Water
Research
Commission

[redacted]

Package Water Treatment Plant Selection
Part 1- Guidelines.

WJ Voortman and CD Reddy

WRC Report NO. 450/1/97

UMGENI WATER

PROCESS EVALUATION FACILITY
SCIENTIFIC SERVICES DIVISION

and

UNIVERSITY OF NATAL

POLLUTION RESEARCH GROUP
DEPARTMENT OF CHEMICAL ENGINEERING

Report to the

WATER RESEARCH COMMISSION

on

PACKAGE WATER TREATMENT PLANT SELECTION

PART 1

GUIDELINES

by

WJ VOORTMAN AND CD REDDY

WRC Report No. 450/1/97
ISBN No. 1 86845 301 4

PRETORIA

Executive Summary

Performance Criteria for Package Water Treatment Plants

by

W J VOORTMAN AND C D REDDY

Umgeni Water
P O Box 9
Pietermaritzburg
3200

Project Leader:	G E RENCKEN D A B KERDACHI
Project Researchers	W J VOORTMAN C D REDDY

Executive Summary

Background

The supply of potable water to rural and peri-urban areas is considered to be a national development priority and this is reflected in the recent white paper on water and sanitation compiled by the Department of Water Affairs and Forestry. The Water Research Commission has also acknowledged that research into appropriate technology for rural and peri-urban areas requires more attention than it has received in the past. This is highlighted in the 1991 WRC master plