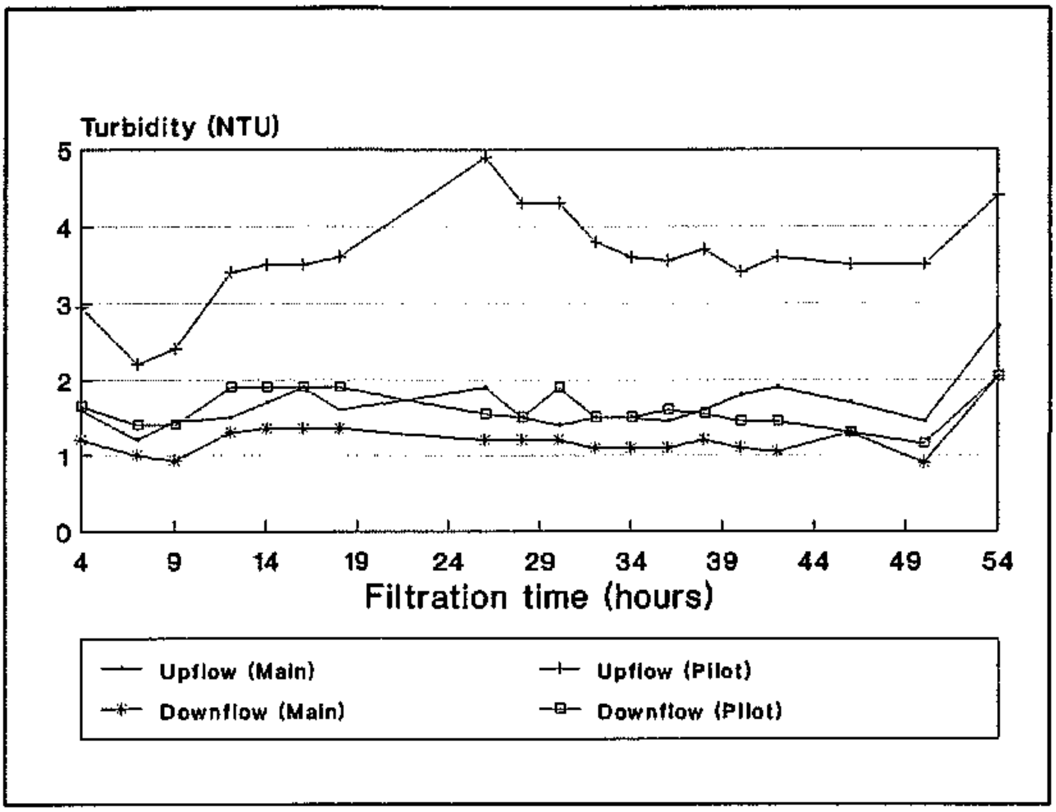


Figure B9 Turbidity removal at Hectorspruit for RUN H20.2: Filtration rate 20 m/h and 1 mg/ℓ LT 22

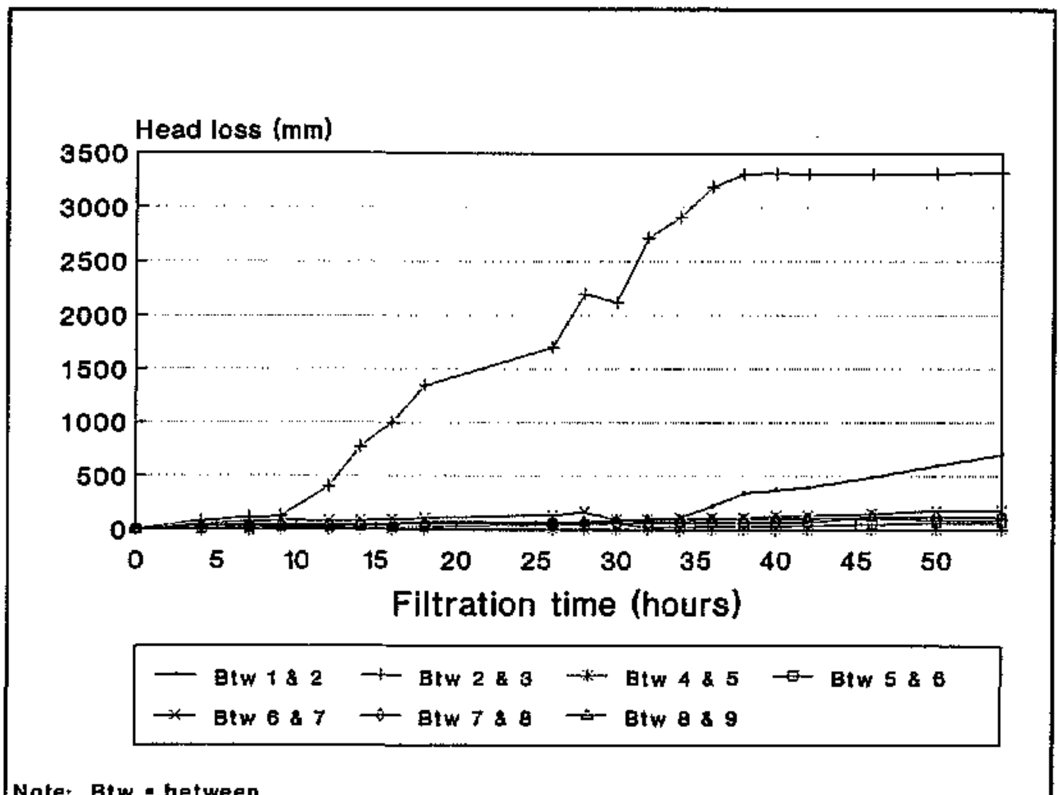


Figure B10 Head loss development in the filter for RUN H20.2: Filtration rate 20 m/h and 1 mg/ℓ LT 22

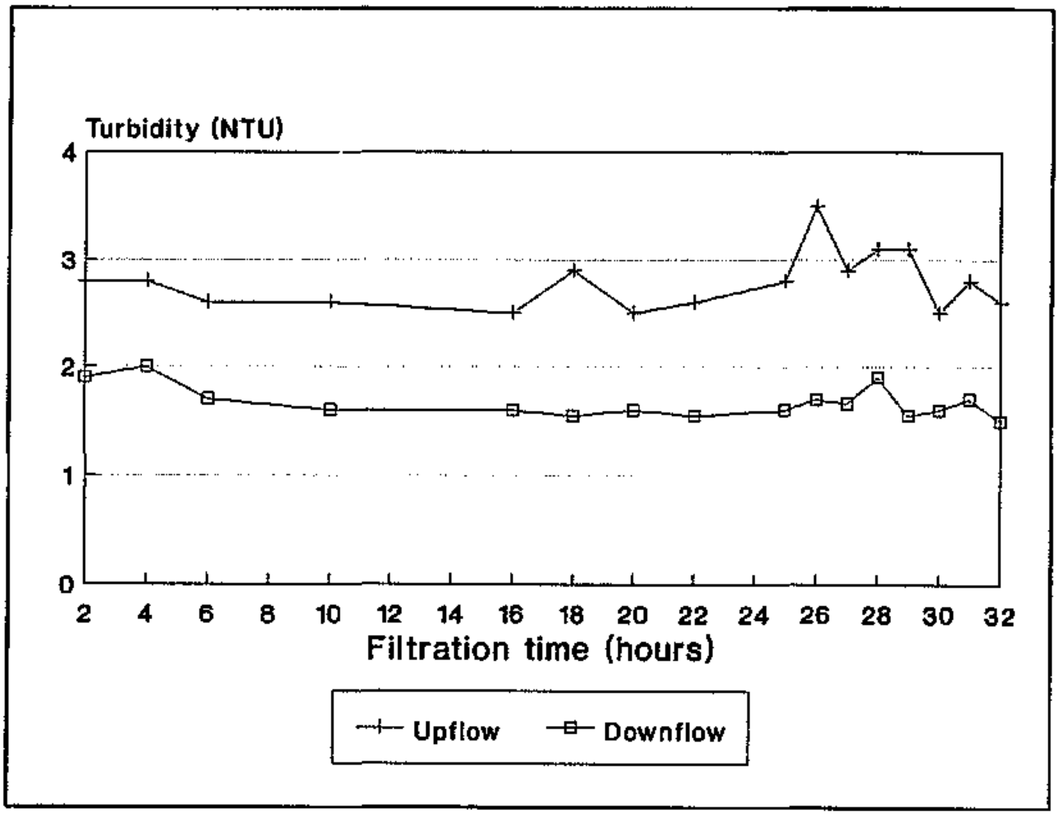


Figure B11 Turbidity removal at Hectorspruit for RUN H30.2: Filtration rate 30 m/h and 1 mg/ℓ LT 22

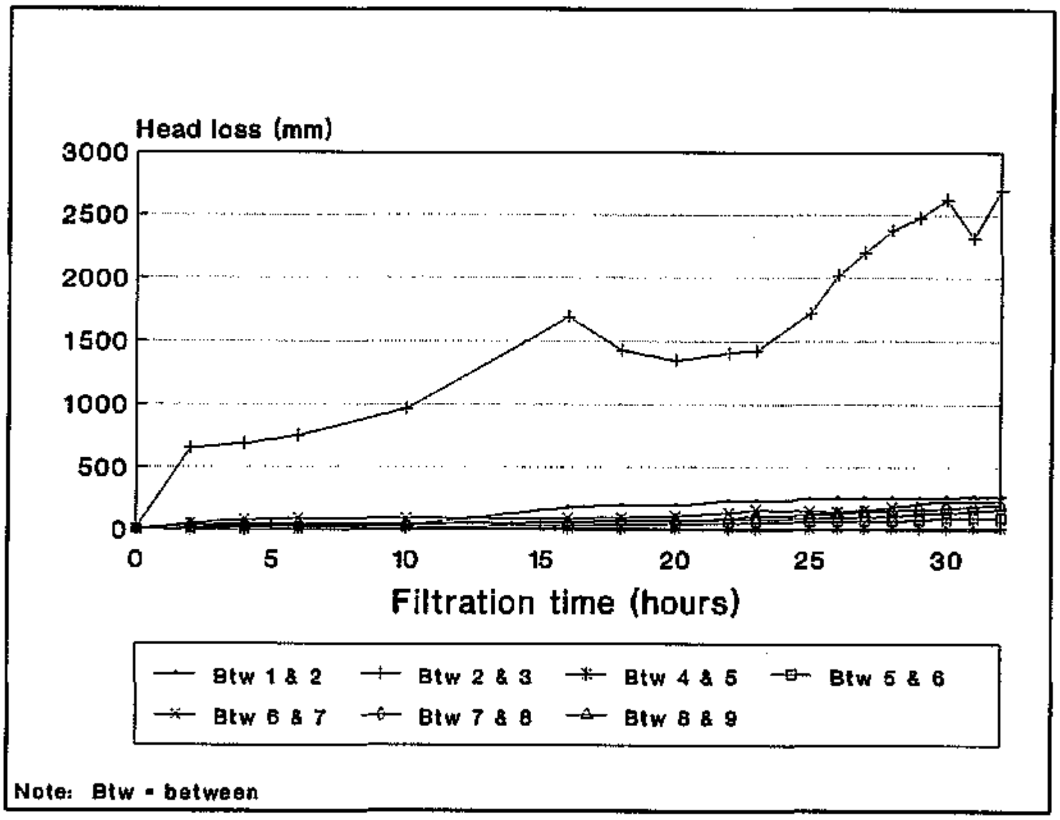


Figure B12 Head loss development in the filter for RUN H30.2: Filtration rate 30 m/h and 1 mg/ℓ LT 22

APPENDIX C

RESULTS OF PILOT-SCALE TESTS ON HIGH TURBIDITY WATER AT VAALKOP WATER TREATMENT WORKS

RUN V5.1: FILTRATION RATE 5 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ LIME

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
2 hours			
Raw	8.33	27	0.19
After upflow	8.12	0.3	0
After downflow	8.17	0.36	0
4 hours			
Raw	-	-	-
After upflow	7.18	0.22	0
After downflow	7.49	0.22	0.01
6 hours			
Raw	7.10	24	0.33
After upflow	7.30	0.26	0
After downflow	7.33	0.26	0.02
8 hours			
Raw	-	-	-
After upflow	7.29	0.26	0
After downflow	7.53	0.23	0
10 hours			
Raw	8.09	28	0.32
After upflow	8.64	1.1	0
After downflow	8.36	0.23	0
12 hours			
Raw	-	-	-
After upflow	8.71	0.8	0
After downflow	8.59	0.58	0
14 hours			
Raw	8.00	36	0.25
After upflow	8.70	0.95	0
After downflow	8.72	0.56	0

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
16 hours			
Raw	-	-	-
After upflow	8.63	0.91	0
After downflow	8.68	0.71	0.01
24 hours			
Raw	7.88	44	0.32
After upflow	8.61	6	0.14
After downflow	8.62	0.58	0
26 hours			
Raw	-	50	-
After upflow	8.63	8.25	0.2
After downflow	8.61	0.55	0

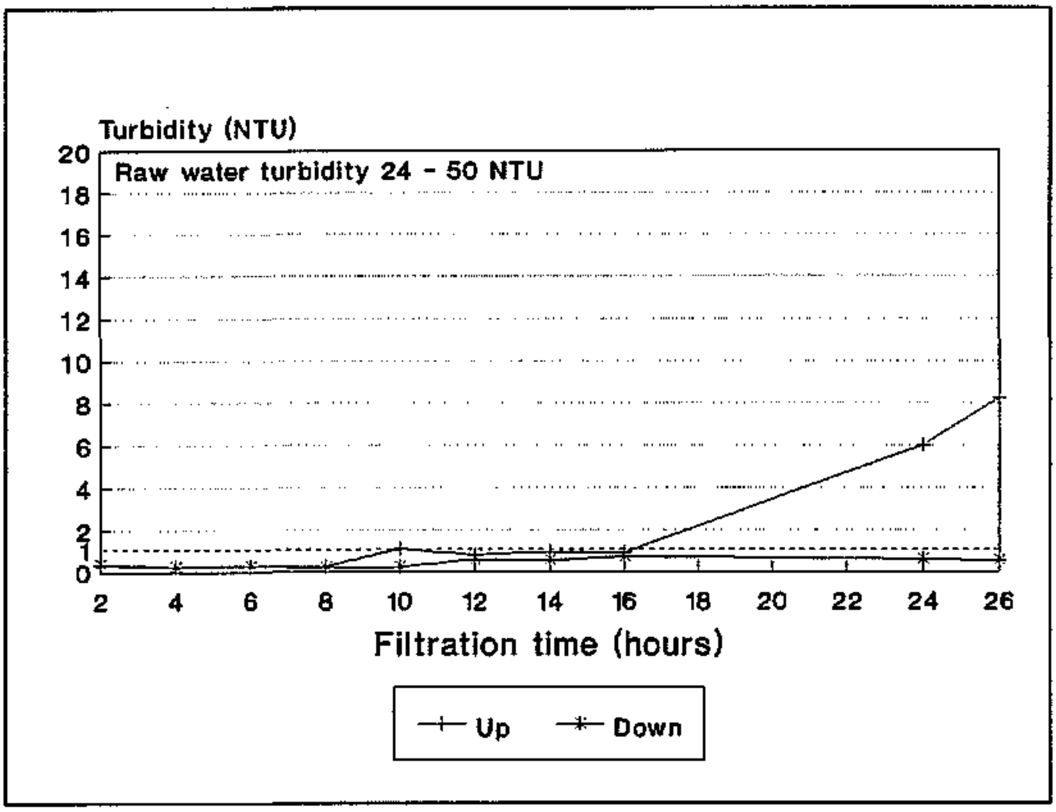


Figure C1 Turbidity removal at Vaalkop for RUN V5.1: Filtration rate 5 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ lime

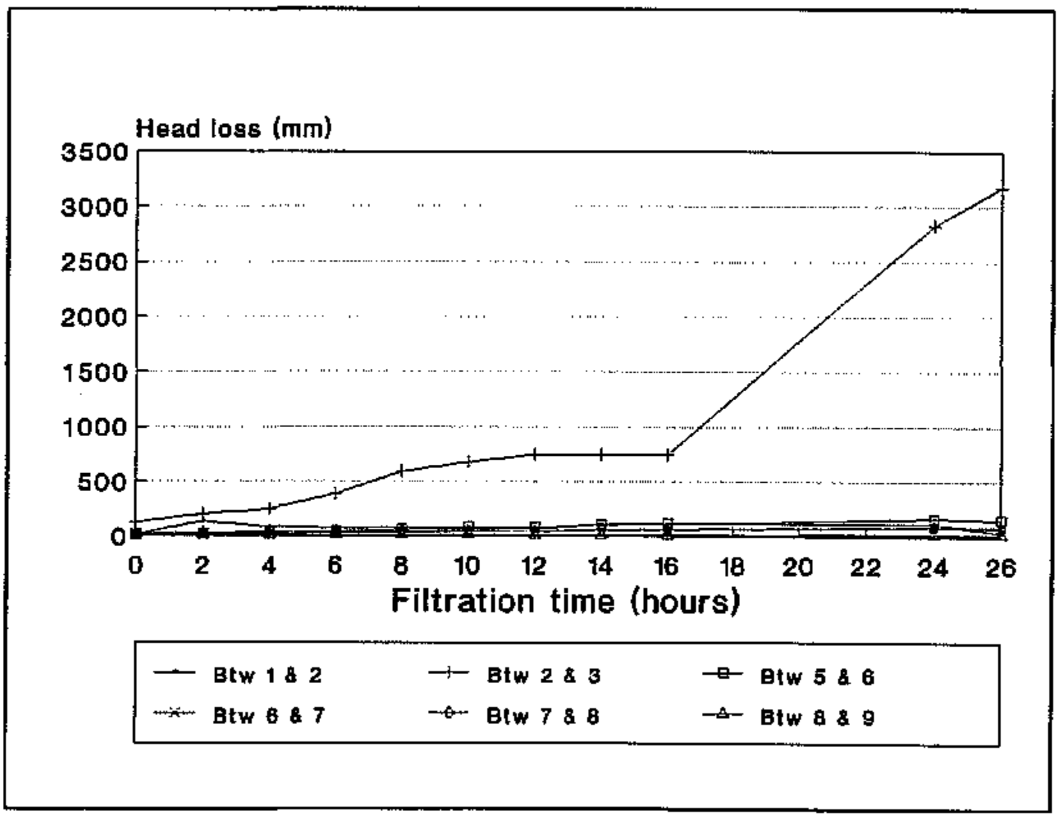


Figure C2 Head loss development in the filter for RUN V5.1: Filtration rate 5 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ lime

RUN V10.1: FILTRATION RATE 10 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ LIME

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
1 hours			
Raw	8.17	38	0.53
After upflow	8.85	2.85	0.02
After downflow	8.67	1.3	0
2 hours			
Raw	8.28	41	0.45
After upflow	8.78	2.65	0.03
After downflow	8.67	1.25	0.02
3 hours			
Raw	8.24	49	0.52
After upflow	8.74	2.3	0.02
After downflow	8.73	1	0.01
4 hours			
Raw	-	-	-
After upflow	8.87	2	0
After downflow	8.84	0.71	0
5 hours			
Raw	-	-	-
After upflow	8.95	1.8	0
After downflow	8.81	0.73	0
6 hours			
Raw	8.03	32	0.29
After upflow	8.82	2.3	0.02
After downflow	8.67	0.33	0.01
7 hours			
Raw	-	-	-
After upflow	8.55	15.5	0.63
After downflow	8.71	0.31	0

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
8.5 hours			
Raw	-	40	-
After upflow	8.61	9.4	0.4
After downflow	8.70	0.38	0.01

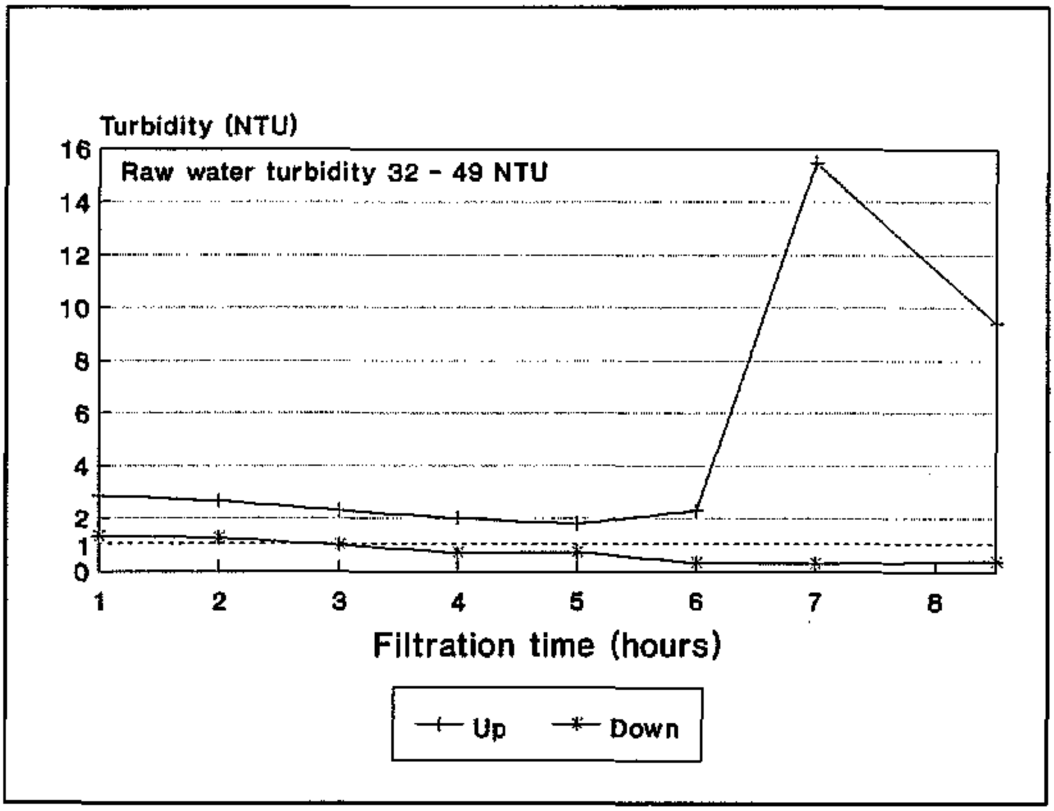


Figure C3 Turbidity removal at Vaalkop for RUN V10.1
Filtration rate 10 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ lime

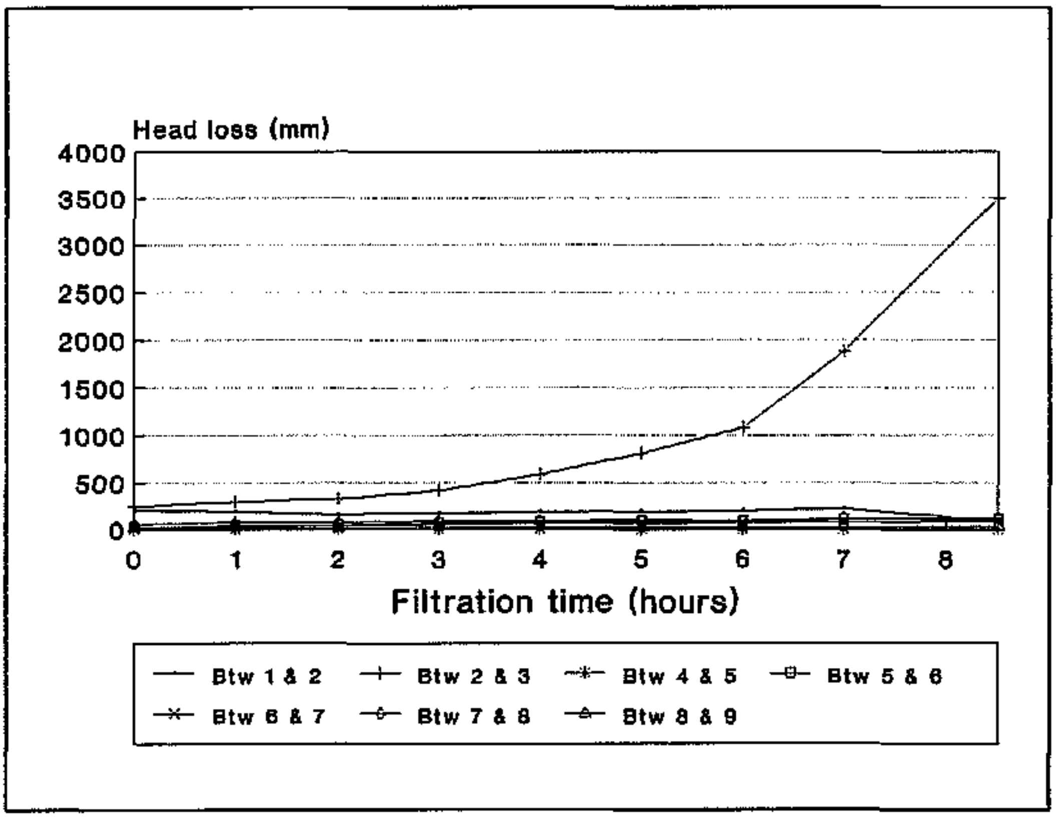


Figure C4 Head loss development in the filter for RUN V10.1:
Filtration rate 10 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ lime

RUN V20.1: FILTRATION RATE 20 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ LIME

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
1 hours			
Raw	8.17	46	-
After upflow	8.81	3.8	0.1
After downflow	8.71	1.3	0.01
1.75 hours			
Raw	8.19	48	0.57
After upflow	8.84	7	0.28
After downflow	8.66	1.95	0.01
2.25 hours			
Raw	8.19	44	0.67
After upflow	8.79	8.1	0.29
After downflow	8.68	1.25	0
2.5 hours			
Raw	-	46	-
After upflow	8.84	8.9	0.32
After downflow	8.67	1.25	0.01

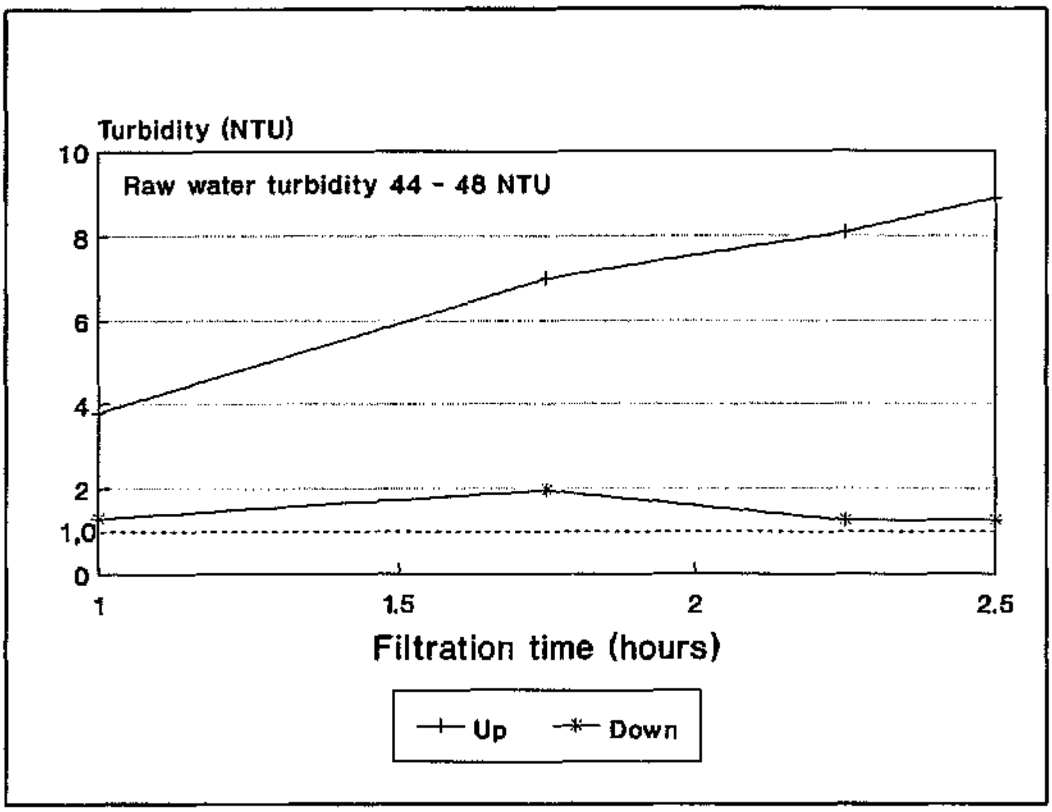


Figure C5 Turbidity removal at Vaalkop for RUN V20.1: Filtration rate 20 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ lime

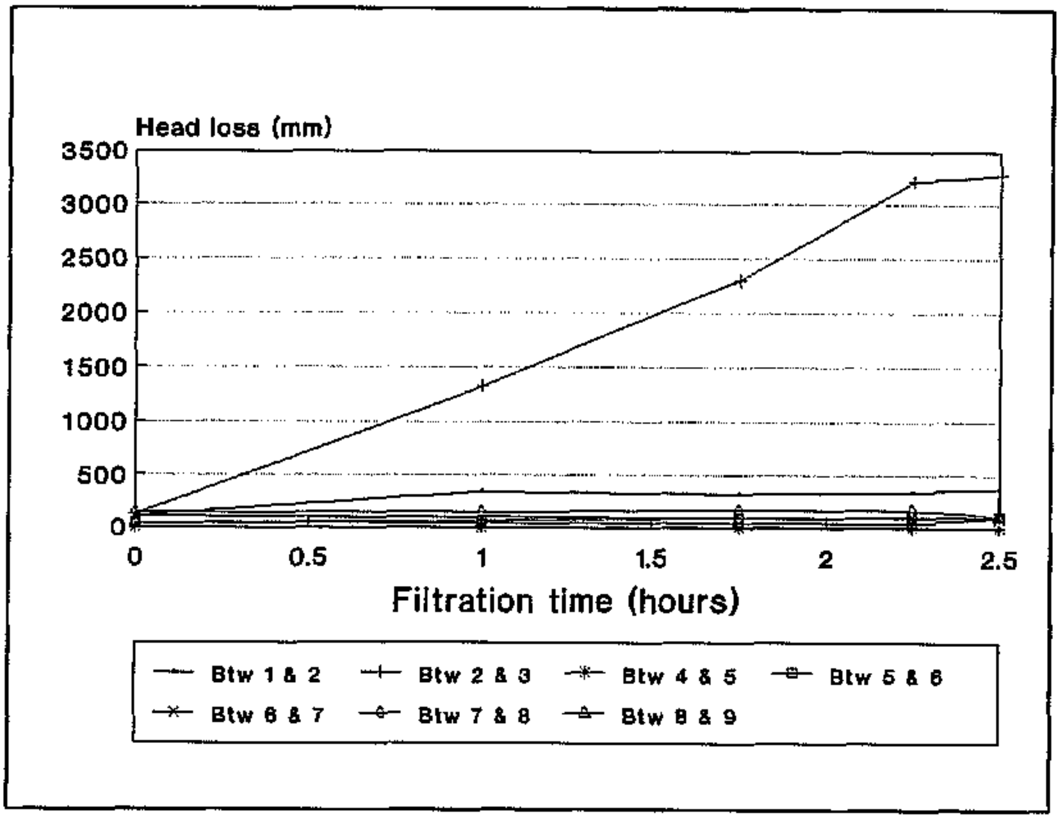


Figure C6 Head loss development in the filter for RUN V20.1: Filtration rate 20 m/h, 7,5 mg/ℓ $FeCℓ_3$ and 15 mg/ℓ lime

RUN V5.2: FILTRATION RATE 5 m/h and 40 mg/ℓ ALUM

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
3 hours			
Raw	8.55	45	-
After upflow	7.78	2.25	-
After downflow	7.68	1.5	-
6 hours			
Raw	-	31	0.17
After upflow	7.18	0.85	0.2
After downflow	7.13	0.68	0.18
9 hours			
Raw	8.42	49.5	0.22
After upflow	7.82	1.8	0.2
After downflow	7.82	0.96	0.18
13 hours			
Raw	8.50	44.5	0.2
After upflow	7.74	1.3	0.18
After downflow	7.74	0.79	0.2
20 hours			
Raw	8.47	46	0.12
After upflow	7.62	8.4	0.18
After downflow	7.57	0.52	0.21
24 hours			
Raw	7.02	30	0.17
After upflow	7.19	2.7	0.2
After downflow	7.07	0.56	0.26
26 hours			
Raw	7.06	30.5	0.19
After upflow	7.52	0.51	0.22
After downflow	7.26	0.22	0.22

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
29 hours			
Raw	6.80	20	0.19
After upflow	7.35	0.38	0.16
After downflow	7.20	0.2	0.17

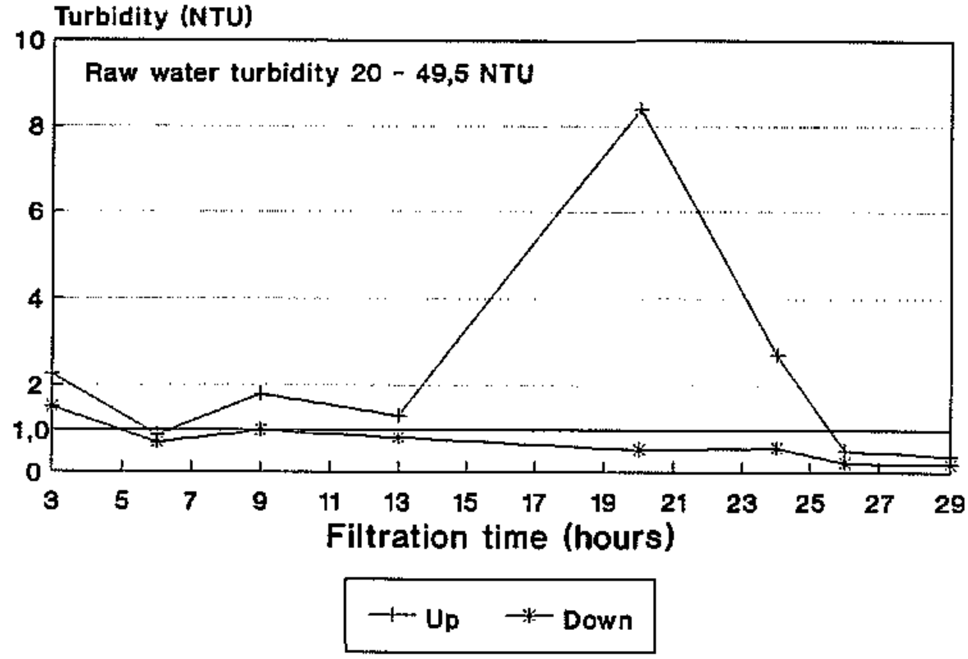


Figure C7 Turbidity removal at Vaalkop for RUN V5.2: Filtration rate 5 m/h and 40 mg/ℓ alum

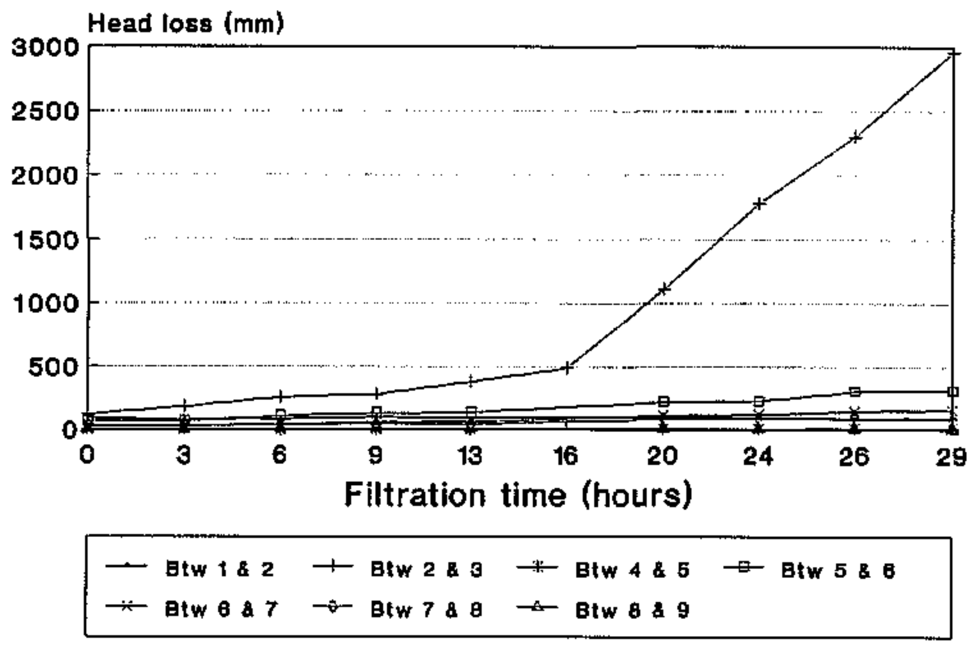


Figure C8 Head loss development in the filter for RUN V5.2: Filtration rate 5 m/h and 40 mg/ℓ alum

RUN V10.2: FILTRATION RATE 10 m/h and 40 mg/ℓ ALUM

Sample	pH	Turbidit (NTU)	Aℓ (mg/ℓ)
1 hours			
Raw	7.11	70	0.17
After upflow	6.91	0.35	0.16
After downflow	7.62	0.29	0.16
2 hours			
Raw	-	45	-
After upflow	7.30	0.44	0.18
After downflow	7.19	0.22	0.18
4 hours			
Raw	7.08	30.5	0.21
After upflow	6.96	30	0.66
After downflow	7.23	0.36	0.2
5 hours			
Raw	-	44	-
After upflow	7.18	42	0.39
After downflow	7.46	0.32	0.16
6 hours			
Raw	7.77	42.5	0.19
After upflow	7.44	42	0.37
After downflow	7.80	0.32	0.22
7.5 hours			
Raw	7.38	37.5	0.18
After upflow	7.31	36	0.37
After downflow	7.46	0.28	0.23

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
29 hours			
Raw	6.80	20	0.19
After upflow	7.35	0.38	0.16
After downflow	7.20	0.2	0.17

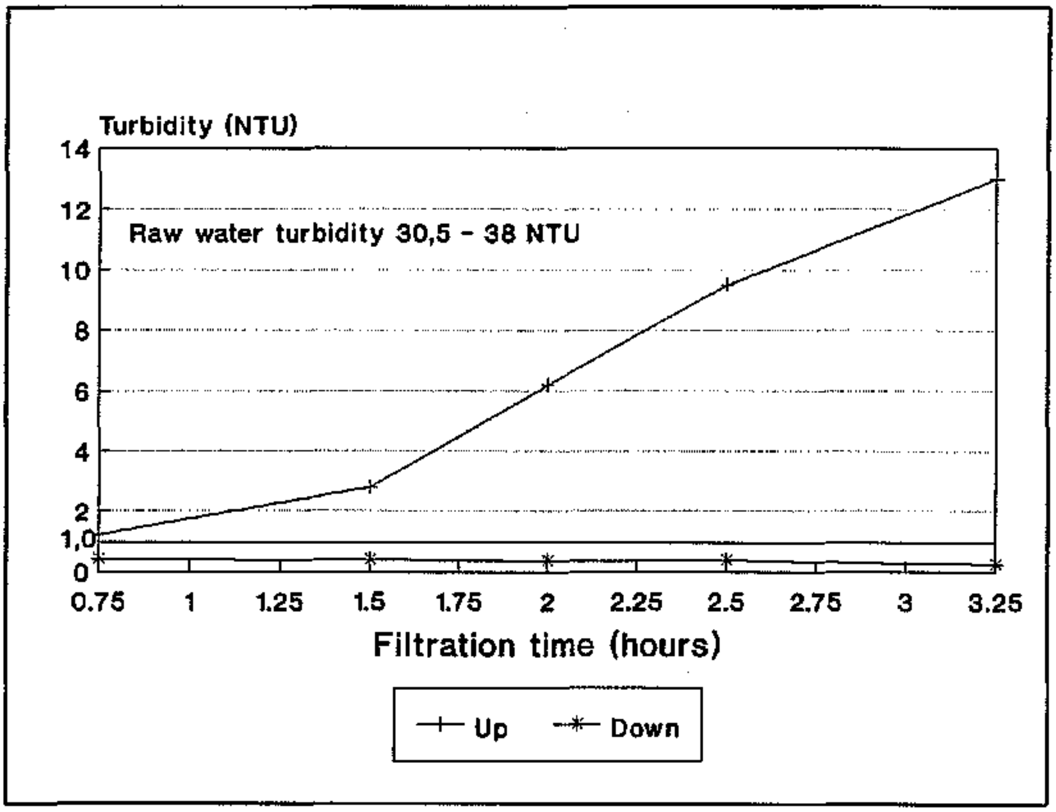


Figure C11 Turbidity removal at Vaalkop for RUN V20.2: Filtration rate 20 m/h and 45 mg/ℓ alum

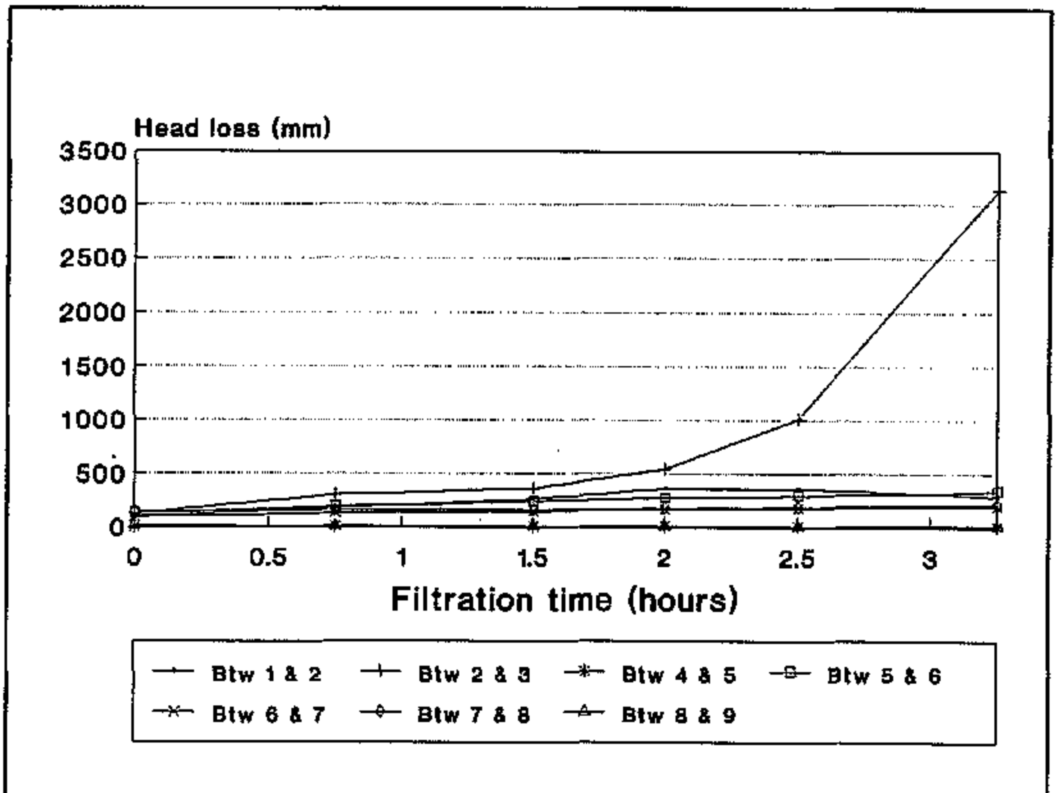


Figure C12 Head loss development in the filter for RUN V20.2: Filtration rate 20 m/h and 45 mg/ℓ alum

RUN V5.3: FILTRATION RATE 5 m/h and 5 mg/ℓ ULTRAFLOC

Sample	pH	Turbidity (NTU)
2.5 hours		
Raw	7.13	69
After upflow	7.36	0.26
After downflow	7.48	0.16
5 hours		
Raw	6.98	72
After upflow	7.49	0.19
After downflow	7.56	0.14
8 hours		
Raw	8.15	78
After upflow	9.02	0.23
After downflow	9.06	0.18
10 hours		
Raw	-	83
After upflow	8.76	1.8
After downflow	8.79	0.68
13 hours		
Raw	8.06	93
After upflow	8.75	1
After downflow	8.74	0.4
15 hours		
Raw	8.04	96
After upflow	8.85	17
After downflow	8.79	0.32
17 hours		
Raw	8.04	83
After upflow	8.65	21.5
After downflow	8.65	0.33

Sample	pH	Turbidity (NTU)
20 hours		
Raw	8.15	100
After upflow	8.65	48.5
After downflow	8.62	0.31
24 hours		
Raw	-	116
After upflow	8.74	62.5
After downflow	8.74	0.36

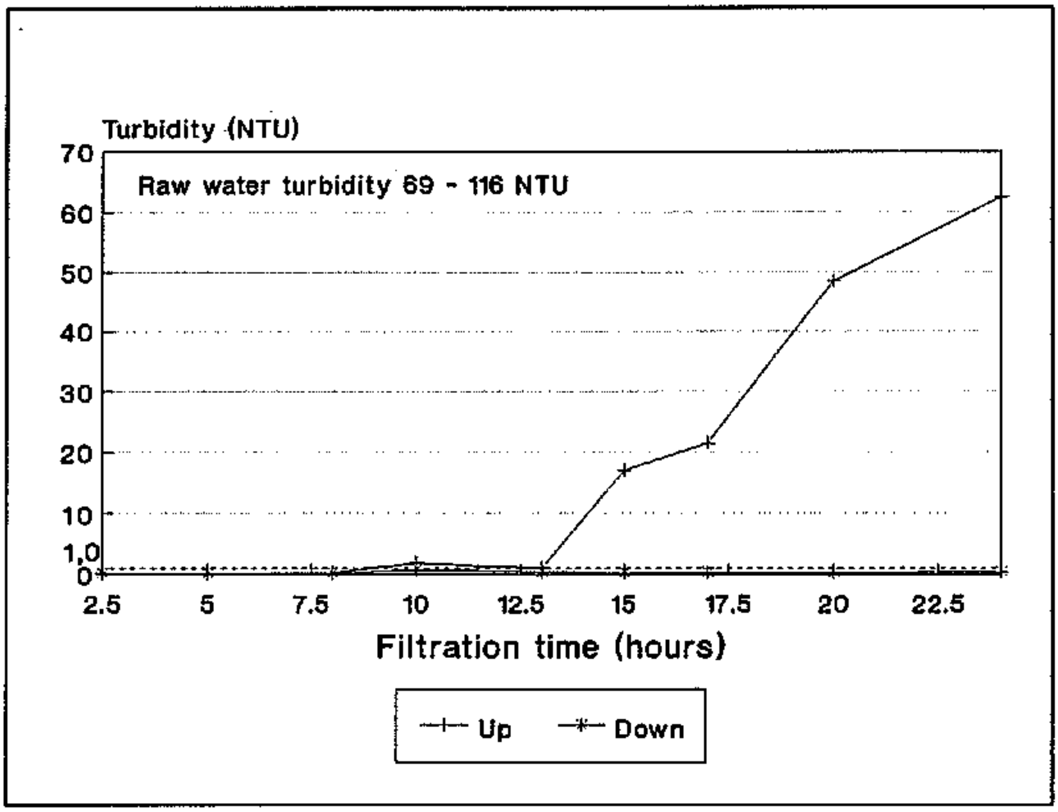


Figure C13 Turbidity removal at Vaalkop for RUN V5.3: Filtration rate 5 m/h and 6 mg/ℓ Ultrafloc

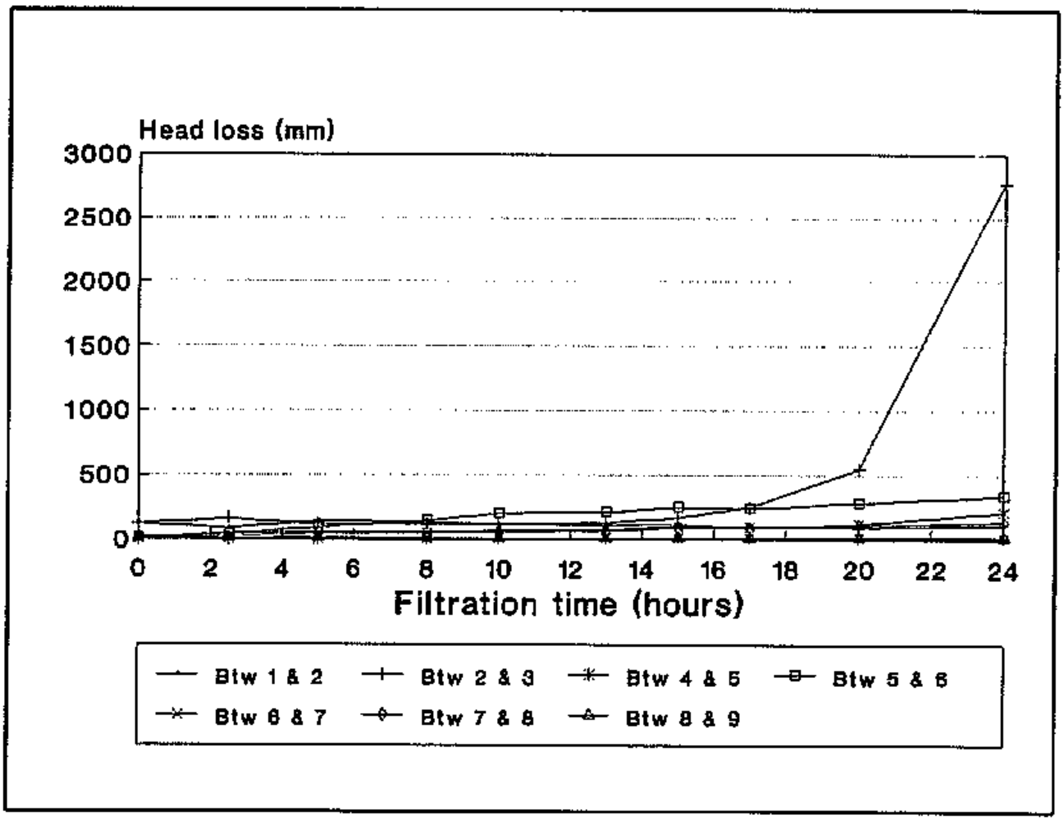


Figure C14 Head loss development in the filter for RUN V5.3: Filtration rate 5 m/h and 6 mg/ℓ Ultrafloc

RUN V10.3: FILTRATION RATE 10 mg/ℓ and 10 mg/ℓ ULTRAFLOC

Sample	pH	Turbidity (NTU)
1 hour		
Raw	6.89	27
After upflow	7.49	0.39
After downflow	7.47	0.19
2 hours		
Raw	-	30
After upflow	7.58	0.28
After downflow	7.59	0.17
3 hours		
Raw	6.94	33
After upflow	7.43	0.26
After downflow	7.59	0.21
4 hours		
Raw	-	44
After upflow	7.48	0.24
After downflow	7.52	0.18
5 hours		
Raw	6.83	32
After upflow	6.88	0.24
After downflow	7.42	0.18
6.5 hours		
Raw	-	32
After upflow	7.56	0.22
After downflow	7.58	0.19
8 hours		
Raw	6.77	31.5
After upflow	7.58	0.22
After downflow	7.49	0.16

Sample	pH	Turbidity (NTU)
8.75 hours		
Raw	-	31.5
After upflow	7.53	0.21
After downflow	7.48	0.16

RUN V20.3: FILTRATION RATE 20 mg/ℓ and 10 mg/ℓ ULTRAFLOC

Sample	pH	Turbidity (NTU)
0.5 hour		
Raw	8.12	120
After upflow	9.10	23
After downflow	9.10	0.42
1 hour		
Raw	8.12	110
After upflow	9.14	9.25
After downflow	9.14	0.3
1.25 hours		
Raw	-	100
After upflow	9.09	18
After downflow	9.11	0.3
1.75 hours		
Raw	8.19	87
After upflow	9.12	30
After downflow	9.12	0.25

RUN V5.4: FILTRATION RATE 5 m/h, 10,5 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
2 hours			
Raw	6.93	26	0.22
After upflow	7.25	1.25	0
After downflow	7.25	0.83	0
5 hours			
Raw	6.91	31	0.26
After upflow	7.28	0.59	0.02
After downflow	7.41	0.43	0.01
8 hours			
Raw	6.99	36	0.34
After upflow	7.23	0.73	0.02
After downflow	7.29	0.61	0
11 hours			
Raw	7.12	33	0.38
After upflow	7.03	0.63	0.01
After downflow	7.28	0.52	0
17 hours			
Raw	6.99	32.5	0.2
After upflow	7.25	0.48	0
After downflow	7.31	0.47	0
20 hours			
Raw	6.89	27	0.52
After upflow	7.36	0.45	0.04
After downflow	7.39	0.49	0.01
23 hours			
Raw	6.84	33	0.61
After upflow	6.97	0.27	0.02
After downflow	7.38	0.61	0.01

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
25 hours			
Raw	6.96	28	0.33
After upflow	7.19	0.77	0
After downflow	7.30	0.68	0

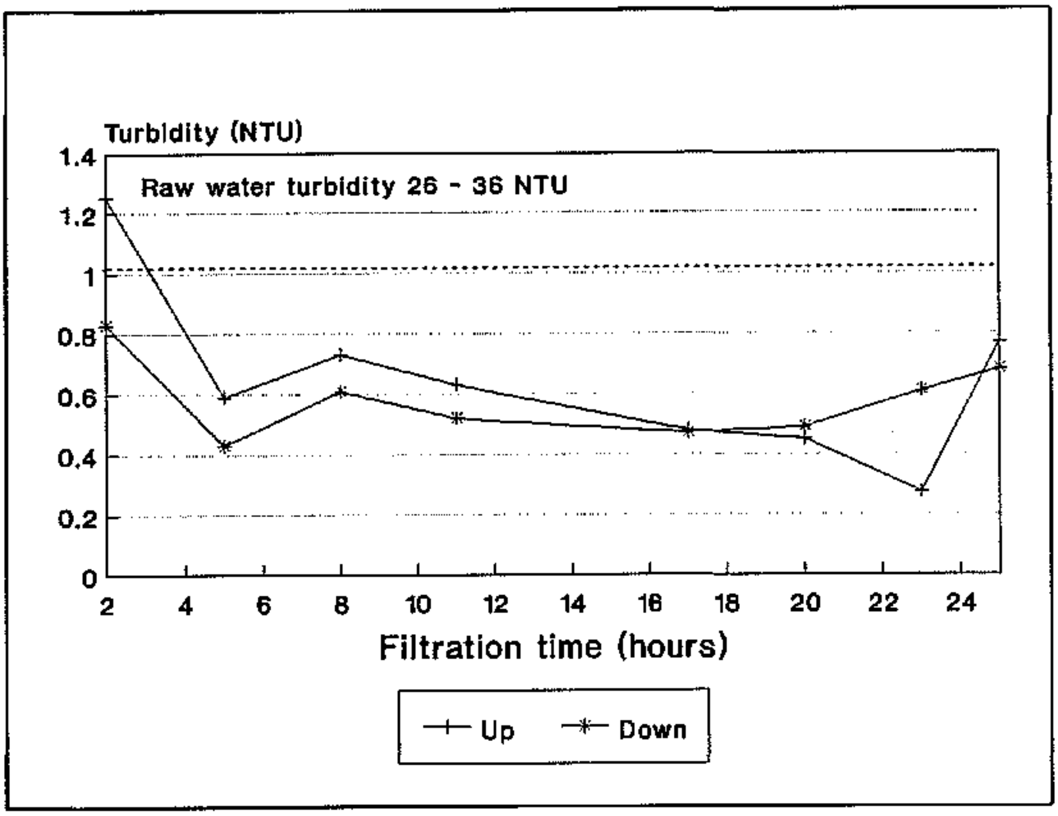


Figure C15 Turbidity removal at Vaalkop for RUN V5.4: Filtration rate 5 m/h, 10,5 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

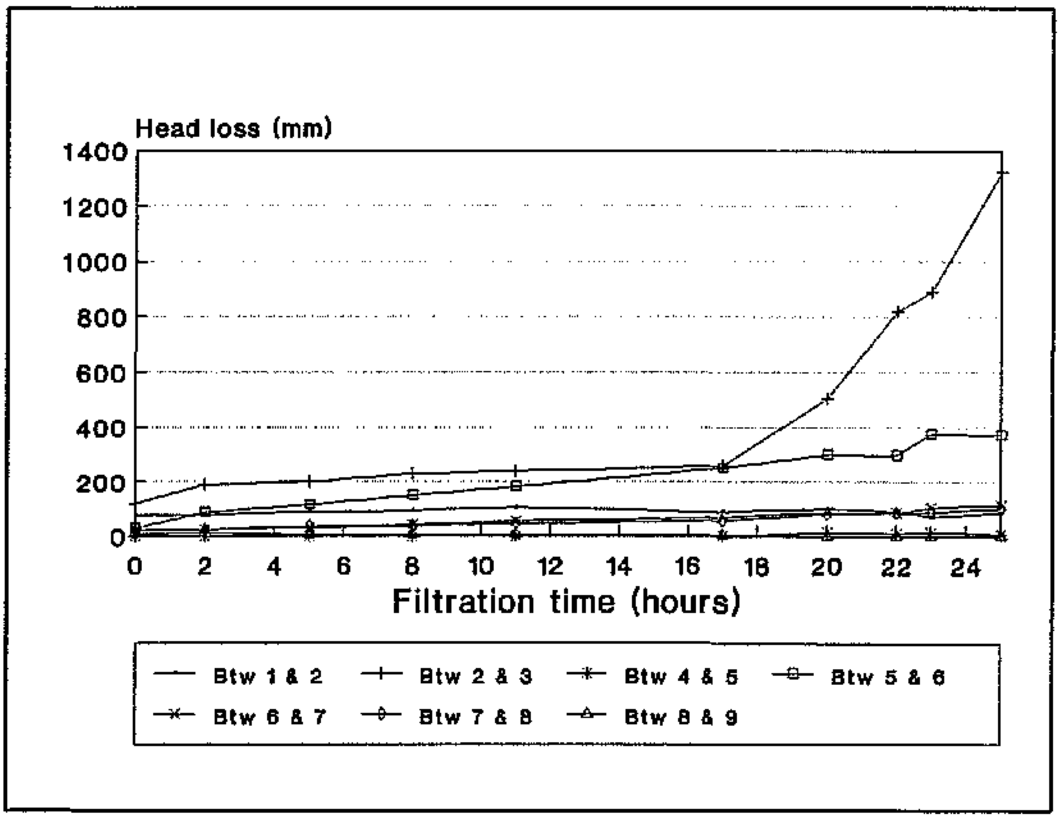


Figure C16 Head loss development in the filter for RUN V5.4: Filtration rate 5 m/h, 10,5 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

RUN V10.4: FILTRATION RATE 10 m/h, 7,8 mg/ℓ $FeC\ell_3$ and 0,5 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
1 hour			
Raw	8.12	75	0.79
After upflow	8.89	2.4	0
After downflow	8.85	0.88	0
2 hours			
Raw	8.34	78	-
After upflow	8.34	2.2	0
After downflow	8.84	0.75	0.01
3 hours			
Raw	8.35	85	0.58
After upflow	8.89	1.8	0.01
After downflow	8.87	0.67	0.01
4 hours			
Raw	-	95	-
After upflow	8.89	1.8	0
After downflow	8.86	0.68	0.01
5 hours			
Raw	8.29	120	1.4
After upflow	7.28	0.52	0
After downflow	7.33	0.39	0
6 hours			
Raw	-	1.5	-
After upflow	7.39	0.24	0
After downflow	7.08	0.28	0
7 hours			
Raw	7.10	64	0.87
After upflow	7.68	0.24	0
After downflow	7.61	0.2	0

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
8.5 hours			
Raw	-	65	-
After upflow	7.17	0.26	0
After downflow	7.32	0.16	0

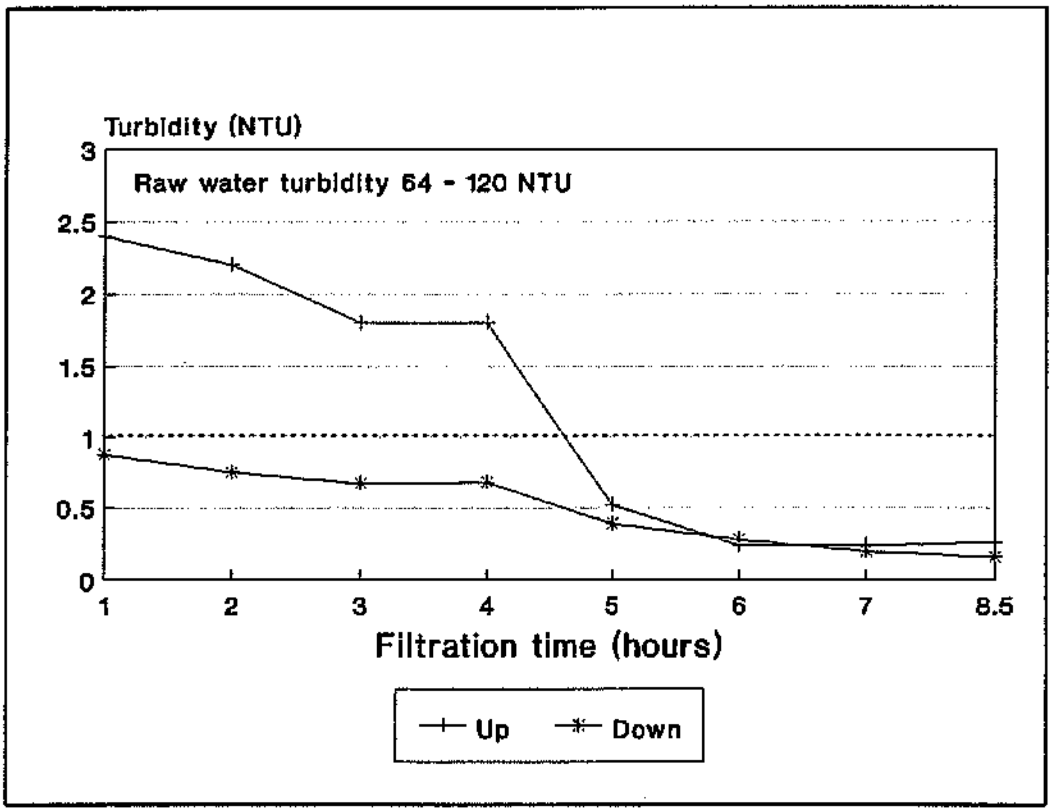


Figure C17 Turbidity removal at Vaalkop for RUN V10.4: Filtration rate 10 m/h, 7,8 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

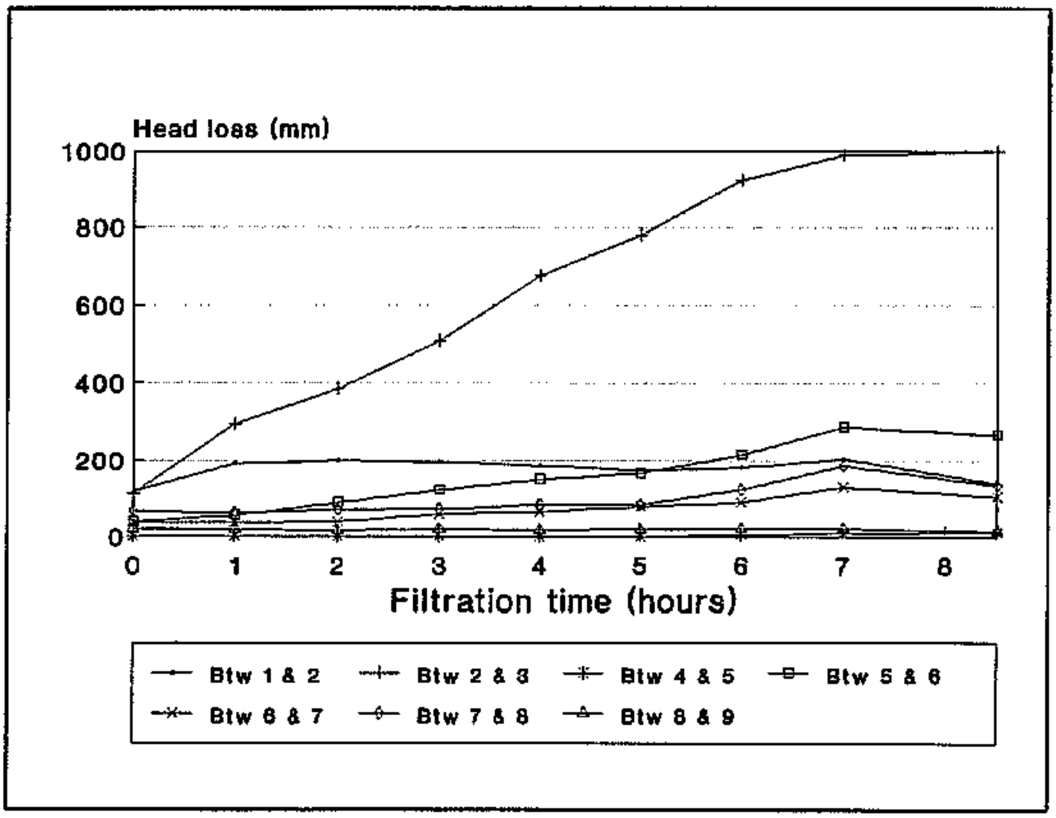


Figure C18 Head loss development in the filter for RUN V10.4: Filtration rate 10 m/h, 7,8 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

RUN V20.4: FILTRATION RATE 20 m/h, 7,6 mg/ℓ $FeC\ell_3$ and 0,5 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Fe (mg/ℓ)
0.75 hours			
Raw	8.10	84	0.91
After upflow	8.68	4.4	0.02
After downflow	8.66	1.5	0.01
1.5 hours			
Raw	-	81	-
After upflow	8.88	12.5	0.2
After downflow	8.80	0.8	0.01
2.25 hours			
Raw	8.11	74	0.67
After upflow	8.89	5.6	0.01
After downflow	8.86	0.57	0

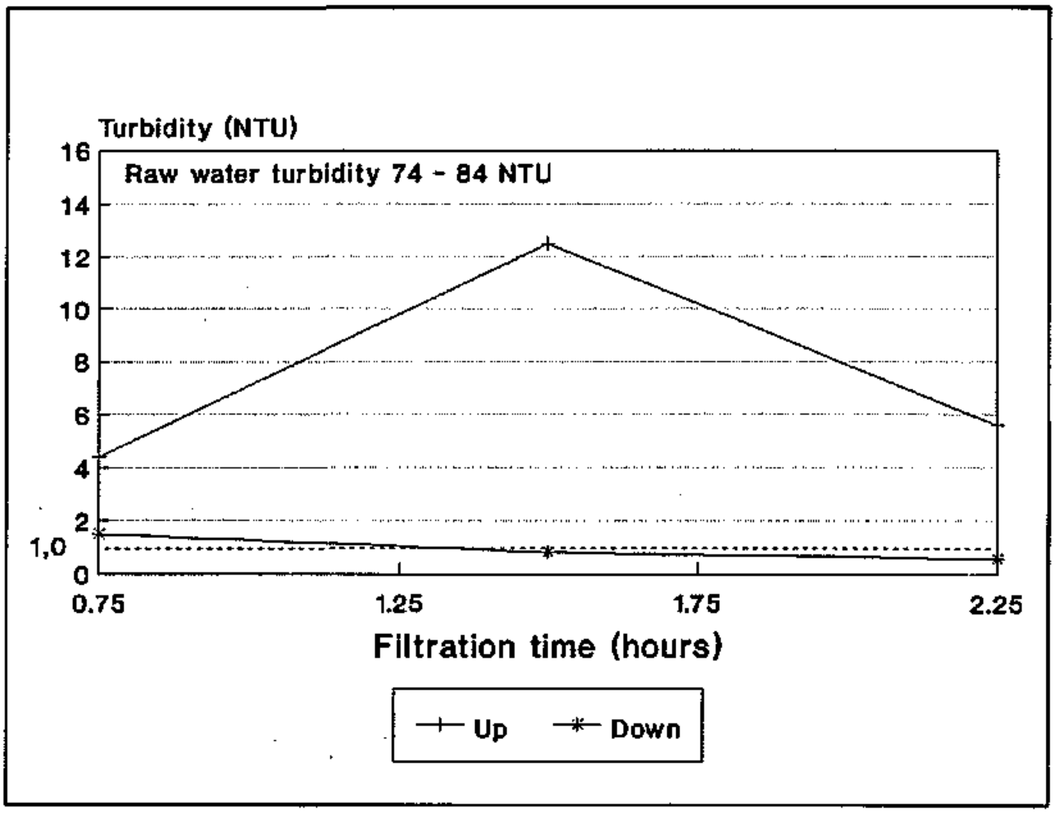


Figure C19 Turbidity removal at Vaalkop for RUN V20.4: Filtration rate 20 m/h, 7,6 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

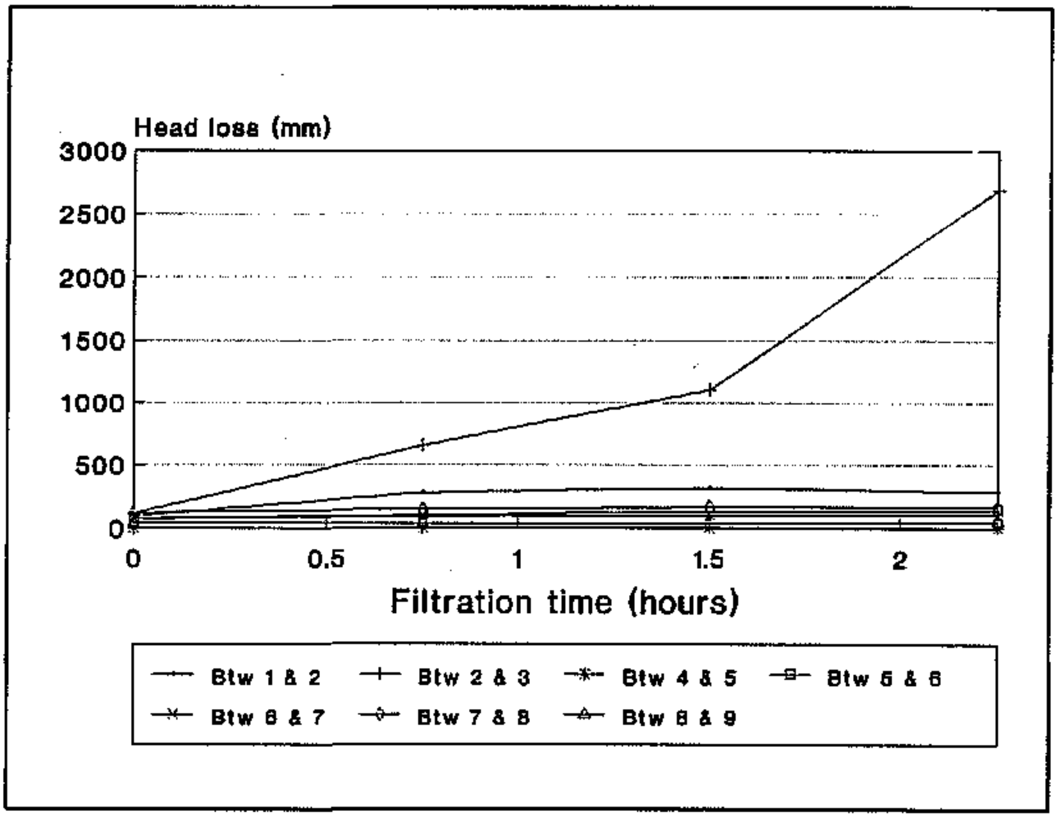


Figure C20 Head loss development in the filter for RUN V20.4): Filtration rate 20 m/h, 7,6 mg/ℓ $FeCℓ_3$ and 0,5 mg/ℓ LT 22

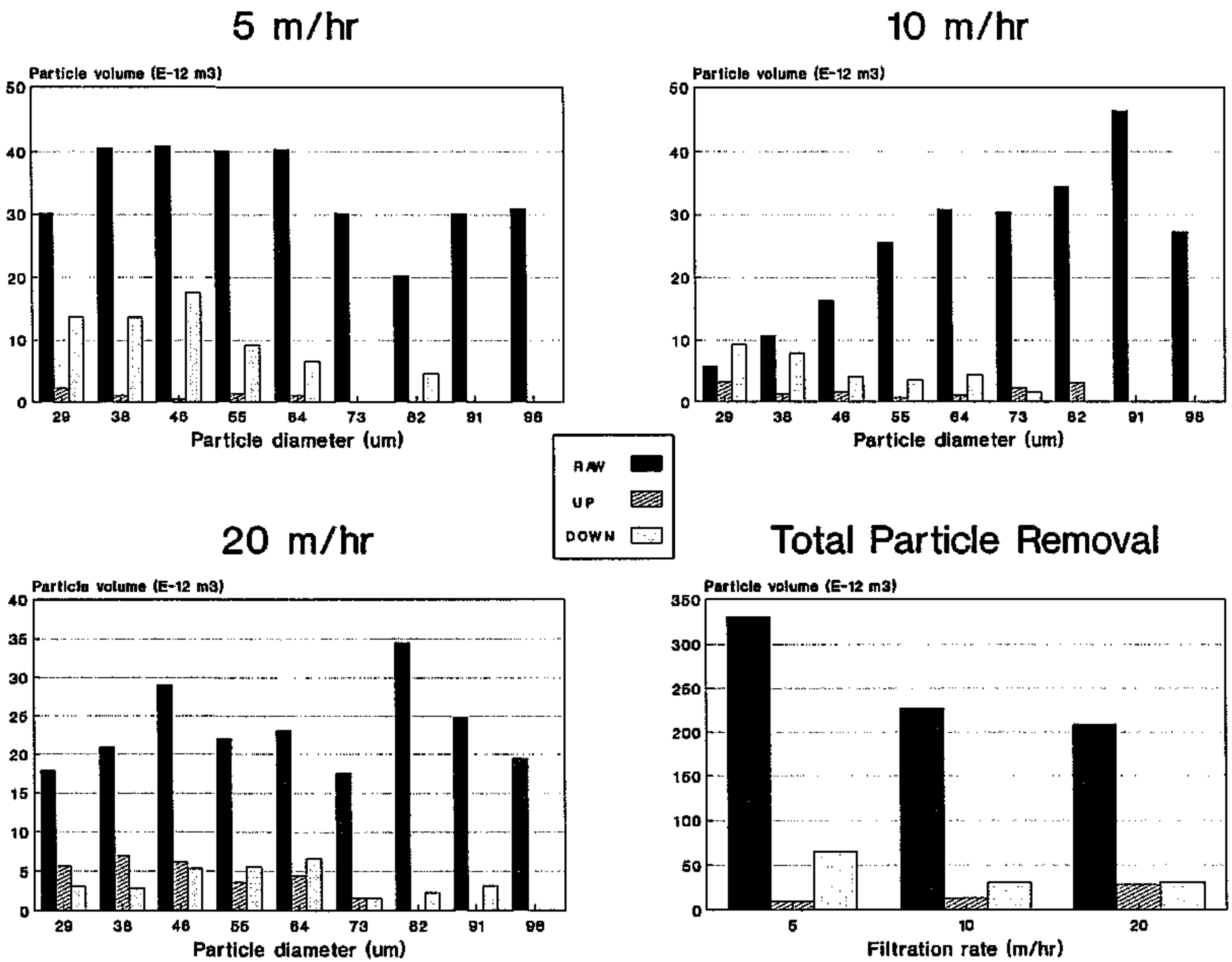


Figure C21 Particle removal in the series filtration system at different filtration rates for high turbidity water from the Vaalkop Dam

APPENDIX D

RESULTS OF PILOT-SCALE TESTS ON EUTROPHIC WATER AT ROODEPLAAT DAM

RUN R5.1: FILTRATION RATE 5 m/h and 35 mg/ℓ ALUM

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
1.5 hours				
Raw	7.44	5.8	34.5	0.17
After upflow	7.15	1.2	11.8	0.19
After downflow	7.21	0.34	7.4	0.17
3 hours				
Raw	7.32	58	31.8	0.16
After upflow	7.31	1.3	12.9	0.16
After downflow	7.19	0.26	4.7	0.17
4.5 hours				
Raw	7.42	5.5	4.33	0.17
After upflow	7.31	1.5	2.11	0.22
After downflow	7.12	0.46	0.96	0.18
6 hours				
Raw	7.56	5.3	7.45	0.15
After upflow	7.34	2.3	5.06	0.36
After downflow	7.14	0.43	1.79	0.18
7.5 hours				
Raw	7.24	5.1	7.1	0.18
After upflow	7.24	1.4	2.08	0.38
After downflow	7.21	0.81	0.62	0.20
9 hours				
Raw	7.34	5.25	7.97	0.18
After upflow	7.14	1.1	1.66	0.21
After downflow	7.14	0.47	2.13	0.18
10 hours				
Raw	7.12	5.7	5.84	0.15
After upflow	7.11	0.9	1.78	0.27
After downflow	7.07	0.44	0.37	0.26

Sample	pH	Turbidity (NTU)	Chlorophyll *a* ($\mu g/\ell$)	Al (mg/ℓ)
12 hours				
Raw	7.13	4.6	10.13	0.17
After upflow	7.11	1.1	4.01	0.20
After downflow	7.10	0.42	3.09	0.21
14 hours				
Raw	7.12	6.1	8.34	0.64
After upflow	7.08	3.15	7.91	0.79
After downflow	7.13	0.72	5.5	0.73
16 hours				
Raw	7.12	6.8	8.04	0.83
After upflow	7.56	1.5	5.5	1.03
After downflow	7.63	0.74	5.05	0.99
18 hours				
Raw	7.33	5.5	13.4	0.69
After upflow	7.22	1.1	7.15	0.74
After downflow	7.20	0.48	7.46	0.52
20 hours				
Raw	7.47	5.4	12.03	0.63
After upflow	7.22	1.3	6.3	0.73
After downflow	7.08	1.2	4.48	0.20

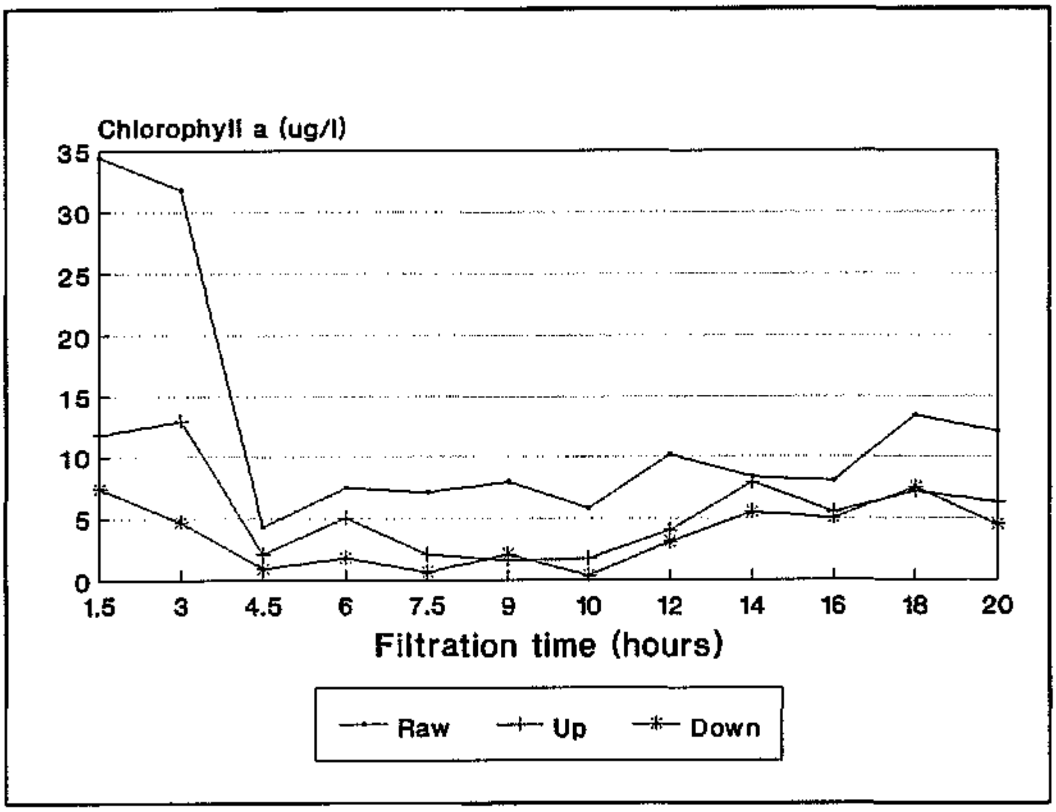


Figure D1 Algae removal at Roodeplaat Dam for RUN R5.1: Filtration rate 5 m/h and 35 mg/ℓ alum

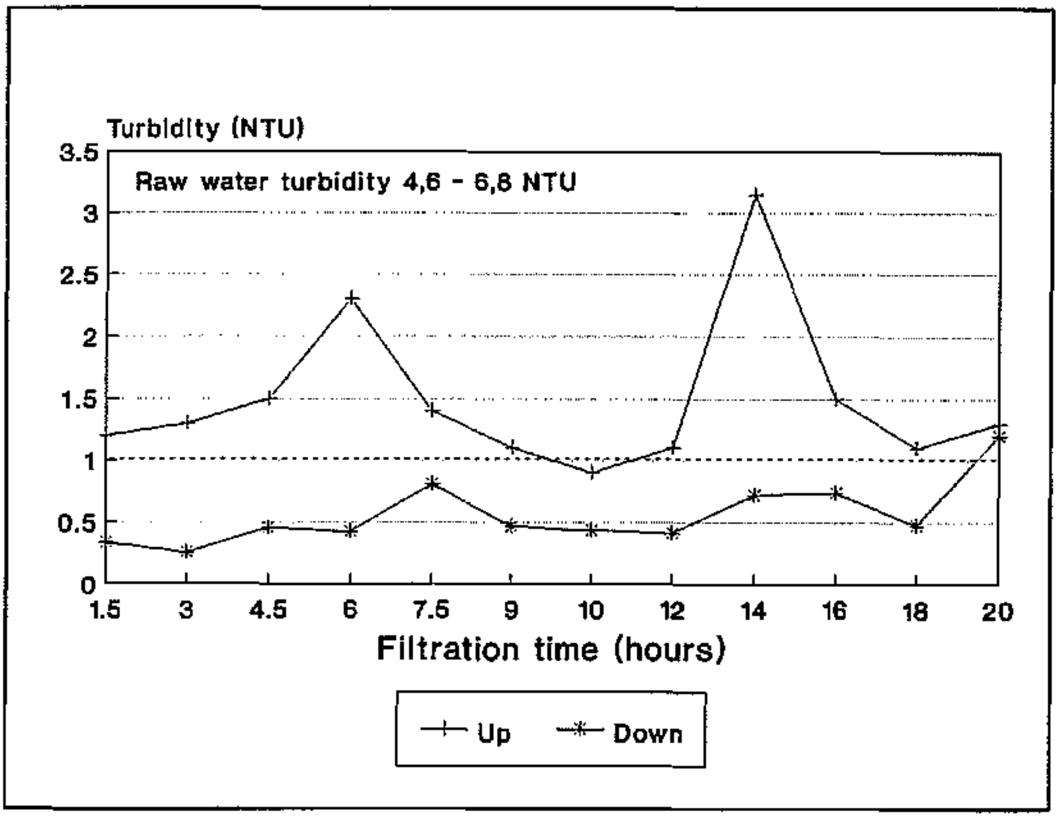


Figure D2 Turbidity removal at Roodeplaat Dam for RUN R5.1: Filtration rate 5 m/h and 35 mg/ℓ alum

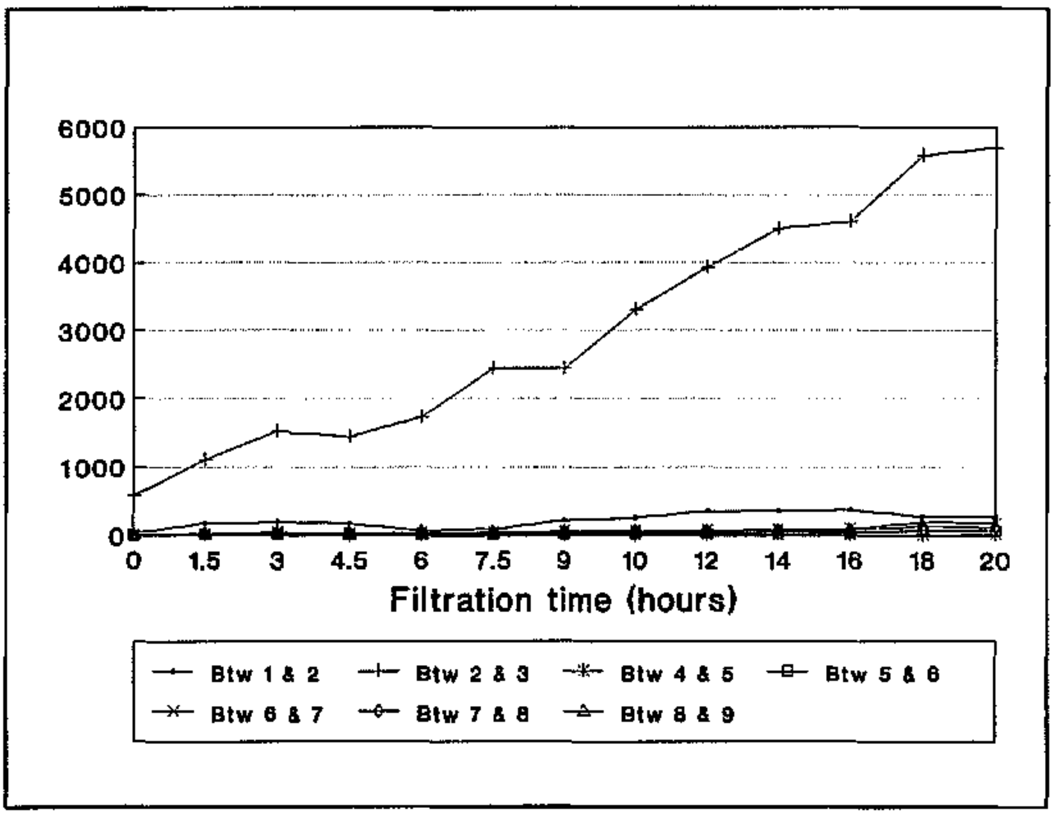


Figure D3 **Head loss development in the filter for RUN 5.1: Filtration rate 5 m/h and 35 mg/ℓ alum**

RUN R10.1: FILTRATION RATE 10 m/h and 30 mg/ℓ ALUM

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
hours				
Raw	7.82	6.1	10	0
After upflow	7.96	5.3	4	0.03
After downflow	7.96	3.4	0.8	0.13
hours0.8				
Raw	8.03	10	9	0.25
After upflow	7.98	2.6	4	0.26
After downflow	8.03	2.1	0.7	0.18
hours				
Raw	7.86	15	5	0.65
After upflow	8.03	3.5	3	0.39
After downflow	8.02	2.2	0.5	0.13
hours				
Raw	7.77	10	12	0.53
After upflow	7.90	1.8	7.16	0.24
After downflow	7.79	0.59	0.8	0.11
hours				
Raw	7.91	12	32.3	0.29
After upflow	7.86	3.25	15.8	0.19
After downflow	7.87	2	8.5	0.09
hours				
Raw	7.84	15	1.26	0.91
After upflow	7.77	2.25	0.83	0.37
After downflow	7.79	0.59	0.83	0.09
hours				
Raw	7.71	9.6	2.98	0.63
After upflow	7.56	1.9	1.6	0.30
After downflow	7.59	0.46	0	0.10

Sample	pH	Turbidity (NTU)	Chlorophyll *a* ($\mu g/\ell$)	Al (mg/ℓ)
8 hours				
Raw	7.73	12	2.5	0.38
After upflow	7.57	1.8	0.75	0.33
After downflow	7.57	0.48	0.75	0.07
9 hours				
Raw	7.86	14	3.32	0.39
After upflow	7.51	22.4	0.83	0.26
After downflow	7.52	0.45	0	0.08

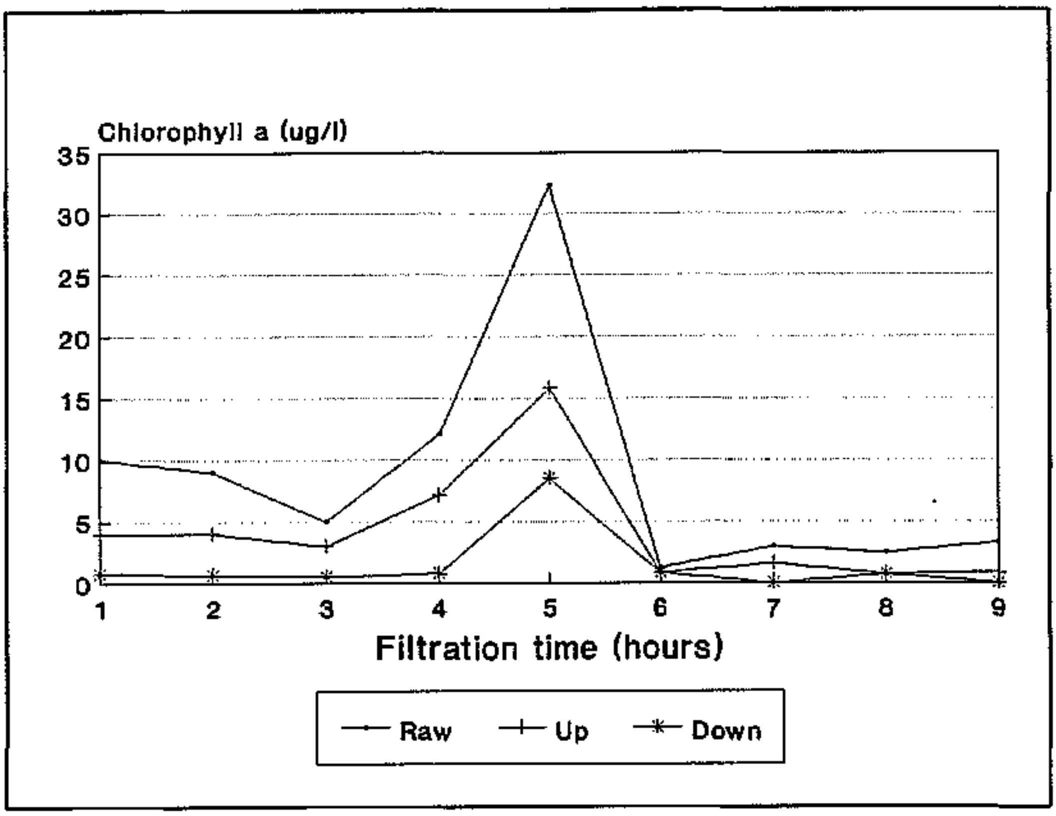


Figure D4 Algae removal at Roodeplaat Dam for RUN R10.1: Filtration rate 10 m/h and 30 mg/ℓ alum

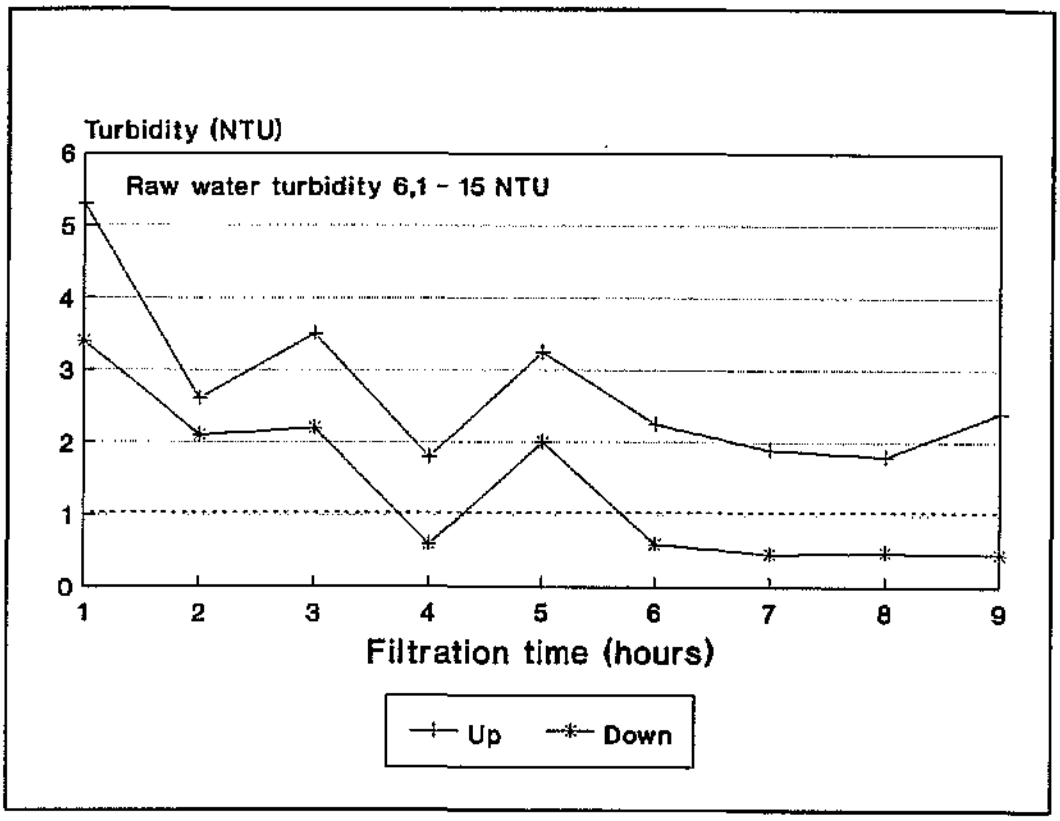


Figure D5 Turbidity removal at Roodeplaat Dam for RUN R10.1: Filtration rate 10 m/h and 30 mg/ℓ alum

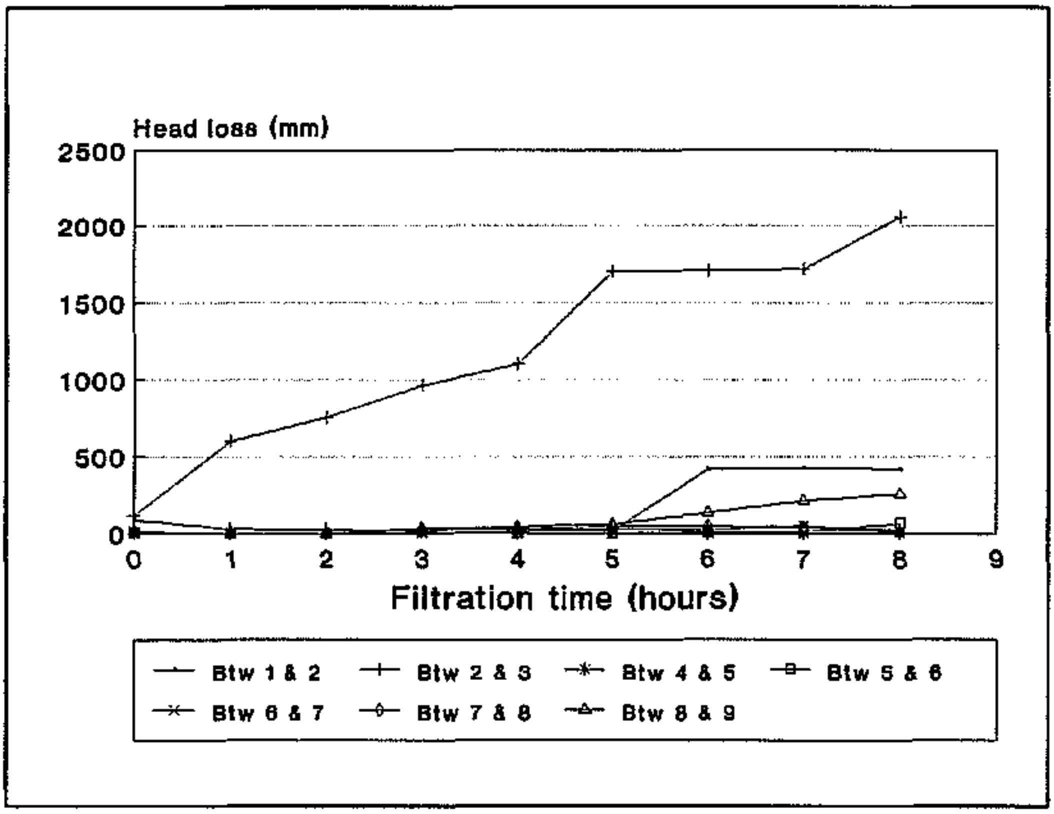


Figure D6 **Head loss development in the filter RUN R10.1: Filtration rate 10 m/h and 30 mg/ℓ alum**

RUN R20.1: FILTRATION RATE 20 m/h and 30 mg/ℓ ALUM

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
0.25 hour				
Raw	6.51	24	ND	0.02
After upflow	6.52	22	ND	0.05
After downflow	6.64	0.43	ND	0
0.5 hour				
Raw	6.63	22.5	30.3	0.01
After upflow	6.67	1.5	11.17	0.04
After downflow	6.64	0.36	6.64	0
1 hour				
Raw	6.97	18	30.2	0
After upflow	6.76	1.2	11.46	0.07
After downflow	6.71	0.42	7.21	0
1.5 hours				
Raw	7.16	12	30.2	0.01
After upflow	6.76	1.3	7.8	0.11
After downflow	6.77	0.35	7.4	0.02
2 hours				
Raw	7.06	9	ND	0.01
After upflow	6.77	0.92	12.37	0.05
After downflow	6.85	0.7	11.51	0
2.5 hours				
Raw	7.15	11	34.3	0
After upflow	7.00	2.2	13.75	0.18
After downflow	6.88	0.86	13.17	0.02
3 hours				
Raw	7.21	12	30.9	0
After upflow	7.05	2.6	20.16	0.10
After downflow	6.96	0.89	14.66	0.02

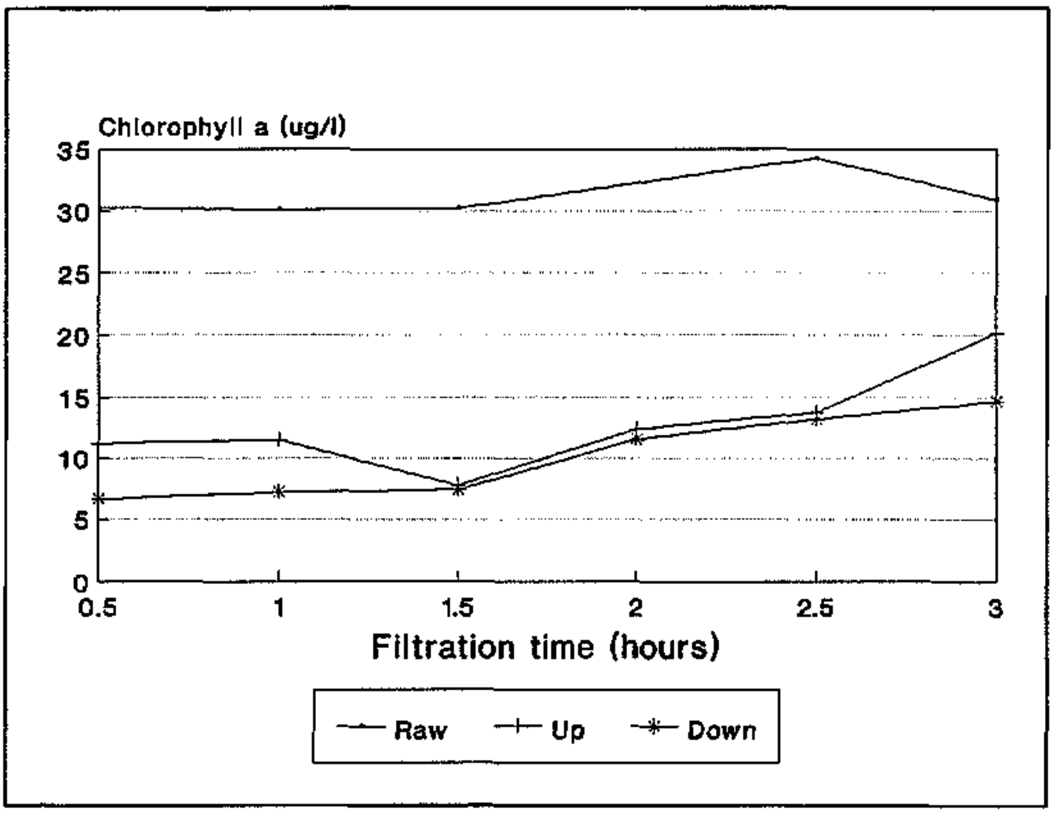


Figure D7 Algae removal at Roodeplaat Dam for RUN R20.1: Filtration rate 20 m/h and 30 mg/ℓ alum

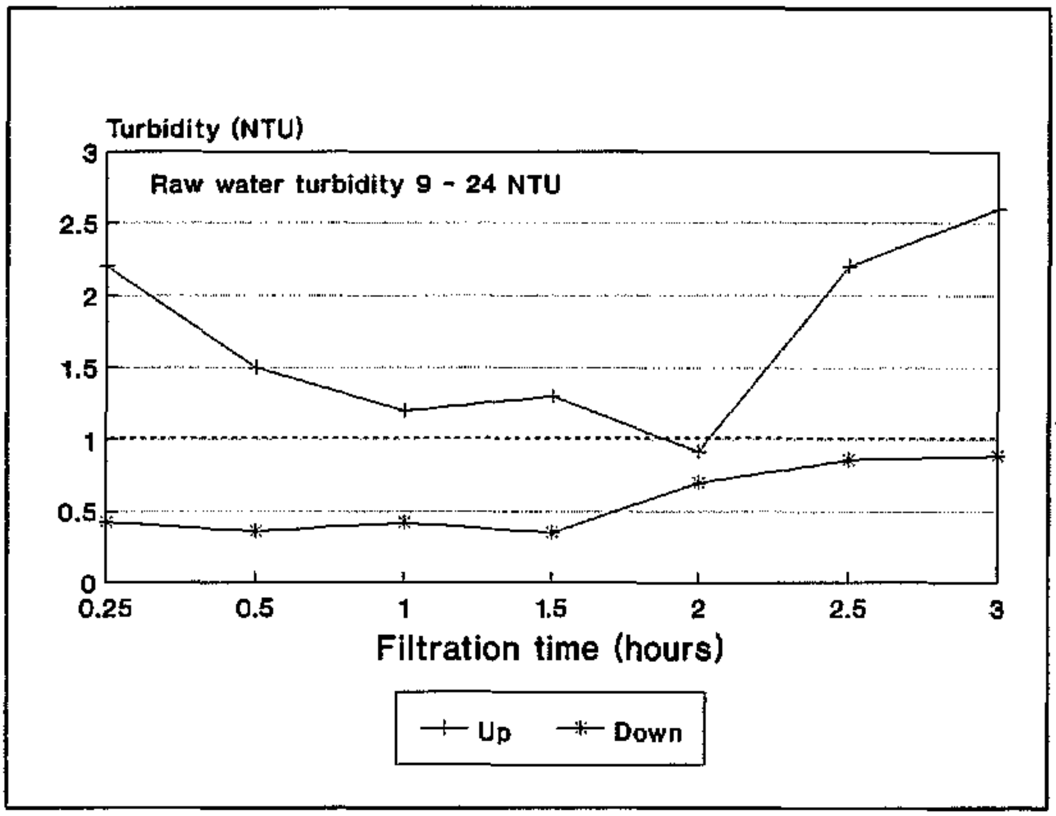


Figure D8 Turbidity removal at Roodeplaat Dam for RUN R20.1: Filtration rate 20 m/h and 30 mg/ℓ alum

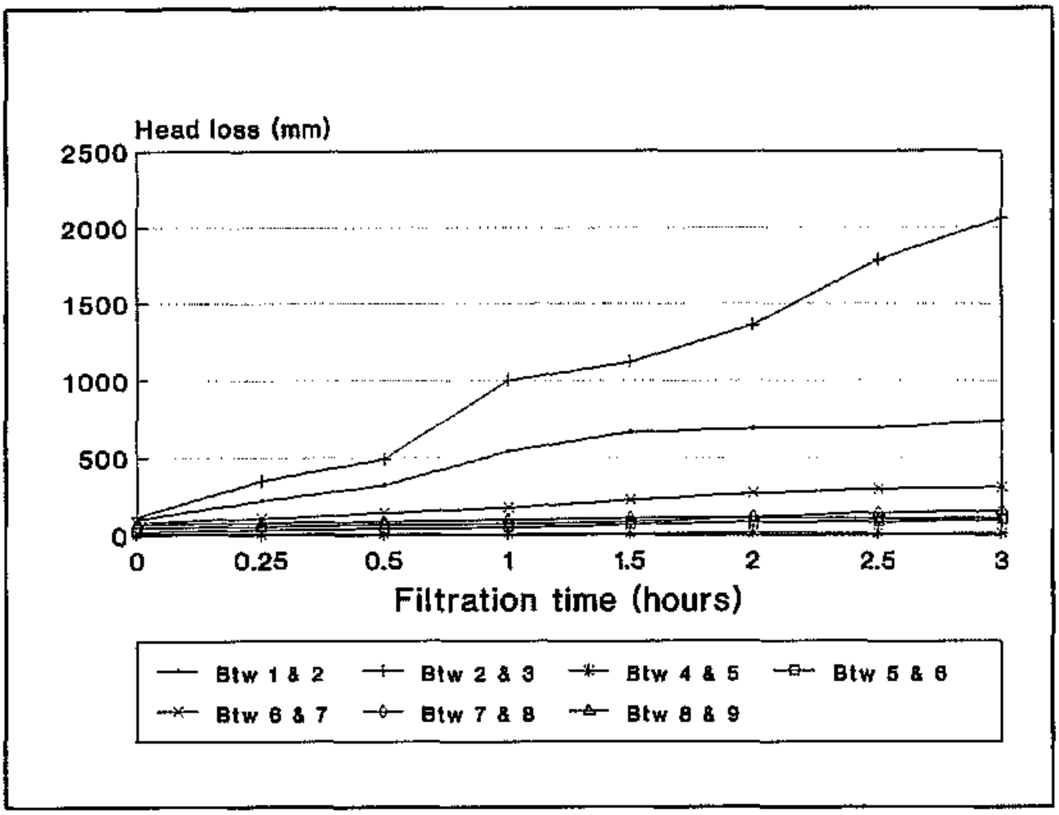


Figure D9 Head loss development in the filter for RUN R20.1: Filtration rate 20 m/h and 30 mg/ℓ alum

RUN R5.2: FILTRATION RATE 5 m/h and 35 mg/ℓ $FeCℓ_3$

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (µg/ℓ)	Al (mg/ℓ)
2 hours				
Raw	7.40	2	11.75	0.86
After upflow	7.55	0.45	5.8	0.30
After downflow	7.44	0.18	4.81	0.04
4 hours				
Raw	7.50	1.2	14.61	0.19
After upflow	7.47	0.41	3.7	0.22
After downflow	7.39	0.15	3.7	0.02
6 hours				
Raw	7.68	1.1	14.43	0.17
After upflow	7.51	0.25	2.17	0.09
After downflow	7.45	0.15	0.24	0.01
8 hours				
Raw	7.55	4.8	15.24	0.21
After upflow	7.44	0.19	3.78	0.04
After downflow	7.34	0.13	1.47	0
10 hours				
Raw	7.52	8.4	8.97	0.45
After upflow	7.97	0.25	2.48	0.06
After downflow	7.63	0.13	2.48	0.01
12 hours				
Raw	7.57	4.9	8.66	0.50
After upflow	7.47	0.23	3.71	0.06
After downflow	7.48	0.17	2.89	0.03
14 hours				
Raw	7.55	4.9	10.65	0.51
After upflow	7.38	0.35	5.5	0.11
After downflow	7.32	0.15	3.53	0.01

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
16 hours				
Raw	7.55	8.4	15.81	0.43
After upflow	7.43	0.38	5.16	0.14
After downflow	7.34	0.19	4.4	0.02
18 hours				
Raw	7.59	3.1	14.83	0.28
After upflow	7.55	0.41	6.5	0.18
After downflow	7.40	0.16	3.87	0.02

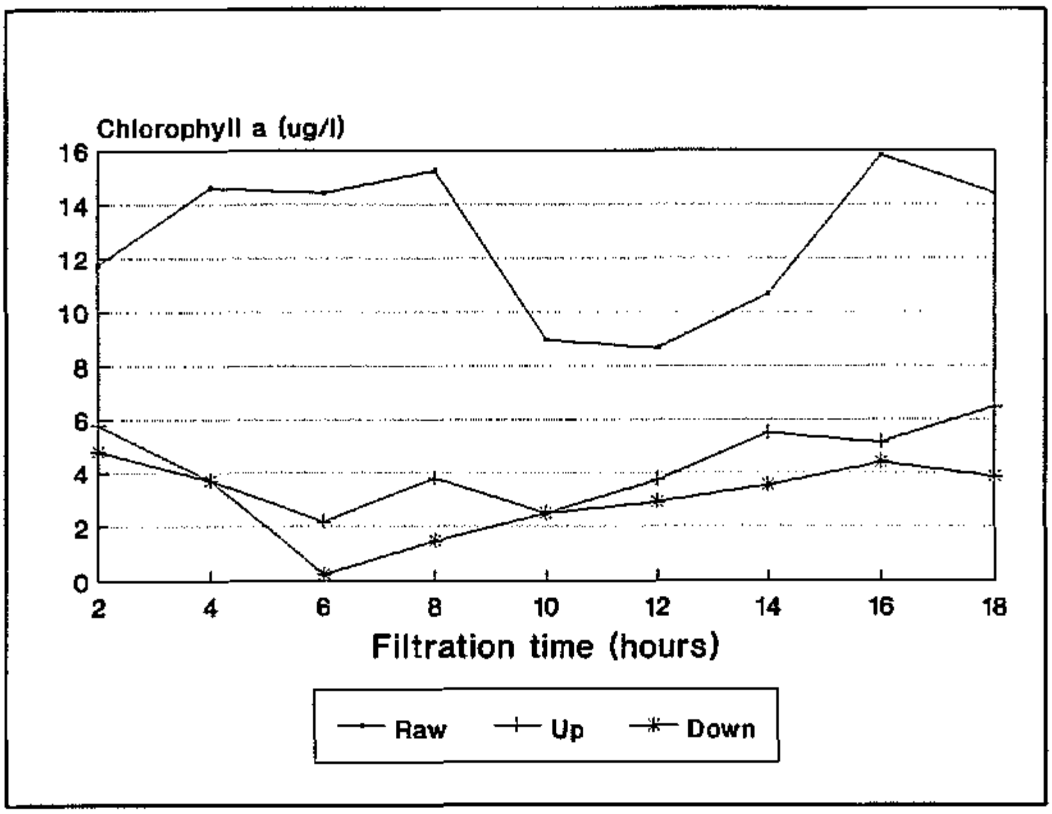


Figure D10 Algae removal at Roodeplaat Dam for RUN R5.2: Filtration rate 5 m/h and 35 mg/ℓ $FeCl_3$

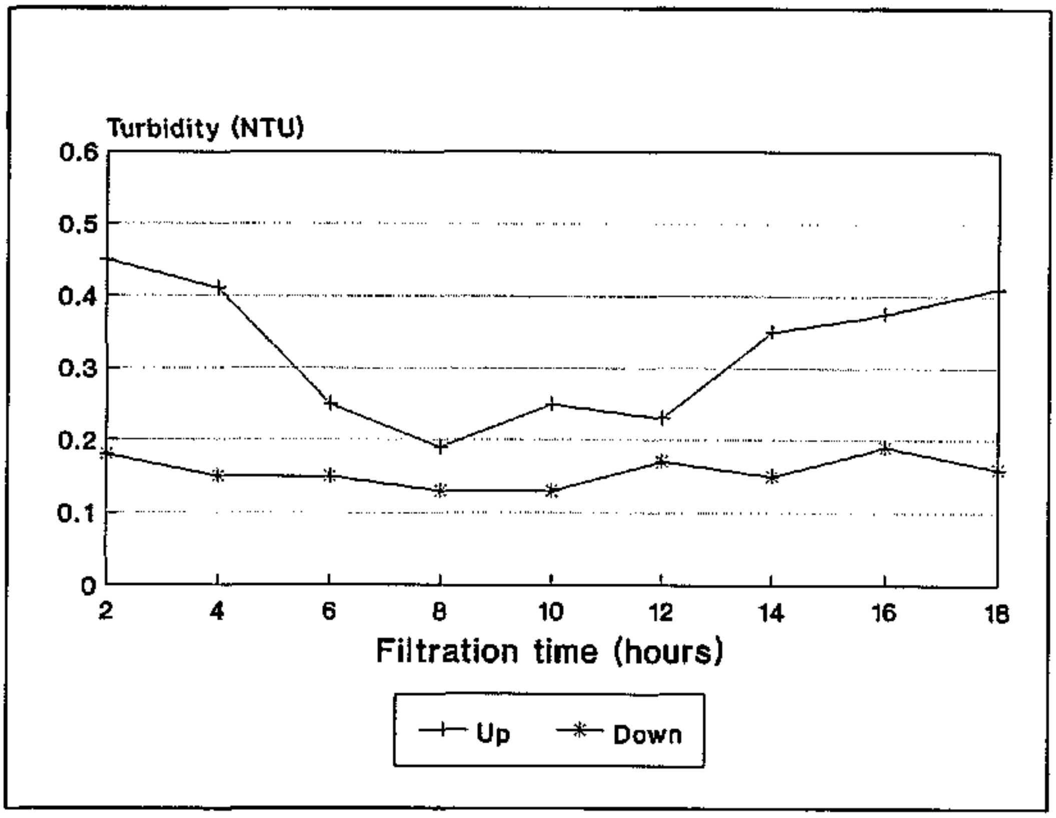


Figure D11 Turbidity removal at Roodeplaat Dam for RUN R5.2: Filtration rate 5 m/h and 35 mg/ℓ $FeCl_3$

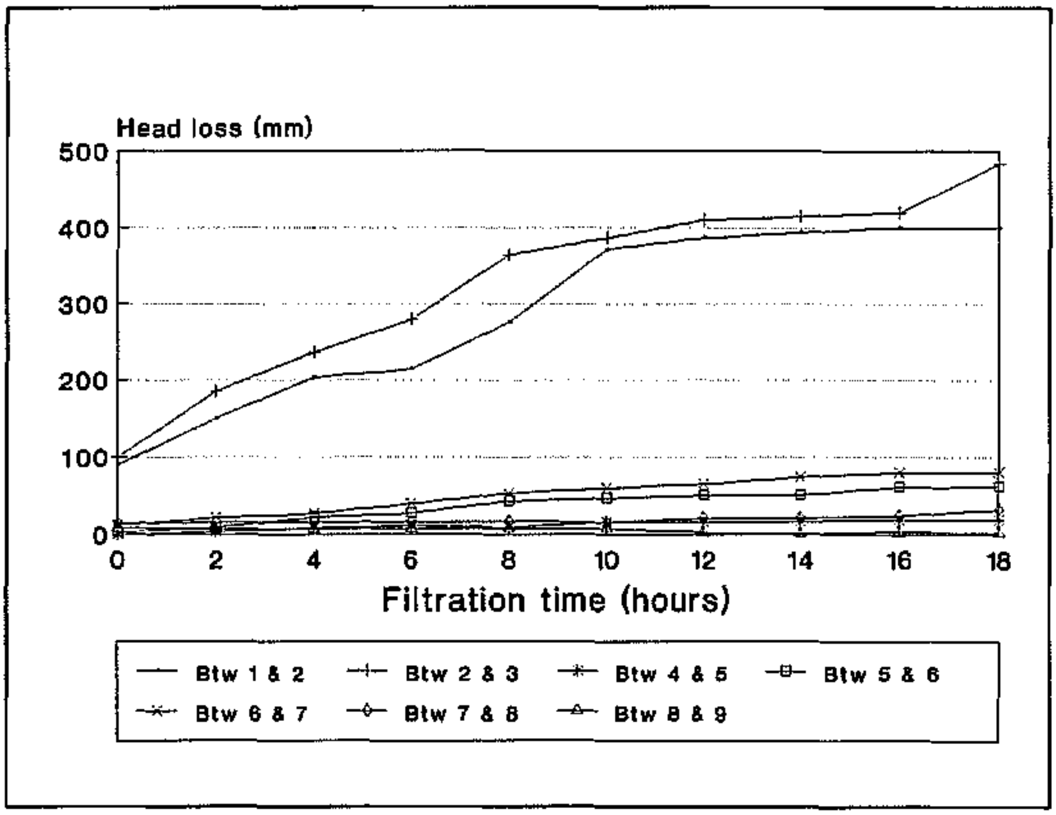


Figure D12 **Head loss development in the filter for RUN R5.2: Filtration rate 5 m/h and 35 mg/ℓ $FeCl_3$**

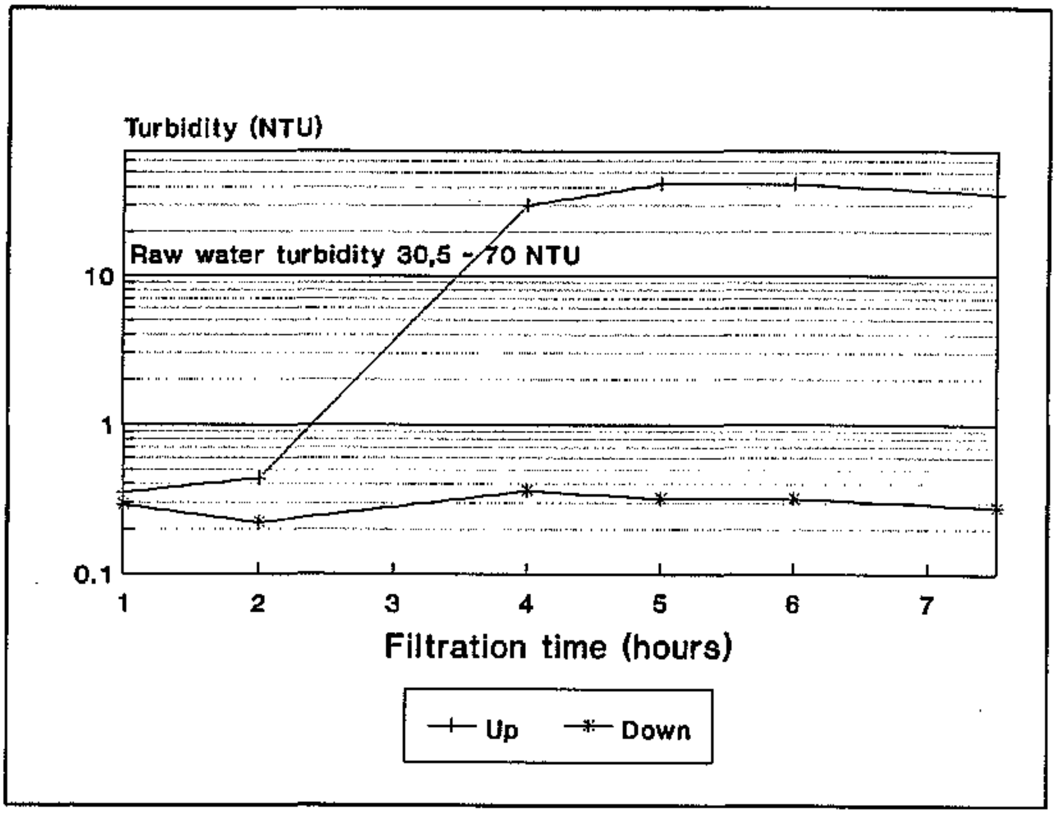


Figure C9 Turbidity removal at Vaalkop for RUN V10.2: Filtration rate 10 m/h and 40 mg/ℓ alum

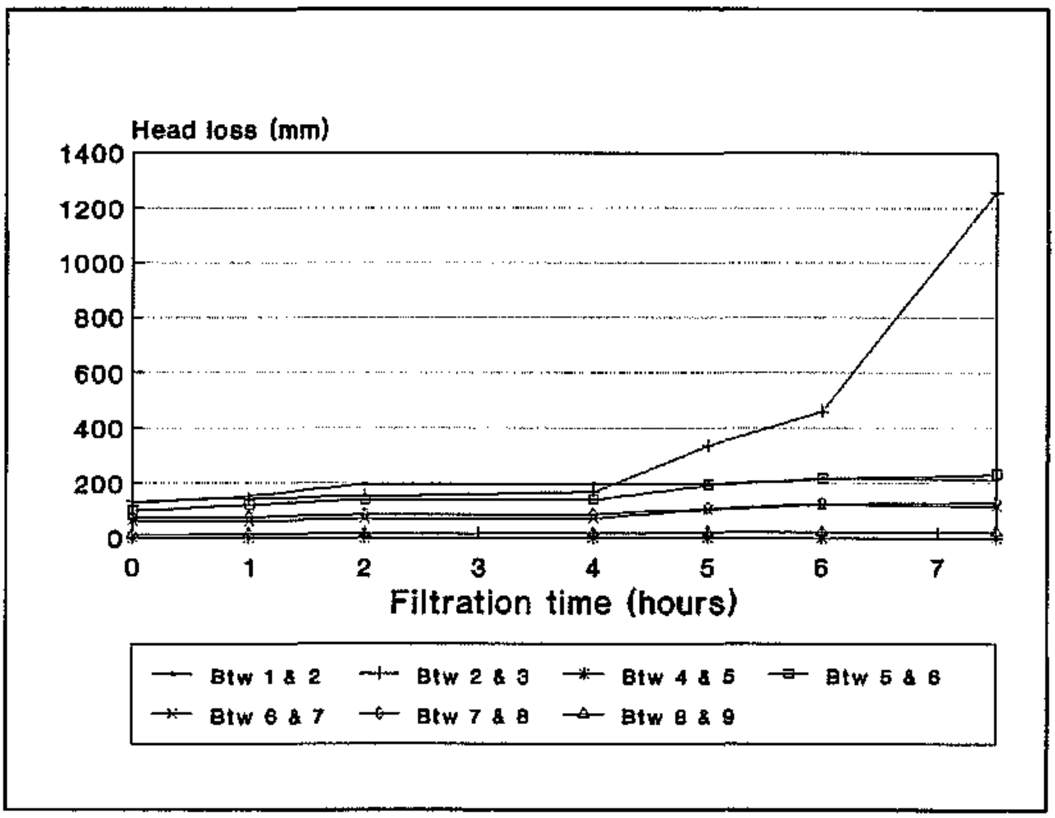


Figure C10 Head loss development in the filter for RUN V10.2: Filtration rate 10 m/h and 40 mg/ℓ alum

RUN V20.2: FILTRATION RATE 20 m/h and 40 mg/ℓ ALUM

Sample	pH	Turbidity (NTU)	Aℓ (mg/ℓ)
0.75 hours			
Raw	6.99	38	0.25
After upflow	7.20	1.2	0.19
After downflow	7.03	0.41	0.18
1.5 hours			
Raw	7.32	35	0.23
After upflow	7.69	2.8	0.23
After downflow	7.14	0.4	0.21
2 hours			
Raw	7.09	32.5	0.21
After upflow	7.19	6.2	0.20
After downflow	7.01	0.35	0.14
2.5 hours			
Raw	-	-	-
After upflow	7.29	9.5	0.2
After downflow	7.27	0.38	0.18
3.25 hours			
Raw	7.09	30.5	0.13
After upflow	7.10	13	0.18
After downflow	7.21	0.25	0.15

RUN R10.2: FILTRATION RATE 10 m/h and 30 mg/ℓ $FeCℓ_3$

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (µg/ℓ)	Al (mg/ℓ)
1 hour				
Raw	7.21	4	7.16	0.58
After upflow	6.83	0.8	0	0.25
After downflow	6.85	0.43	0	0.09
2 hours				
Raw	7.15	4.2	8.31	0.57
After upflow	6.66	0.44	1.66	0.20
After downflow	6.67	0.24	0.69	0.05
3 hours				
Raw	7.05	5	11.34	2.98
After upflow	6.83	0.33	4.35	0.16
After downflow	6.78	0.35	0	0.04
4 hours				
Raw	7.41	4.3	3.87	0.67
After upflow	6.75	0.76	1.55	0.28
After downflow	6.77	0.43	0	0.05
5 hours				
Raw	7.49	3.8	2.33	0.92
After upflow	6.77	0.62	1.6	0.50
After downflow	6.77	0.5	0	0.08
6 hours				
Raw	7.53	5.3	ND	0.31
After upflow	6.70	0.53	3	0.33
After downflow	6.76	0.22	0	0.07
7 hours				
Raw	7.53	4.8	3.72	0.38
After upflow	7.17	0.34	0	0.16
After downflow	6.79	0.2	0	0.05

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
8 hours				
Raw	7.60	4.8	6.19	0.14
After upflow	7.16	1.2	6	0.13
After downflow	6.98	0.33	2.5	0.06

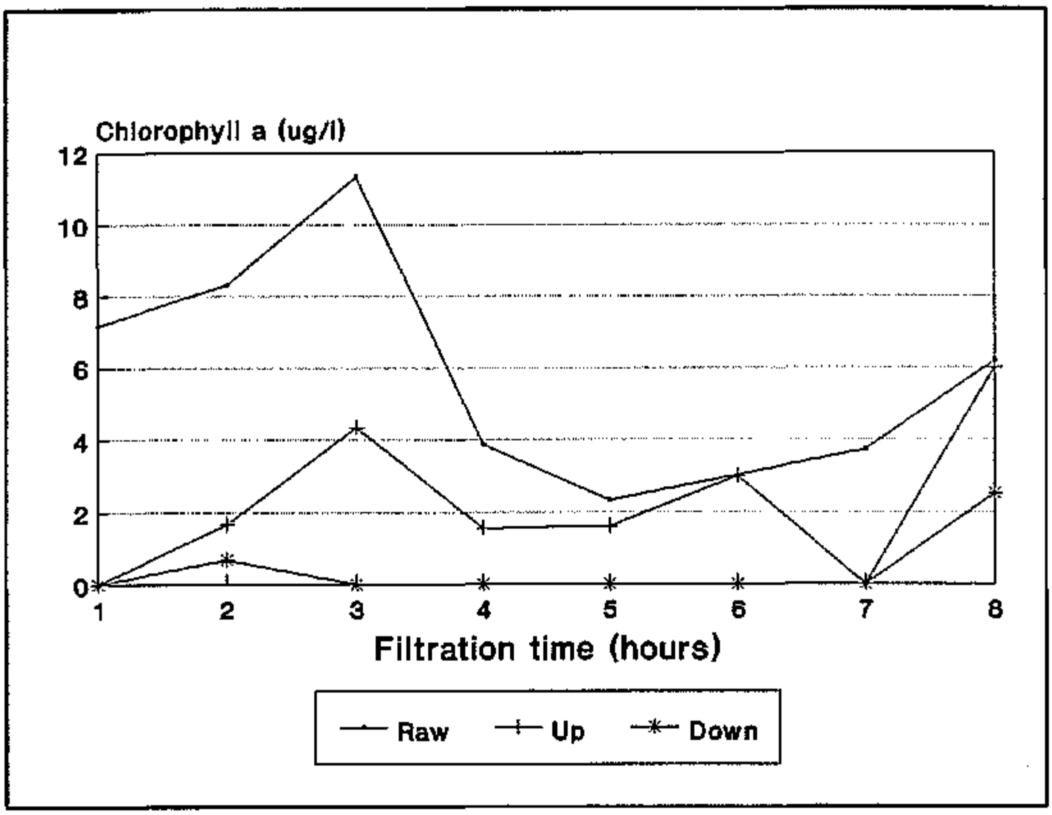


Figure D13 Algae removal at Roodeplaat Dam for RUN R10.2: Filtration rate 10 m/h and 30 mg/ℓ $FeCl_3$

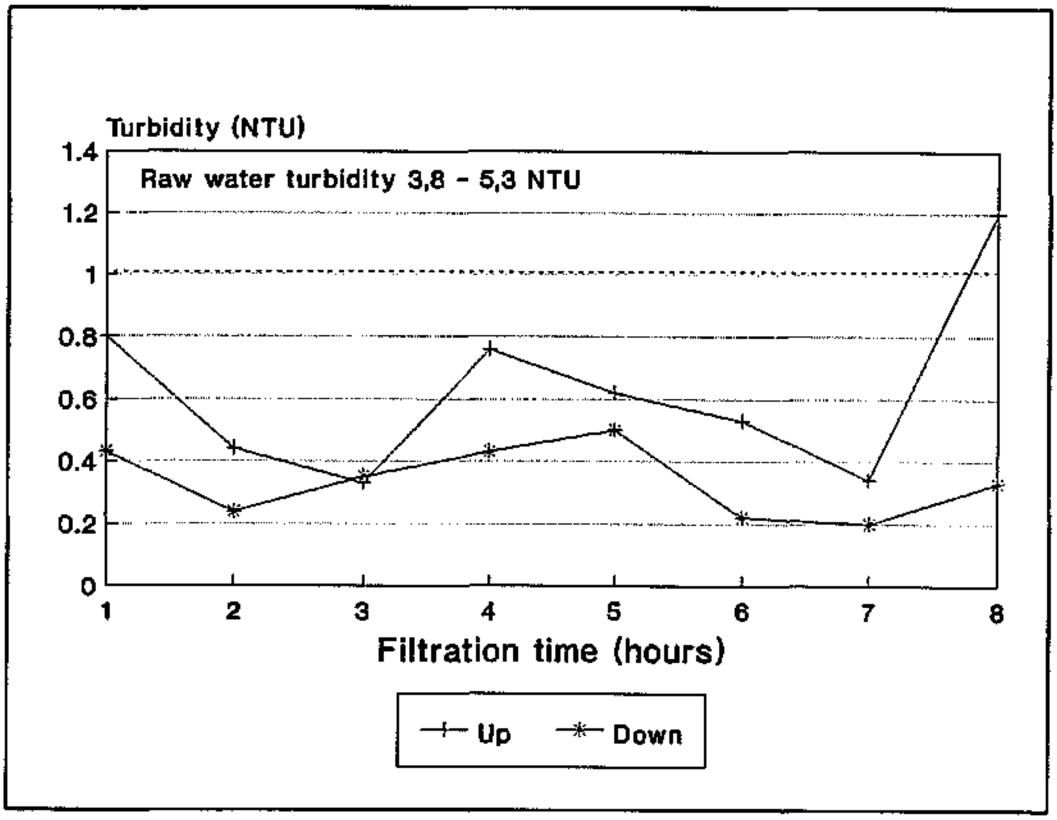


Figure D14 Turbidity removal at Roodeplaat Dam for RUN R10.2: Filtration rate 10 m/h and 30 mg/ℓ $FeCl_3$

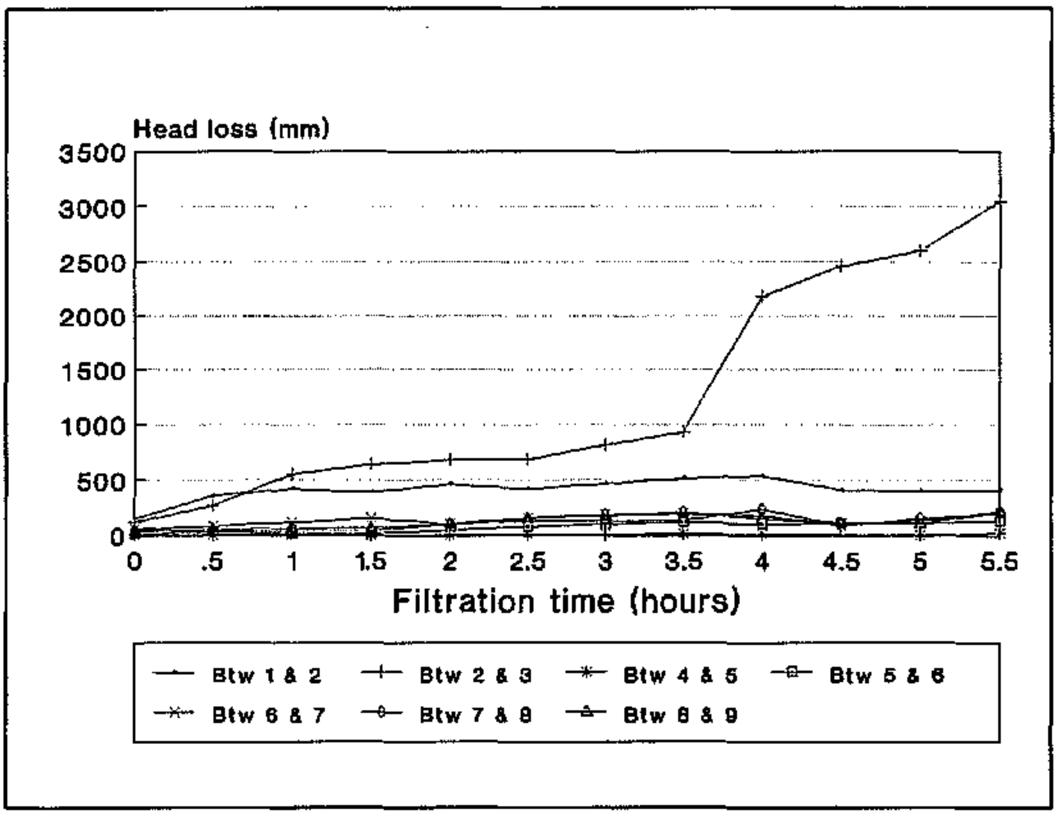


Figure D15 Head loss development in the filter for RUN R10.2: Filtration rate 10 m/h and 30 mg/ℓ $FeCl_3$

RUN R20.2: FILTRATION RATE 20 m/h and 30 mg/ℓ $FeCℓ_3$

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
1 hour				
Raw	6.82	13	7.8	0.04
After upflow	6.74	1.1	5.73	0.40
After downflow	6.68	0.23	3.27	0.03
1.5 hours				
Raw	6.84	13	7.18	0.03
After upflow	6.72	0.66	4.12	0.33
After downflow	6.67	0.24	1.03	0.03
2 hours				
Raw	6.84	8	7.5	0.10
After upflow	6.73	0.68	2.1	0.26
After downflow	6.74	0.31	1.41	0.02
2.5 hours				
Raw	7.37	4.4	7.62	0.15
After upflow	6.70	0.41	2.29	0.14
After downflow	6.76	0.23	1.09	0
3 hours				
Raw7.41	7.46	4.9	7.41	0.18
After upflow3.26	6.69	0.47	3.26	0.15
After downflow0	6.76	0.38	0	0.04
3.5 hours				
Raw	7.46	5.3	6.29	0.18
After upflow	6.61	1.7	3.27	0.18
After downflow	6.72	1.5	0	0.02
4 hours				
Raw	7.47	5.5	5.1	0.18
After upflow	7.55	1.3	2.18	0.62
After downflow	6.64	0.92	0	0.05

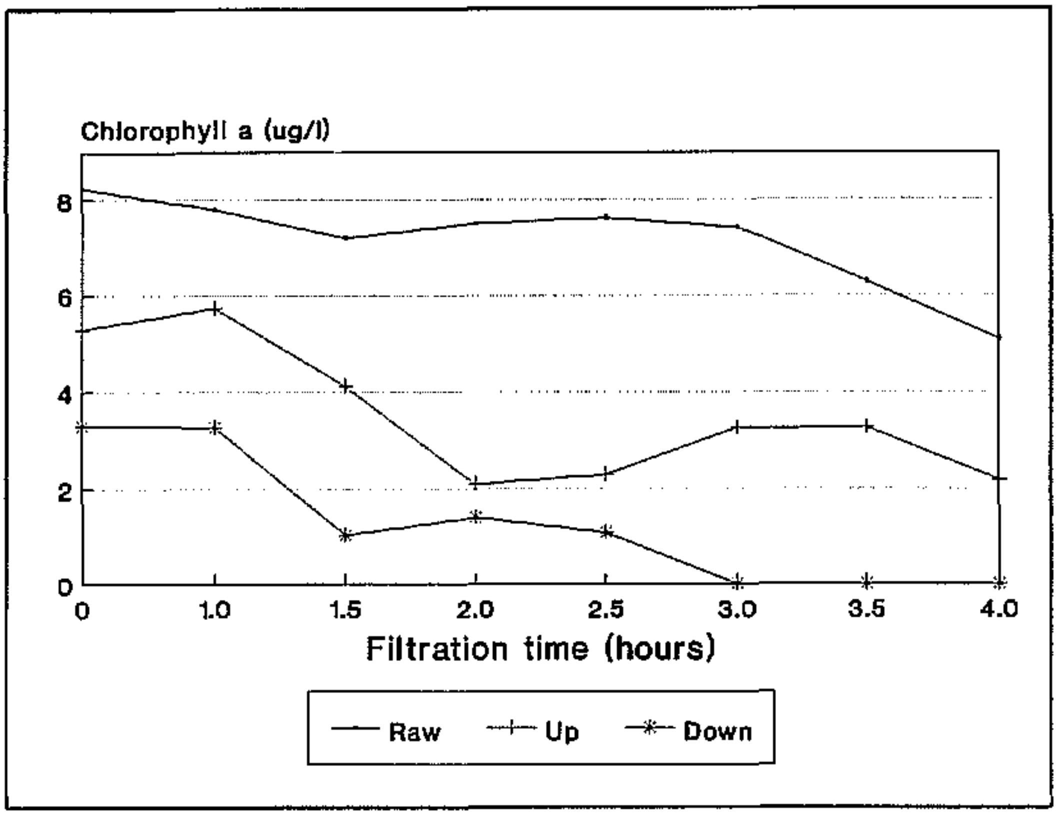


Figure D16 Algae removal at Roodeplaat Dam for RUN R20.2: Filtration rate 20 m/h and 30 mg/ℓ $FeCl_3$

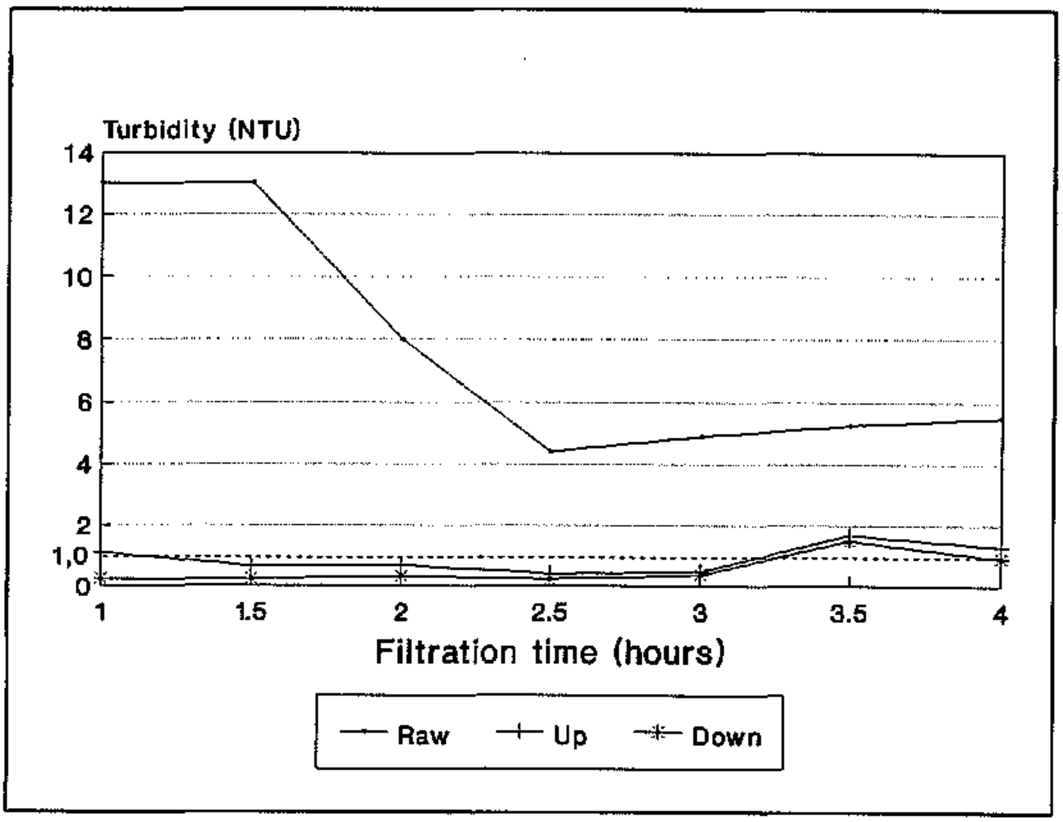


Figure D17 Turbidity removal at Roodeplaat Dam for RUN R20.2: Filtration rate 20 m/h and 30 mg/ℓ $FeCl_3$

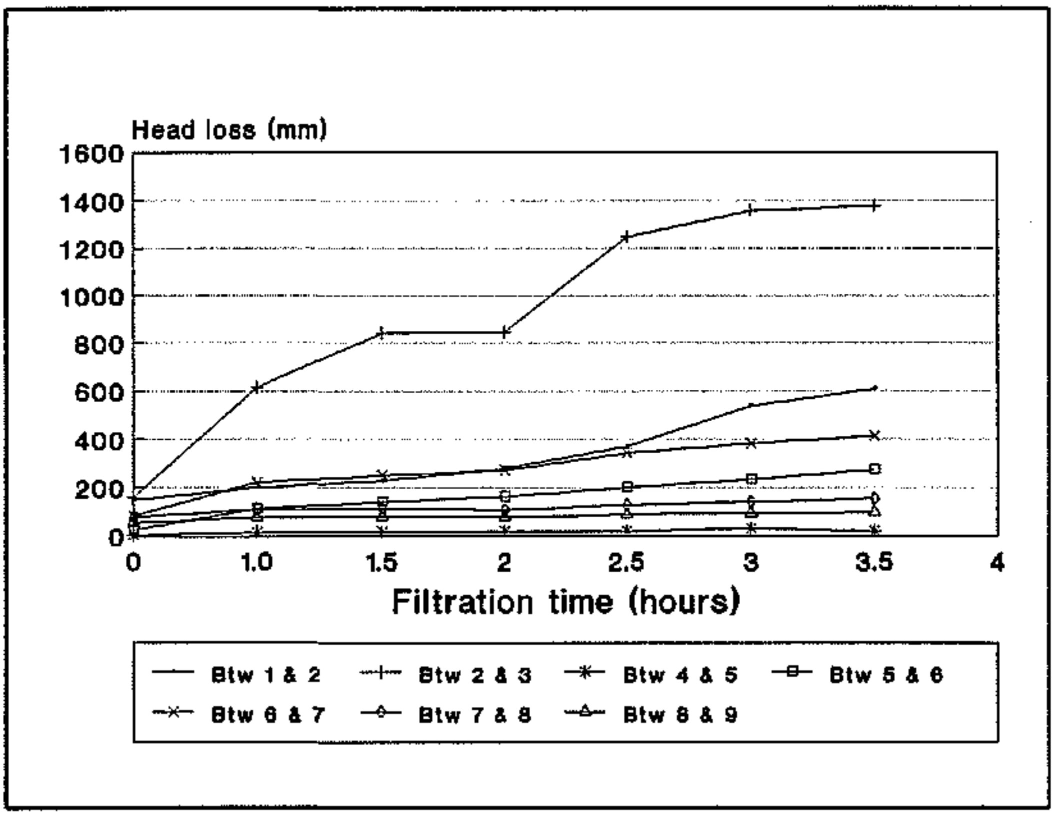


Figure D18 Head loss development in the filter for RUN R20.2: Filtration rate 20 m/h and 30 mg/ℓ $FeCl_3$.

RUN R5.3: FILTRATION RATE 5 m/h and 0,5-1,0 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)
2 hours			
Raw	7.81	1.9	3.32
After upflow	8.46	2.7	1.33
After downflow	8.54	1.3	0.65
4 hours			
Raw	7.99	3.1	3.32
After upflow	7.96	2.3	2.48
After downflow	8.12	1.3	1.99
6 hours			
Raw	8.08	14	2.48
After upflow		6.5	1.93
After downflow		2.2	0
8 hours			
Raw		1.8	2.57
After upflow	7.7	0.73	1.28
After downflow	7.91	0.9	1.33
12 hours			
Raw	7.82	5.4	2.8
After upflow	7.90	1.25	2.66
After downflow	7.96	0.8	0
14 hours			
Raw	7.85	5.6	2.06
After upflow	7.86	1.5	1.99
After downflow	8.00	1.5	1.28
16 hours			
Raw	7.72	6.3	3.09
After upflow	7.91	1.4	2.13
After downflow	7.86	1.75	1.86

Sample	pH	Turbidity (NTU)	Chlorophyll *a* ($\mu g/\ell$)
19 hours			
Raw	7.92	5	2.75
After upflow	7.76	3.1	2.41
After downflow	8.32	1.4	1.2
23 hours			
Raw	7.98	5.4	3.21
After upflow	8.13	2.8	2.3
After downflow	8.17	1	1
27 hours			
Raw	7.83	3	3.21
After upflow	8.01	1.6	2.23
After downflow	8.04	0.78	0.72
32 hours			
Raw	8.41	4.6	2.98
After upflow	8.51	4.1	2.32
After downflow	8.62	1.7	1.66
36 hours			
Raw	8.54	5.1	2.8
After upflow	8.65	2.3	1.78
After downflow	8.72	1.5	1.6

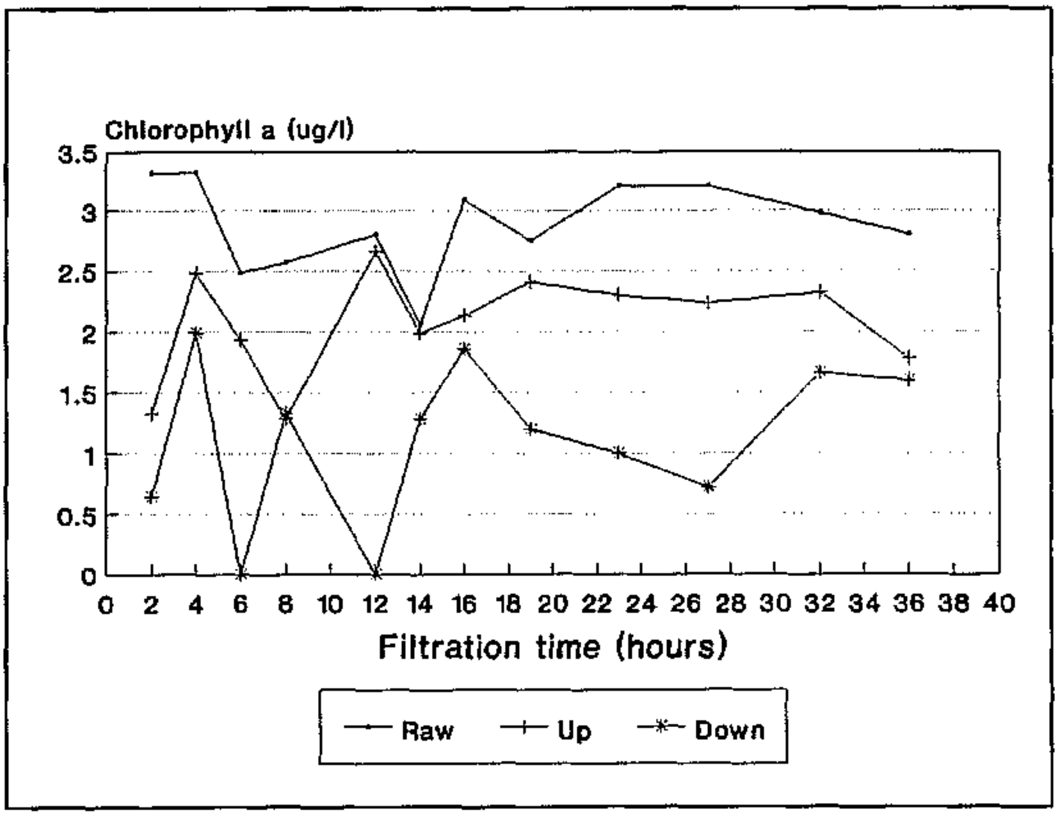


Figure D19 Algae removal at Roodeplaat Dam for RUN R5.3: Filtration rate 5 m/h and 0,5 - 1 mg/ℓ LT 22

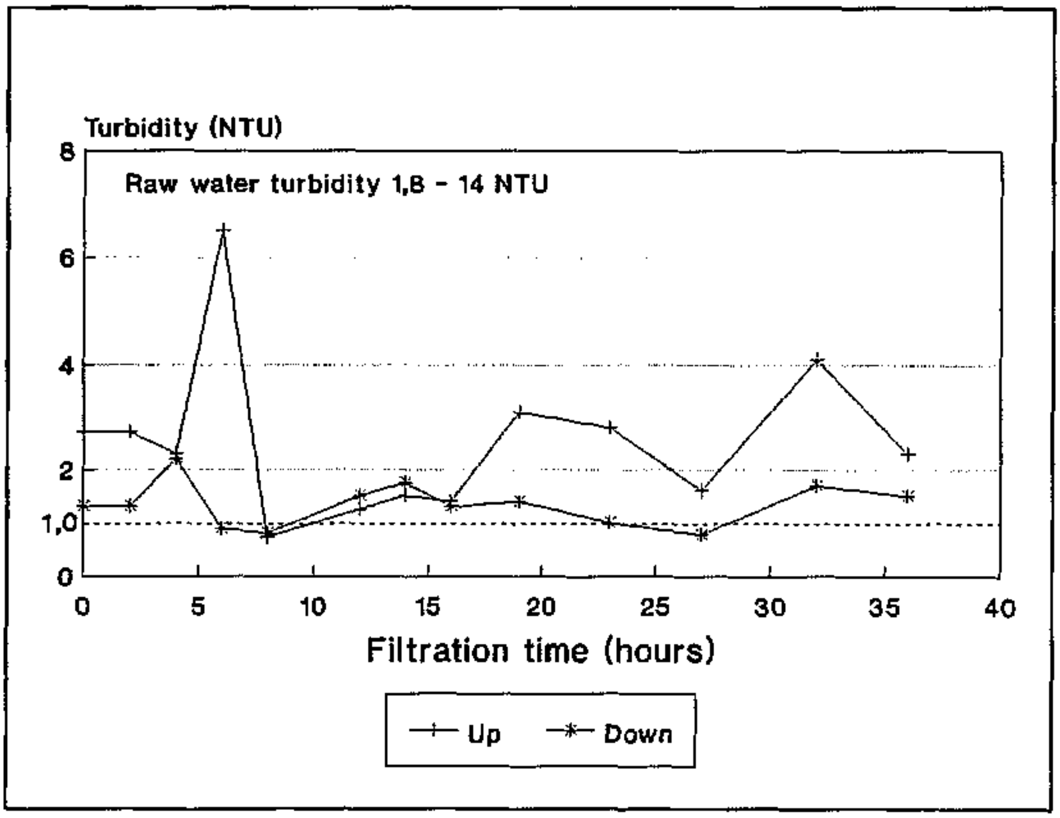


Figure D20 Turbidity removal at Roodeplaat Dam for RUN R5.3: Filtration rate 5 m/h and 0,5 - 1 mg/ℓ LT 22

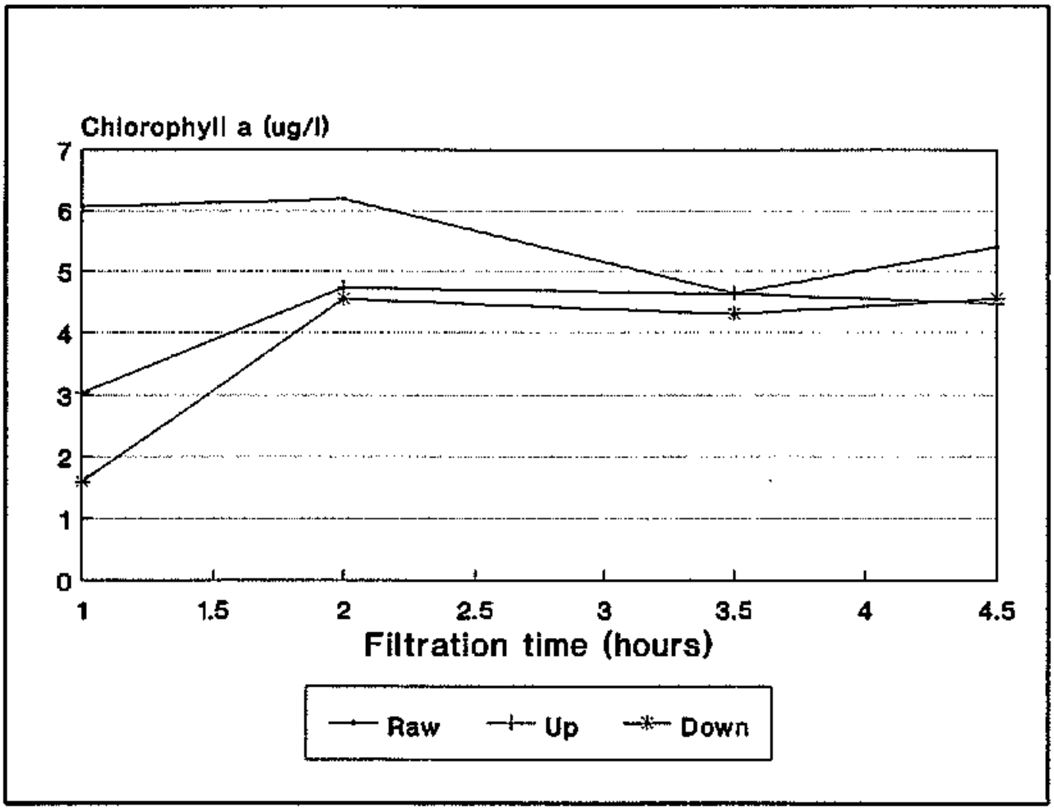


Figure D22 Algae removal at Roodeplaat Dam for RUN R10.3: Filtration rate 10 m/h and 0,5 - 1 mg/ℓ LT 22

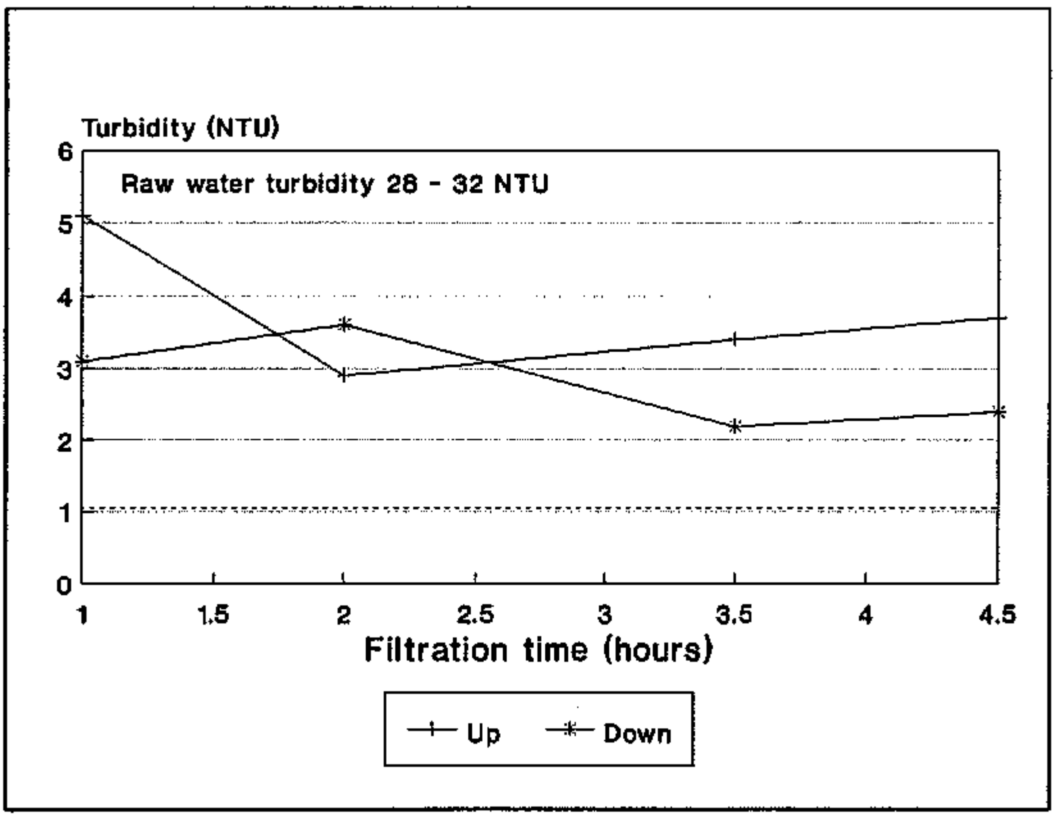


Figure D23 Turbidity removal at Roodeplaat Dam for RUN R10.3: Filtration rate 10 m/h and 0,5 - 1 mg/ℓ LT 22

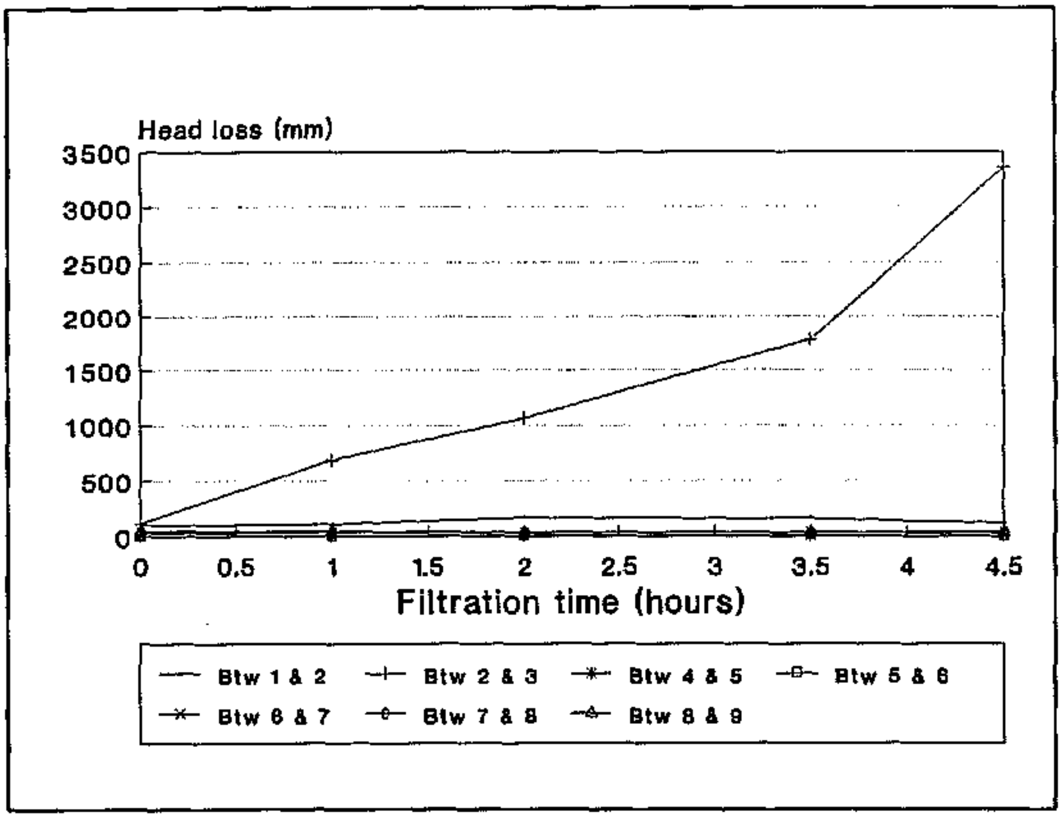


Figure D24 Head loss development in the filter for RUN R10.3: Filtration rate 10 m/h and 0,5 - 1 mg/ℓ LT 22

RUN R20.3: FILTRATION RATE 20 m/h and 0,5 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)
0.5 hours			
Raw	8.70	22	7.45
After upflow	8.67	5.6	1.6
After downflow	8.61	5.6	1.49
1 hours			
Raw	8.67	22	6.5
After upflow	8.60	5.9	3.88
After downflow	8.96	3.8	2.98
2 hours			
Raw	8.88	22	4.21
After upflow	8.59	5.7	3.21
After downflow	8.83	5.3	1.52
5.33 hours			
Raw	8.91	25	4.8
After upflow	8.66	5.25	4.47
After downflow	8.95	4.8	1.55
5 hours			
Raw	8.58	27.5	4.73
After upflow	8.49	6.1	2.75
After downflow	8.92	5.4	0

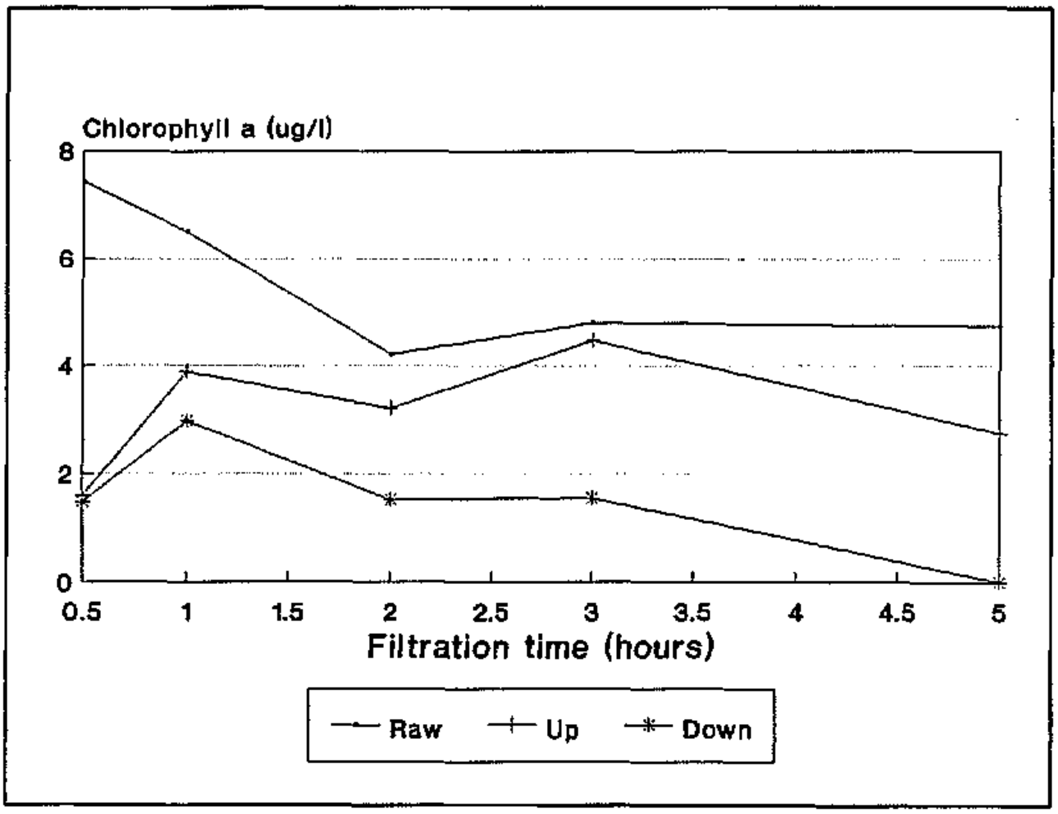


Figure D25 Algae removal at Roodeplaat Dam for RUN R20.3: Filtration rate 20 m/h and 0,5 mg/ℓ LT 22

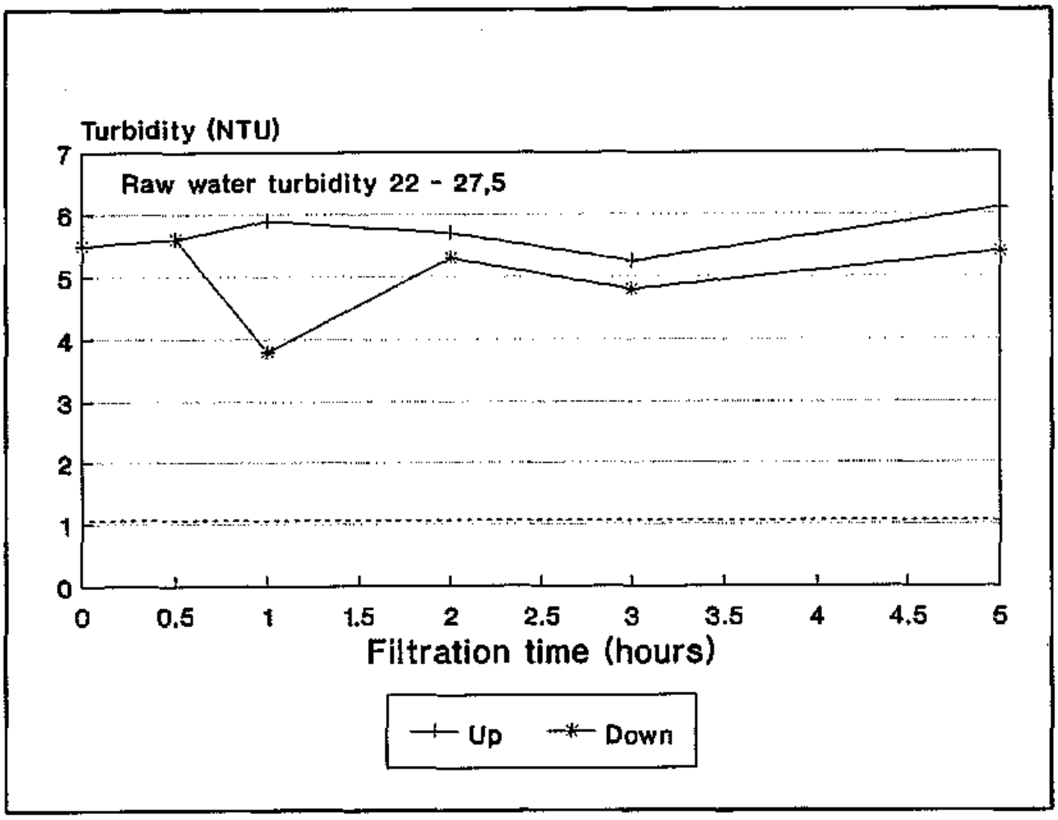


Figure D26 Turbidity removal at Roodeplaat Dam for RUN R20.3: Filtration rate 20 m/h and 0,5 mg/ℓ LT 22

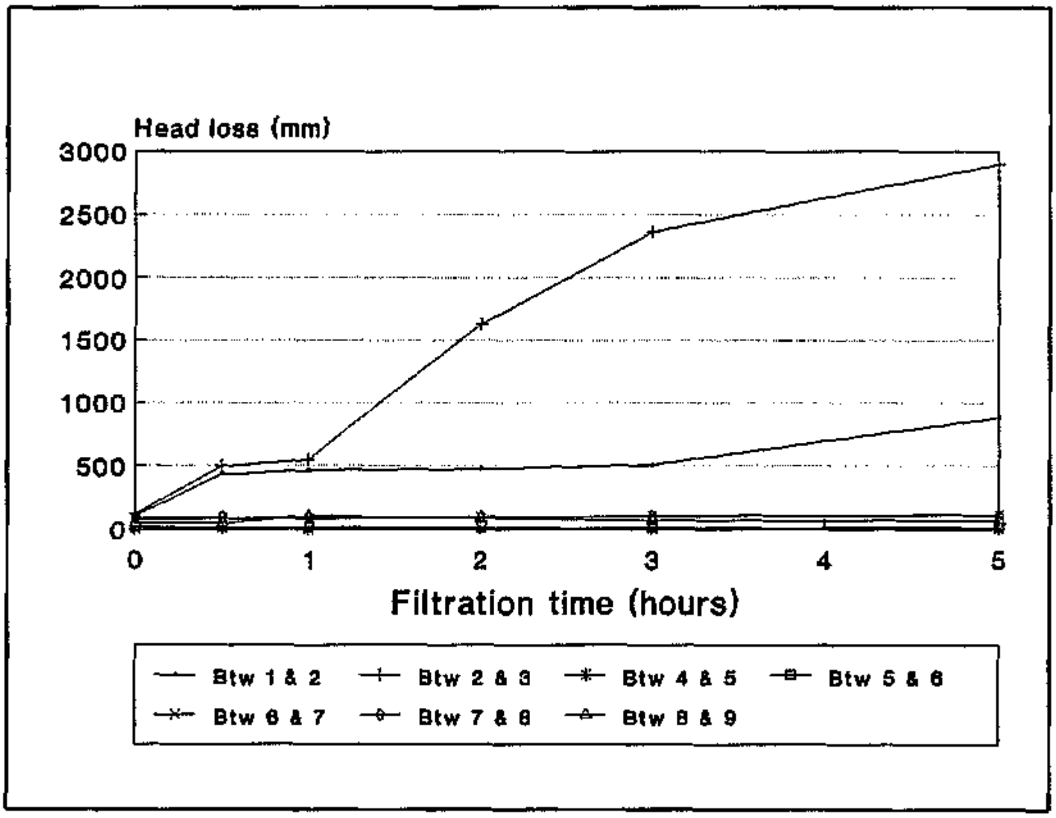


Figure D27 Head loss development in the filter for RUN R20.3: Filtration rate 20 m/h and 0,5 mg/ℓ LT 22

RUN R10.4: FILTRATION RATE 10 m/h, 60 mg/ℓ ALUM and 0,5 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
2 hours				
Raw	8.29	6	75.6	0.23
After upflow	7.71	1.2	14.95	0.37
After downflow	8.05	1.2	5.25	0.27
4 hours				
Raw	8.16	14	75.9	0.19
After upflow	7.60	8.6	47.26	0.80
After downflow	7.99	1.1	3.15	0.17
6 hours				
Raw	7.86	8	76.1	0 15
After upflow	7.80	4	45.09	0.85
After downflow	7.73	1.7	3.07	0.20
8 hours				
Raw	7.98	5	80	0.22
After upflow	7.66	2.7	37.11	0.81
After downflow	7.81	0.42	1.53	0.23
9.5 hours				
Raw	7.84	15	80.5	0.19
After upflow	7.56	12.5	37.12	0.85
After downflow	7.78	0.96	3.61	0.21

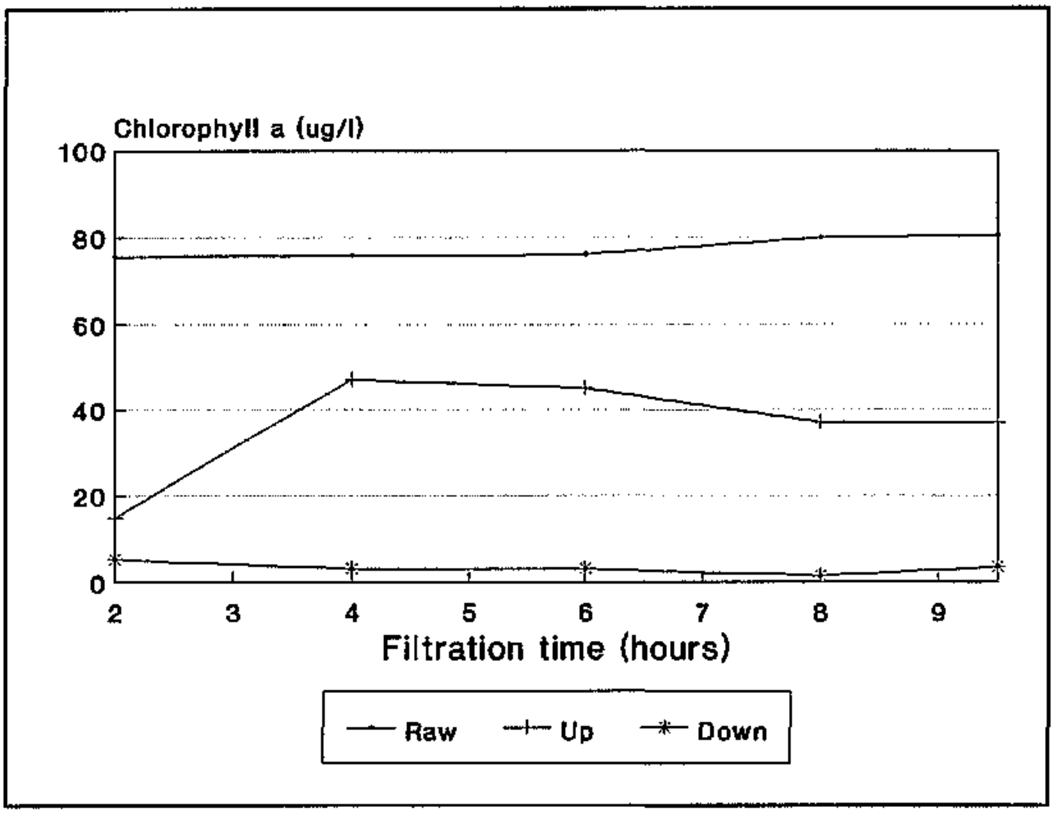


Figure D28 Algae removal at Roodeplaat Dam for RUN R10.4: Filtration rate 10 m/h, 60 mg/ℓ alum and 0,5 mg/ℓ LT 22

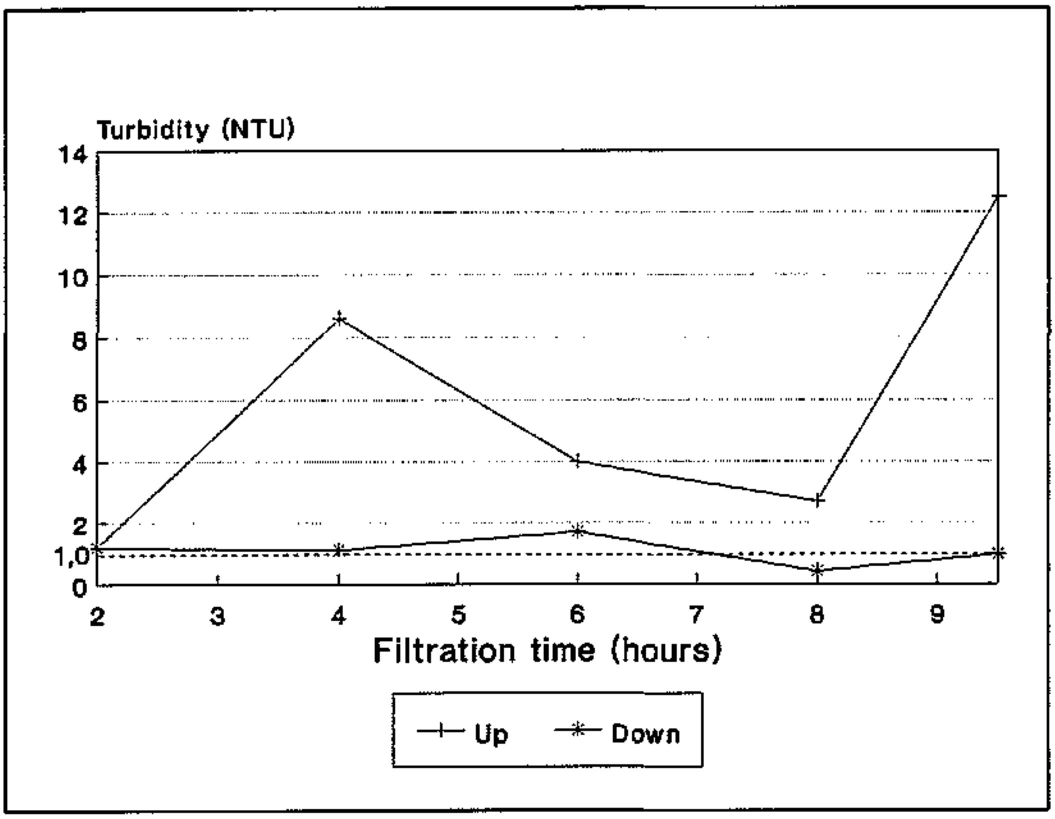


Figure D29 Turbidity removal at Roodeplaat Dam for RUN R10.4: Filtration rate 10 m/h, 60 mg/ℓ alum and 0,5 mg/ℓ LT 22

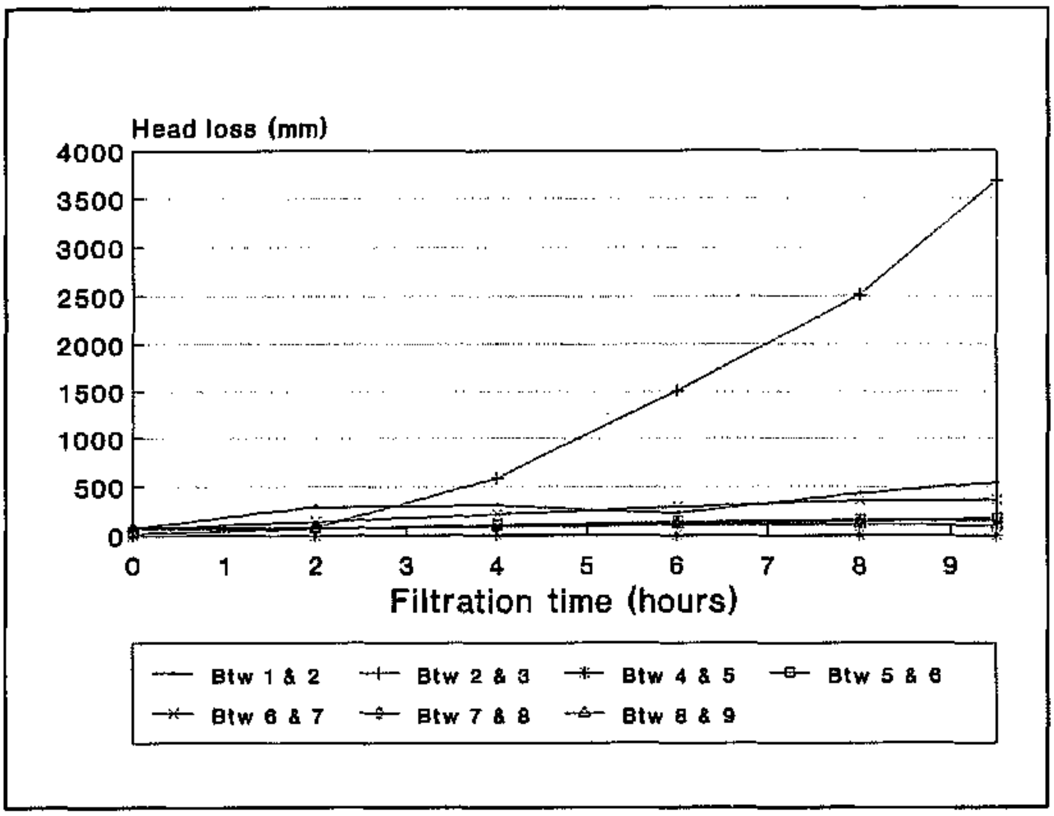


Figure D30 **Head loss development in the filter for RUN 10.4: Filtration rate 10 m/h, 60 mg/ℓ alum and 0,5 mg/ℓ LT 22**

RUN R20.4: FILTRATION RATE 20 m/h, 60 mg/ℓ ALUM and 0,5 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)	Al (mg/ℓ)
1 hours				
Raw	7.24	15	81.2	0.29
After upflow	6.80	3	21.54	0.15
After downflow	6.92	2	14.89	0.17
2 hours				
Raw	7.16	15	74.7	0.17
After upflow	6.91	3	19.73	0.19
After downflow	6.84	1.4	10.02	0.29
3 hours				
Raw	7.56	16	75	0.15
After upflow	6.75	4.8	22.58	0.26
After downflow	6.78	0.57	6.45	0.13
4 hours				
Raw	7.93	-	77.9	0.17
After upflow	7.13	-	40.98	0.35
After downflow	7.46	-	4.12	0.14

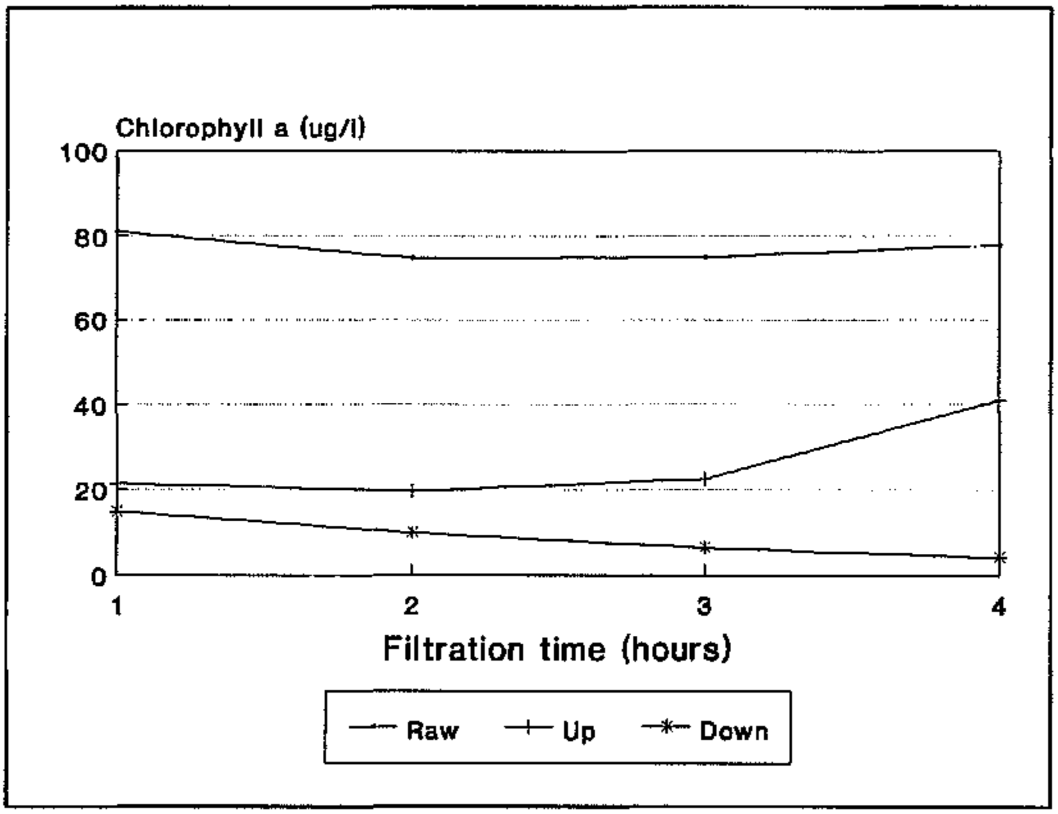


Figure D31 Algae removal at Roodeplaat Dam for RUN R20.4: Filtration rate 20 m/h, 70 mg/ℓ alum and 0,75 mg/ℓ LT 22

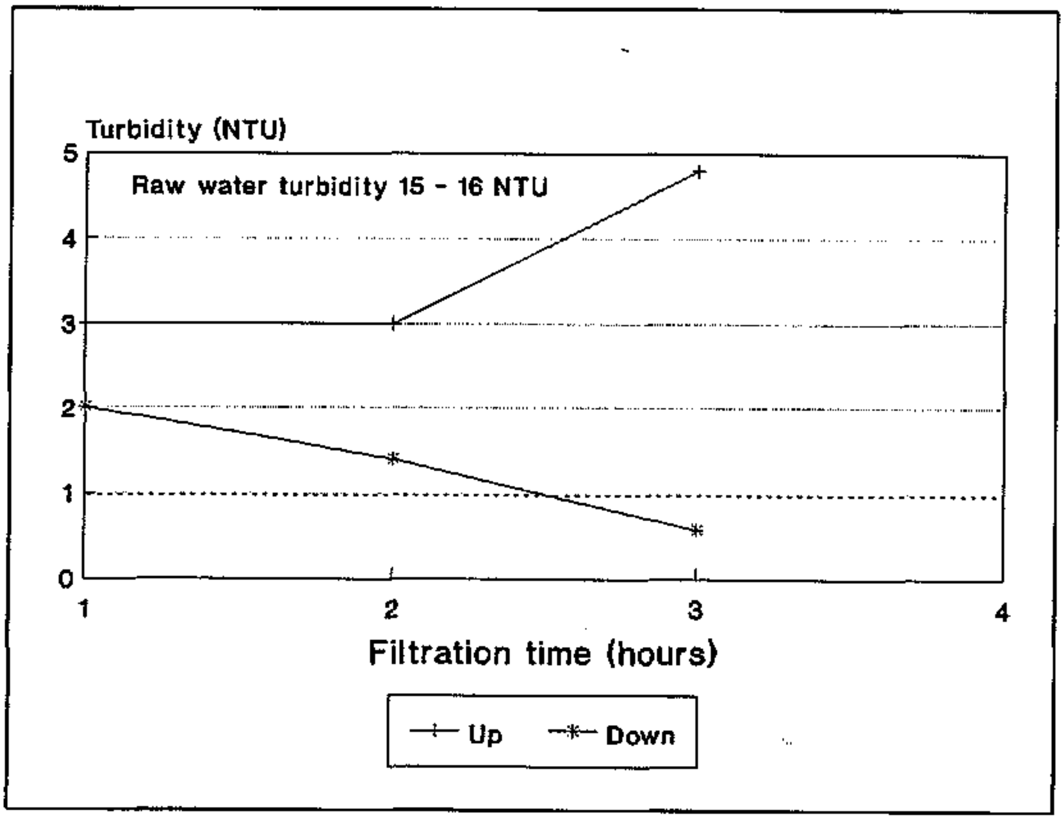


Figure D32 Turbidity removal at Roodeplaat Dam for RUN R20.4: Filtration rate 20 m/h, 70 mg/ℓ alum and 0,75 mg/ℓ LT 22

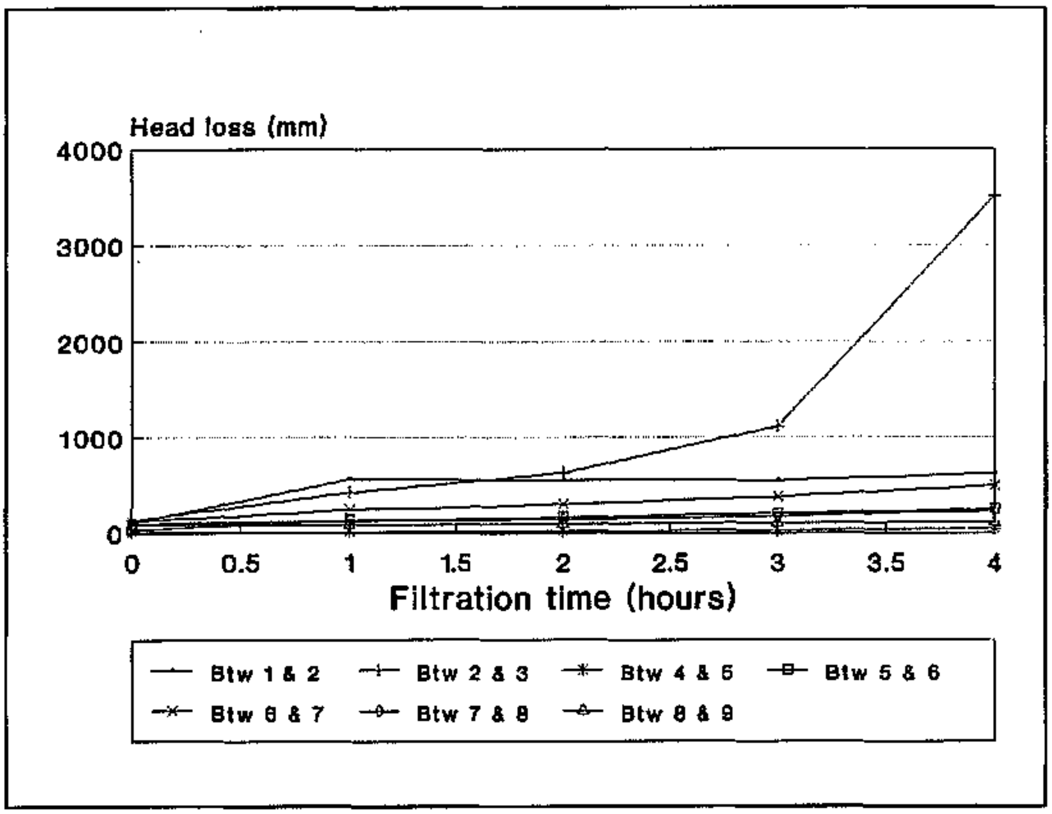


Figure D33 Head loss development in the filter for RUN R20.4: Filtration rate 20 m/h, 70 mg/ℓ alum and 0,75 mg/ℓ LT 22

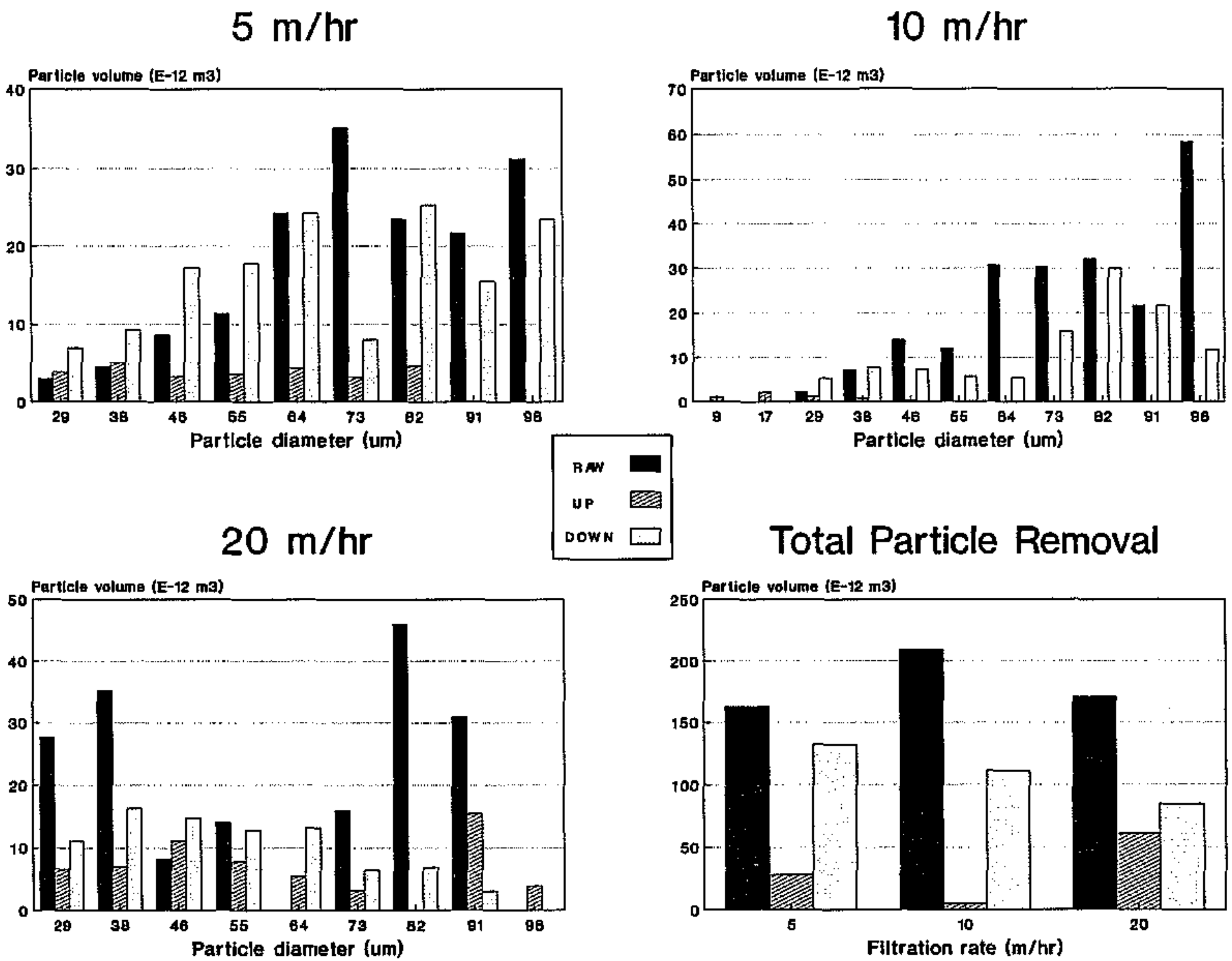


Figure D34 Particle removal in the series filtration system at different filtration rates for eutrophic water from the Roodeplaat Dam

APPENDIX E

RESULTS OF PILOT-SCALE TESTS ON COLOURED WATER AT SANDHOOGTE WATER TREATMENT WORKS, MOSSEL BAY

RUN M5.1: FILTRATION RATE 5 m/h and 100 mg/ℓ ALUM

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Aℓ
		Apparent	True		
2 hours					
Raw	3,99	513	347	0,47	
After upflow	4,73	11	7	9,2	
After downflow	4,70	16	<5	1,6	0,5
4 hours					
Raw	3,94	513	417	0,49	
After upflow	4,99	27	7	12,0	
After downflow	4,80	31	<5	7,5	
6 hours					
Raw	3,95	507	415	0,47	
After upflow	4,47	14	<5	11,0	
After downflow	4,48	23	<5	3,5	
8 hours					
Raw	4,10	515	415	0,45	
After upflow	4,48	22	<5	12,0	
After downflow	4,35	23	<5	2,4	0,4
11 hours					
Raw	3,96	529	428	0,46	
After upflow	4,49	27	<5	14,0	
After downflow	4,41	65	<5	12,0	

13 hours					
Raw	3,93	506	415	0,47	
After upflow	4,70	22	<5	12,0	
After downflow	4,55	40	<5	5,7	3,3
15 hours					
Raw	3,94	513	417	0,49	
After upflow	4,99	27	7	12,0	
After downflow	4,80	31	<5	7,5	
17 hours					
Raw	3,99	509	411	0,48	
After upflow	4,97	31	<5	12,0	
After downflow	4,90	38	<5	7,9	
19 hours					
Raw	4,98	507	411	0,47	
After upflow	4,79	31	<5	11,0	
After downflow	4,75	18	<5	6,7	
21 hours					
Raw	4,09	507	407	0,53	
After upflow	4,47	47	<5	12,0	
After downflow	4,43	33	<5	3,7	5,0

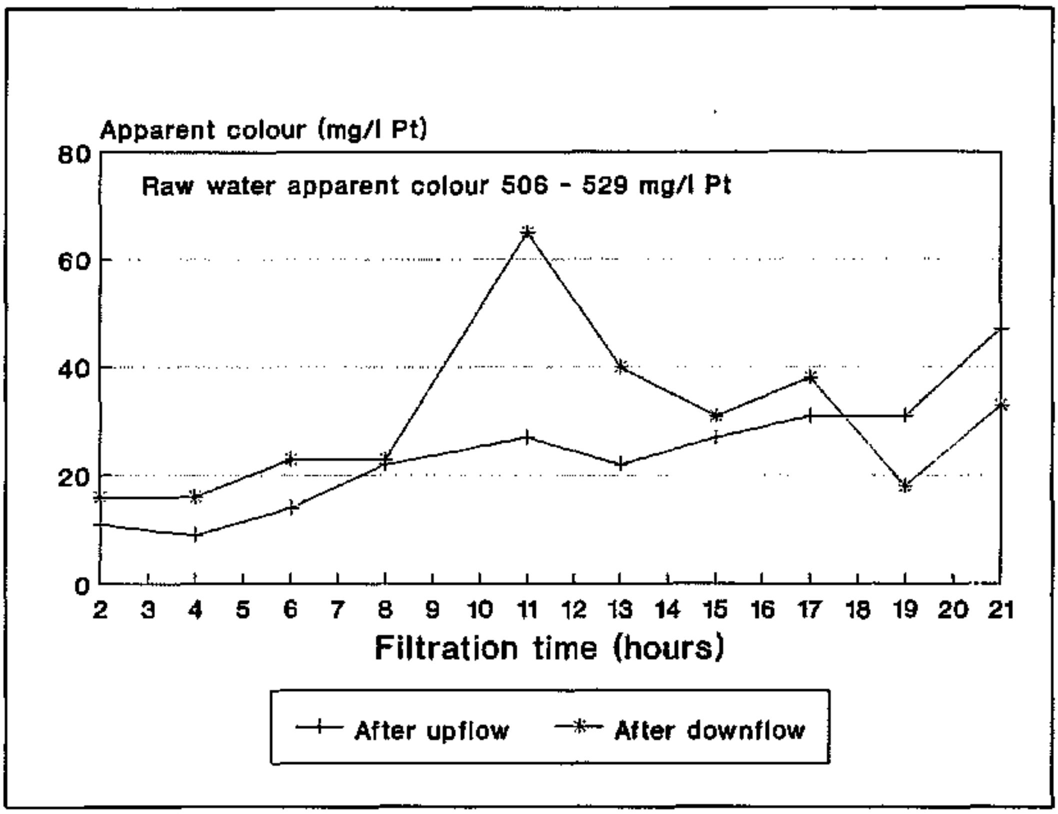


Figure E1 Apparent colour removal at Mossel Bay for RUN M5.1: Filtration rate 5 m/h and 100 mg/ℓ alum

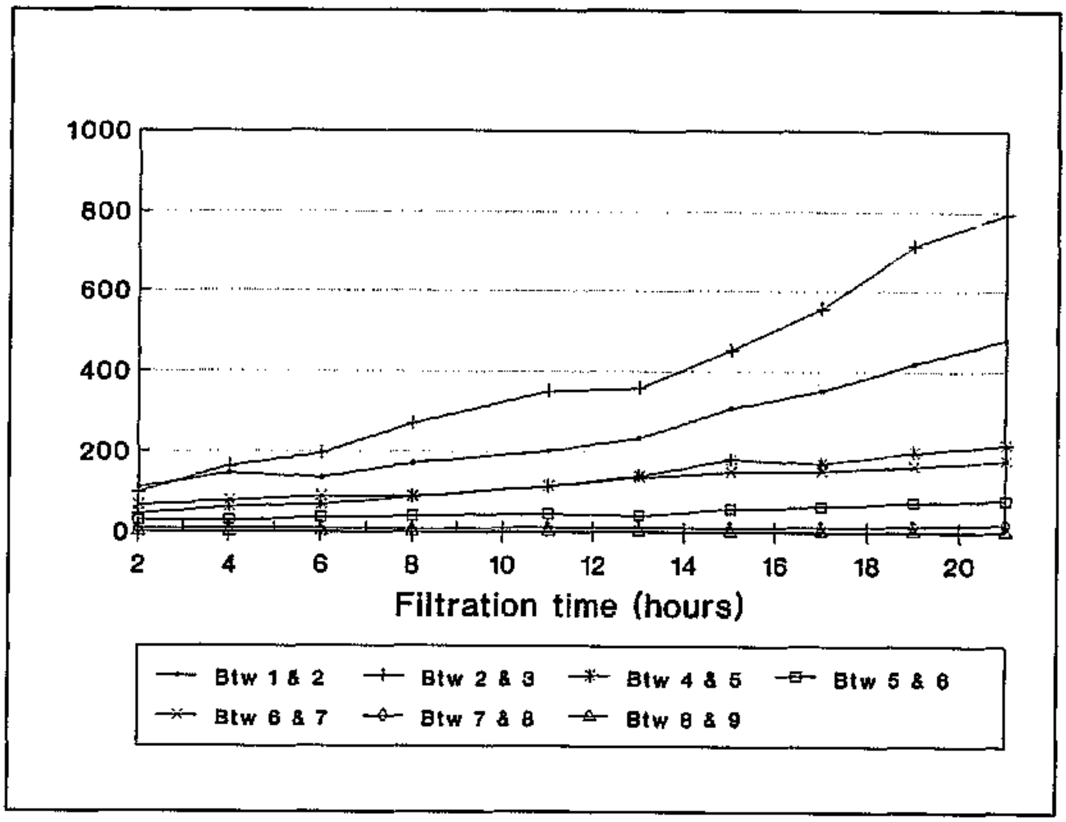


Figure E2 Head loss development in the filter for RUN M5.1: Filtration rate 5 m/h and 100 mg/ℓ alum

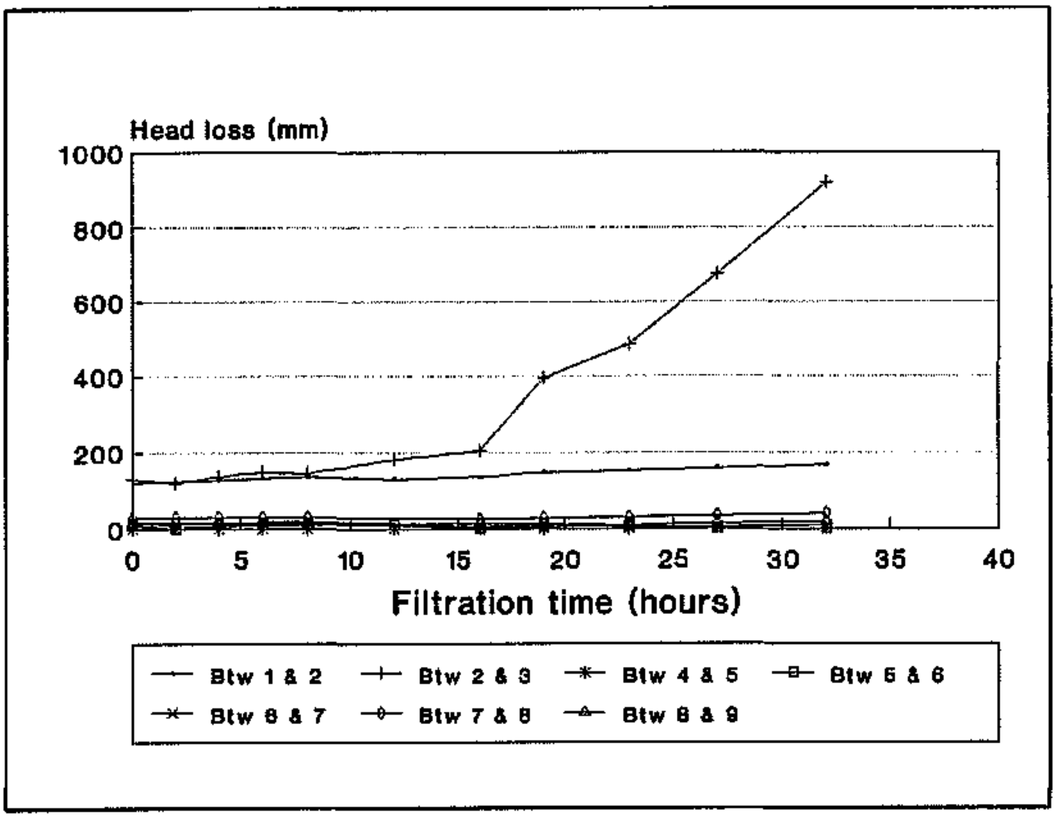


Figure D21 Head loss development in the filter for RUN R5.3: Filtration rate 5 m/h and 0,5 - 1 mg/ℓ LT 22

RUN R10.3: FILTRATION RATE 10 m/h and 0,5-1,0 mg/ℓ LT 22

Sample	pH	Turbidity (NTU)	Chlorophyll *a* (μg/ℓ)
1 hour			
Raw	7.64	28	6.07
After upflow	7.79	5.1	3.04
After downflow	8.04	3.1	1.6
3.12 hours			
Raw	8.56	31	6.2
After upflow	8.44	2.7	4.73
After downflow	8.68	3.6	4.55
3.5 hours			
Raw	8.75	30	4.6
After upflow	8.57	3.4	4.63
After downflow	8.39	2.2	4.3
4.5 hours			
Raw	8.73	32	5.4
After upflow	8.49	3.7	4.447
After downflow	8.71	2.4	4.55

RUN M10.1: FILTRATION RATE 10 m/h and 100 mg/ℓ ALUM

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Aℓ
		Apparent	True		
0.5 hours					
Raw	4,10	509	385	0,8	
After upflow	5,42	18	<5	17,0	
After downflow	5,33	47	11	0,45	0,9
1.5 hours					
Raw	3,80	528	417	0,74	
After upflow	6,54	350	<5	7,6	
After downflow	6,56	392	27	7,7	
2.5 hours					
Raw	3,86	513	409	0,68	
After upflow	5,78	31	<5	7,9	
After downflow	5,31	28	12	3,9	0,8
3.5 hours					
Raw	4,06	515	407	0,9	
After upflow	4,95	22	<5	8,7	
After downflow	5,32	9	<5	0,5	
4.5 hours					
Raw	3,93	533	426	0,74	
After upflow	5,54	91	7	5,6	
After downflow	5,03	56	<5	0,7	1,4

5.5 hours					
Raw	3,81	506	398	0,65	
After upflow	5,41	34	<5	8,6	
After downflow	5,55	49	<5	1,0	
6.5 hours					
Raw	3,99	515	418	0,78	
After upflow	5,78	144	7	8,5	
After downflow	5,56	49	9	8,0	2,5
7.5 hours					
Raw	3,99	509	407	0,43	
After upflow	5,10	135	<5	8,6	
After downflow	4,90	154	7	5,0	
9.5 hours					
Raw	3,96	506	407	0,45	
After upflow	4,89	150	<5	9,3	
After downflow	5,06	108	9	7,9	
10.5 hours					
Raw	3,99	531	415	0,44	
After upflow	5,32	49	<5	1,1	
After downflow	5,63	77	9	1,8	

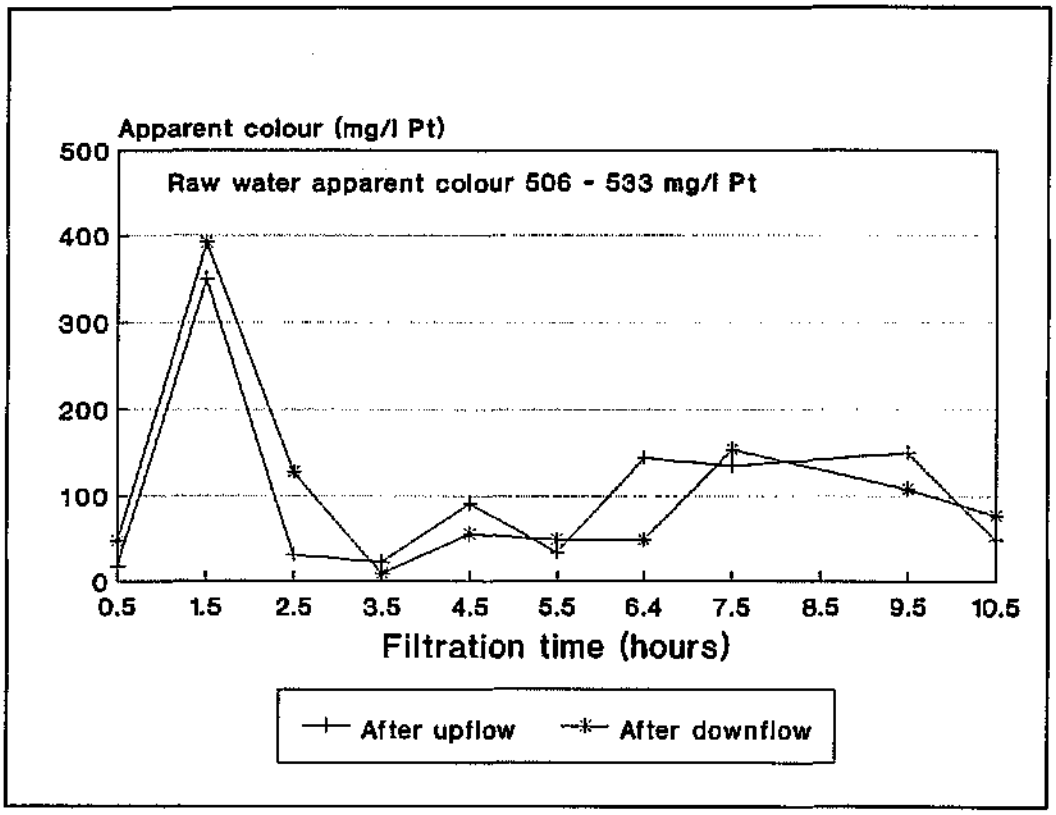


Figure E3 Apparent colour removal at Mossel Bay for RUN M10.1: Filtration rate 10 m/h and 100 mg/ℓ alum

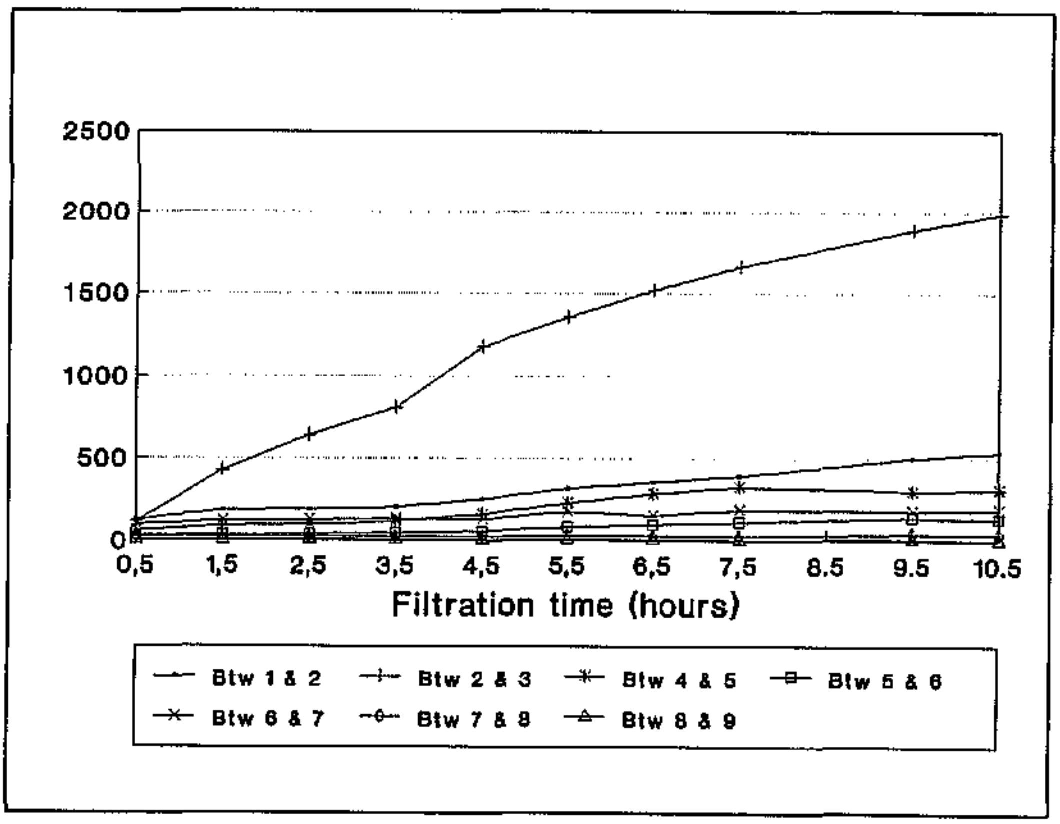


Figure E4 Head loss development in the filter for RUN M10.1): Filtration rate 10 m/h and 100 mg/ℓ alum

RUN M20.1: FILTRATION RATE 20 m/h and 100 mg/ℓ ALUM

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Aℓ
		Apparent	True		
0.5 hours					
Raw	3,88	517	420	0,78	
After upflow	5,12	33	5	16	
After downflow	5,86	192	11	18	0,6
1.5 hours					
Raw	3,81	502	418	0,81	
After upflow	5,18	62	<5	15	
5,40After downflow	5,40	77	16	10	
2.5 hours					
Raw	3,98	502	415	0,79	
After upflow	4,93	33	<5	15	
After downflow	4,93	18	<5	20	1,1
3.5 hours					
Raw	3,92	513	422	0,46	
After upflow	5,29	339	7	7,9	
After downflow	5,50	201	16	6,4	

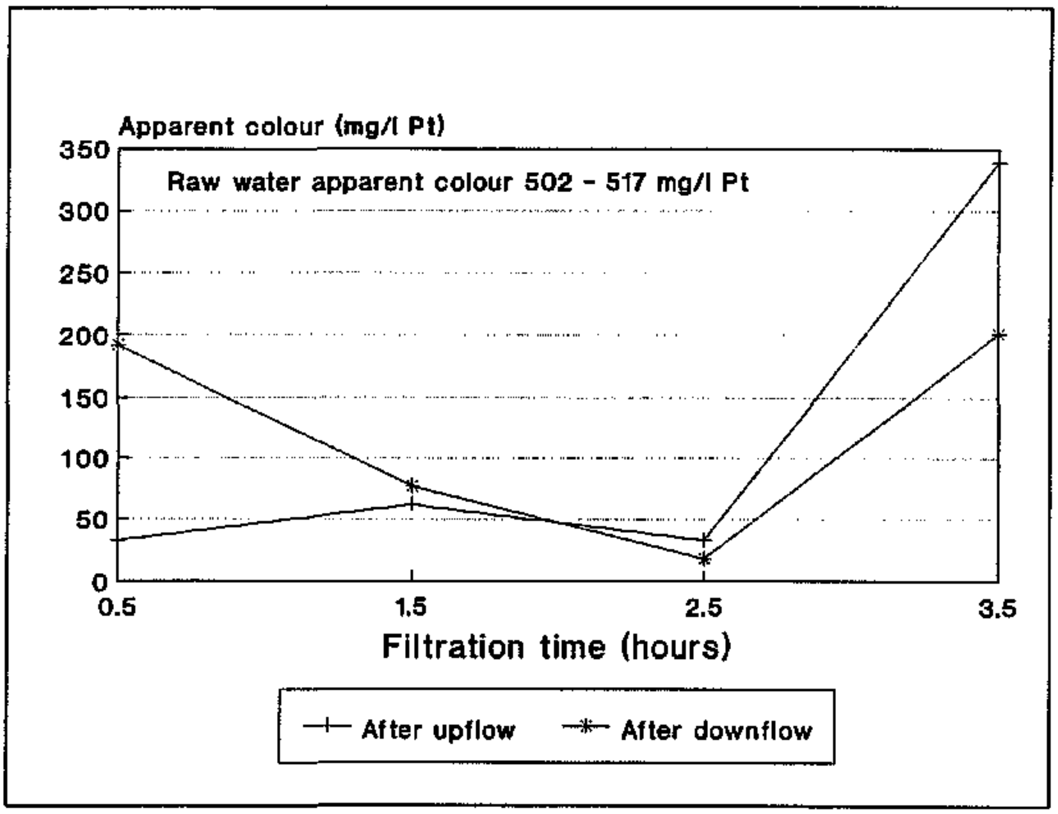


Figure E5 Apparent colour removal at Mossel Bay for RUN M20.1: Filtration rate 20 m/h and 100 mg/ℓ alum

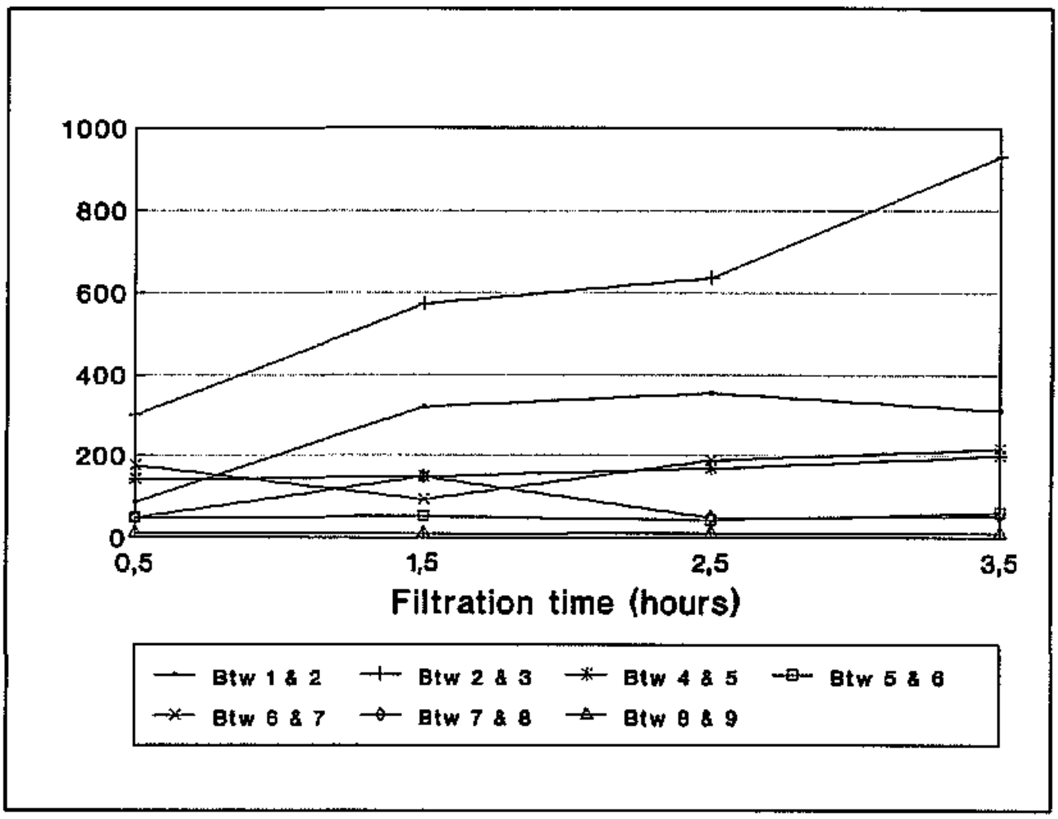


Figure E6 Head loss development in the filter for RUN M20.1: Filtration rate 20 m/h and 100 mg/ℓ alum

RUN M5.2: FILTRATION RATE 5 m/h, 140 mg/ℓ ALUM and 1,0 MG/ℓ LT 22

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Conductivity	Aℓ
		Apparent	True			
4 hours						
Raw	3,99	966	821	0,600	8	-
After upflow	5,31	97	<5	17	14	-
After downflow	5,32	102	7	16	15	-
8 hours						
Raw	4,03	926	814	0,41	8	-
After upflow	5,20	82	9	17	15	-
After downflow	4,80	67	<5	7,7	16	-
11 hours						
Raw	4,01	938	832	0,36	8	-
After upflow	5,07	47	12	17	18	-
After downflow	5,33	55	11	13	19	0,34
13 hours						
Raw	4,06	908	788	0,40	8	-
After upflow	4,53	42	<5	19	19	-
After downflow	5,05	42	<5	15	18	0,18
15 hours						
Raw	4,11	930	782	0,45	8	
After upflow	4,53	38	8	19	19	
After downflow	4,56	34	<5	17	19	0,77

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Conductivity	Aℓ
		Apparent	True			
17 hours						
Raw	4,12	918	795	0,40	8	-
After upflow	4,55	157	<5	19	20	-
After downflow	4,58	42	11	17	20	2,8
19 hours						
Raw	4,17	700	655	0,46	8	-
After upflow	4,52	127	<5	18	20	-
After downflow	4,56	82	<5	17	20	4,3

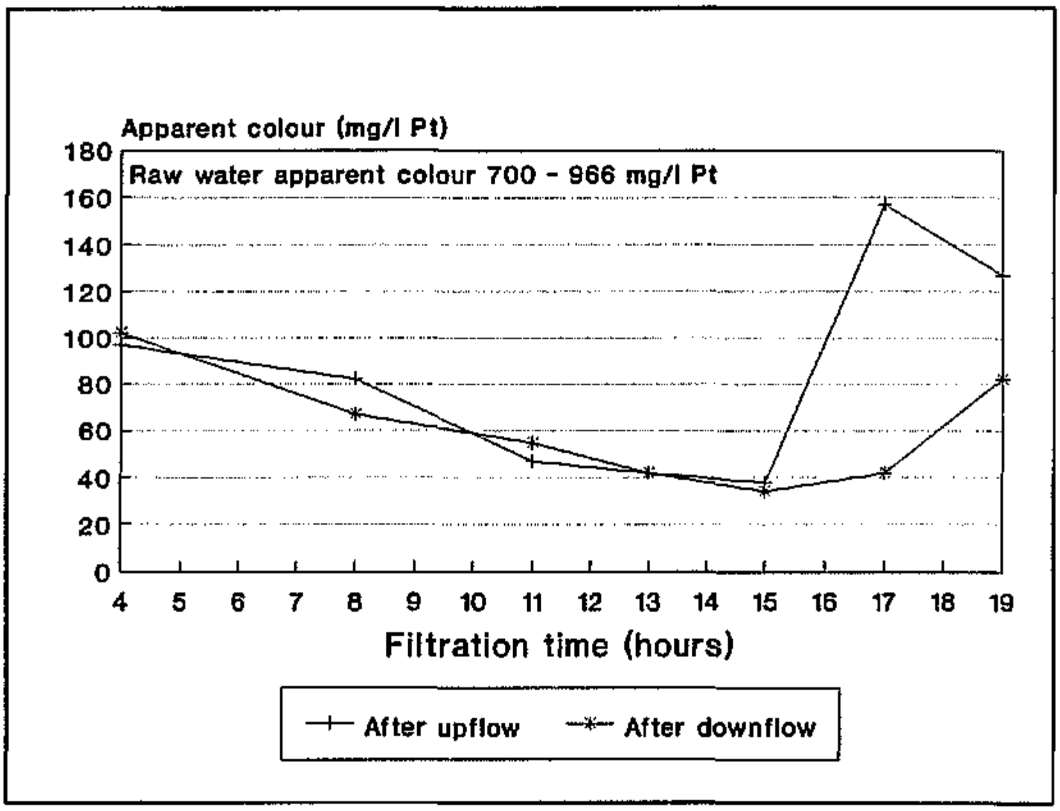


Figure E7 Apparent colour removal at Mossel Bay for RUN M5.2: Filtration rate 5 m/h, 140 mg/ℓ alum and 1,0 mg/ℓ LT 22

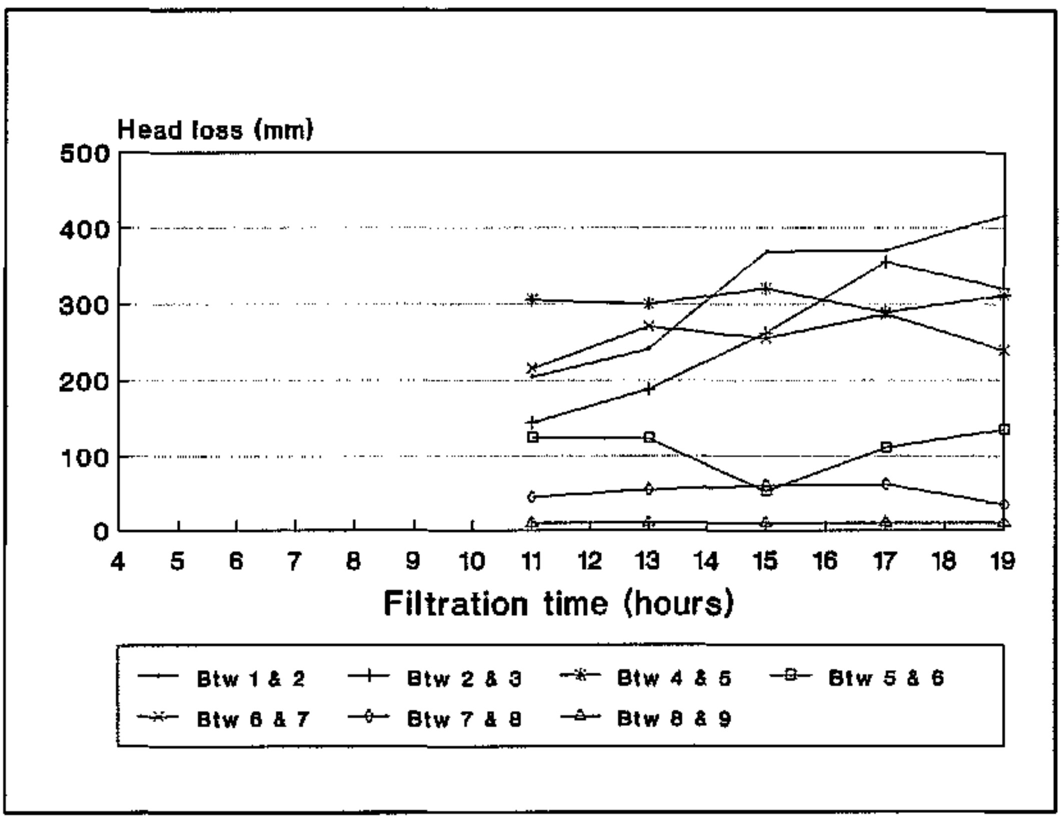


Figure E8 Head loss development in the filter for RUN M5.2: Filtration rate 5 m/h, 140 mg/ℓ alum and 1,0 mg/ℓ LT 22

RUN M10.2: FILTRATION RATE 10 m/h, 140 mg/ℓ ALUM and 1,0 mg/ℓ LT 22

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Conductivity	Aℓ
		Apparent	True			
2 hours						
Raw	3,98	978	827	0,54	8	-
After upflow	6,01	748	179	5,5	18	-
After downflow	5,36	998	122	1,5	18	-
4 hours						
Raw	4,02	954	804	0,52	8	-
After upflow	5,89	247	22	14	20	-
After downflow	5,88	86	6	13	20	0,54
6 hours						
Raw	3,99	950	820	0,55	8	-
After upflow	4,66	38	8	15	19	-
After downflow	4,81	196	18	15	19	0,32
8 hours						
Raw	4,00	938	797	0,60	8	-
After upflow	4,68	38	<5	15	20	-
After downflow	4,75	44	<5	15	20	0,19

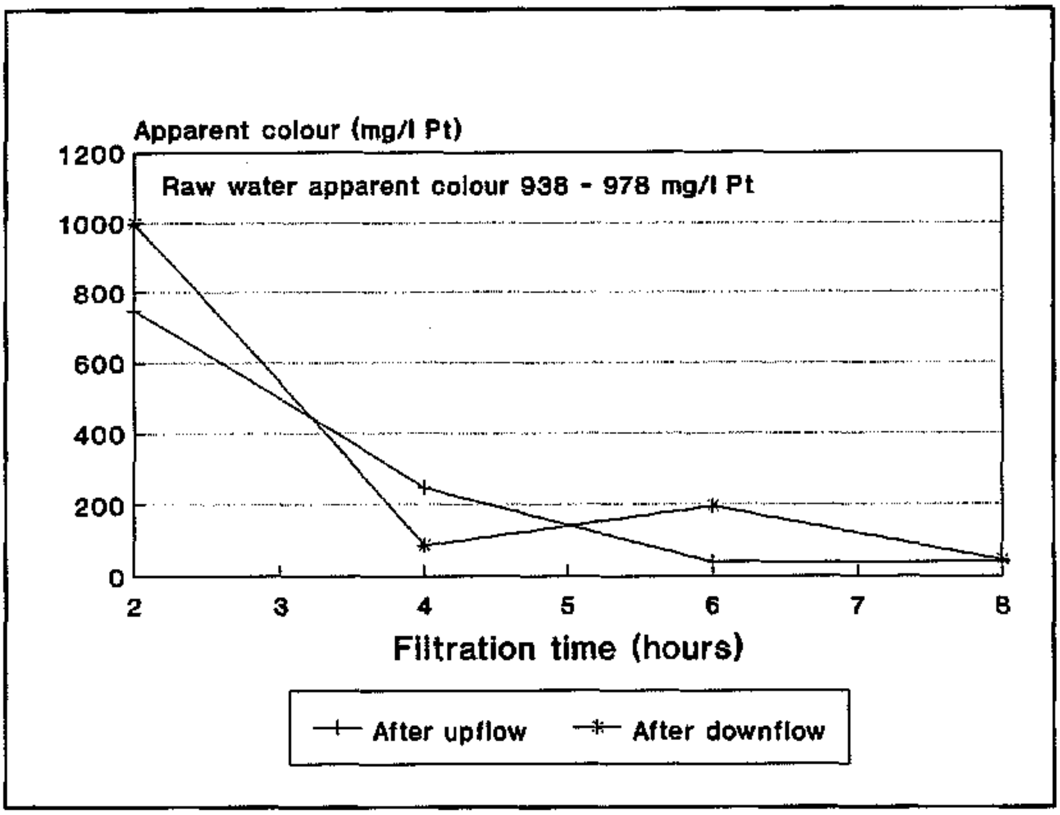


Figure E9 Apparent colour removal at Mossel Bay for RUN M10.2: Filtration rate 10 m/h, 140 mg/ℓ alum and 1,0 mg/ℓ LT 22

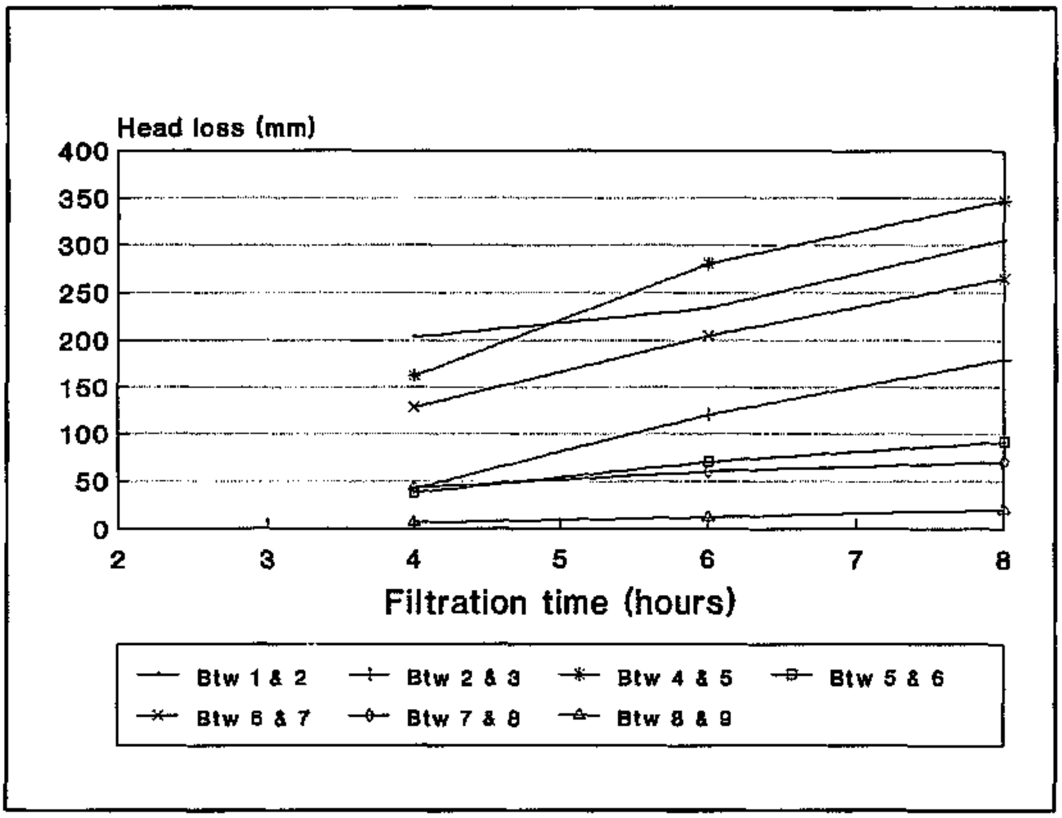


Figure E10 Head loss development in the filter for RUN M10.2: Filtration rate 10 m/h, 140 mg/ℓ alum and 1,0 mg/ℓ LT 22

RUN M20.2: FILTRATION RATE 20 m/h, 140 mg/ℓ ALUM and 1,0 mg/ℓ LT 22

Sample	pH	Colour (mg/ℓ Pt)		Turbidity	Conductivity	Aℓ
		Apparent	True			
2 hours						
Raw	3,95	941	820	0,51	8	-
After upflow	4,62	60	<5	16	17	-
After downflow	4,51	60	<5	15	17	0,31
4 hours						
Raw	3,95	982	836	0,54	8	-
After upflow	4,52	53	<5	16	17	-
After downflow	4,54	62	<5	15	17	0,31

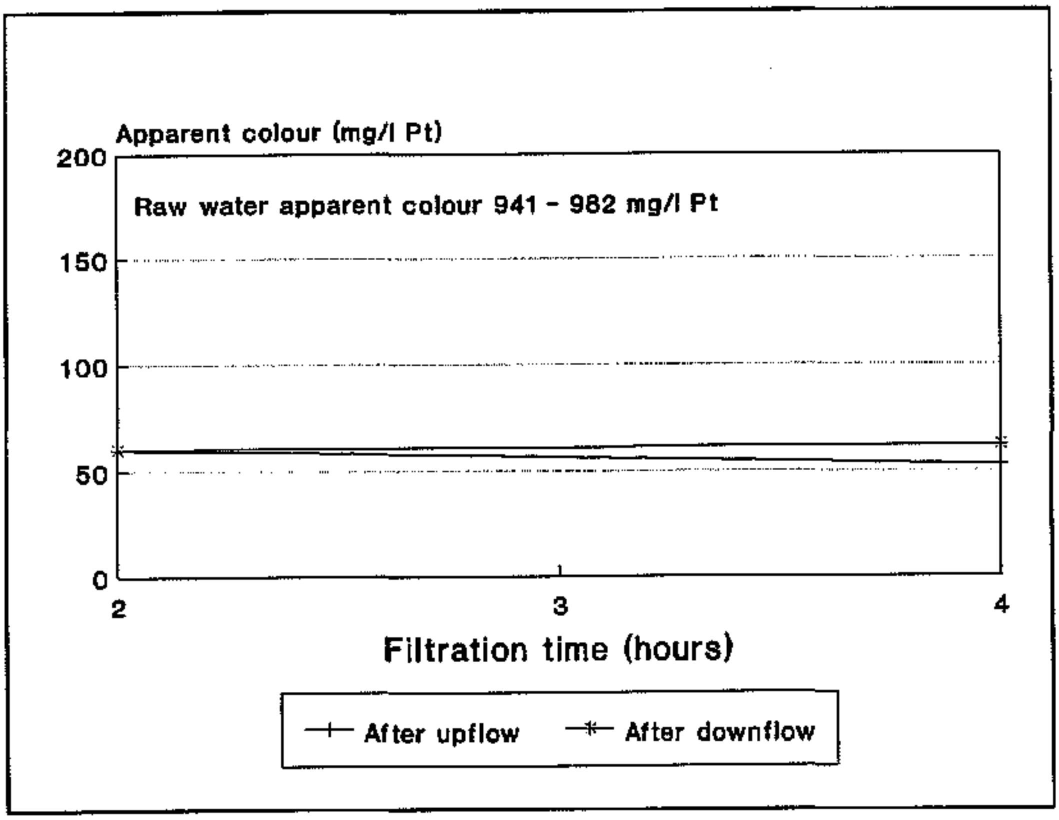


Figure E11 **Apparent colour removal at Mossel Bay for RUN M20.2: Filtration rate 20 m/h, 140 mg/ℓ alum and 1,0 mg/ℓ LT 22**

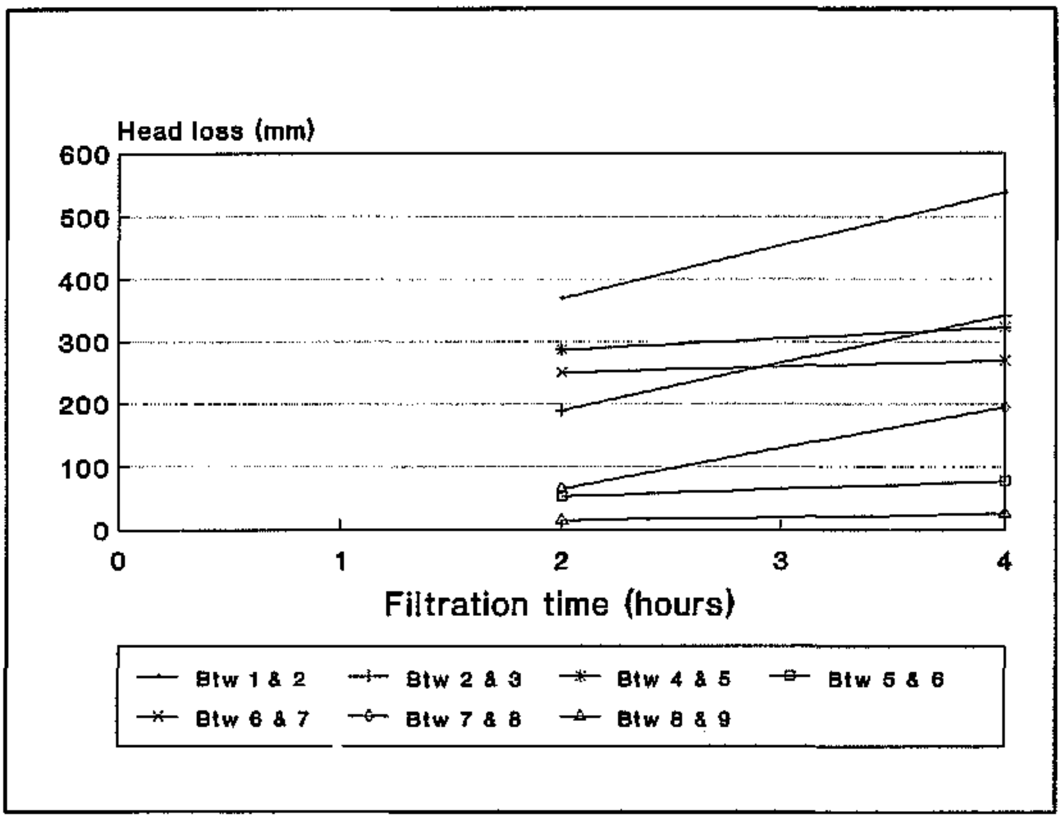


Figure E12 **Head loss development in the filter for RUN M20.2: Filtration rate 20 m/h, 140 mg/ℓ alum and 1,0 mg/ℓ LT 22**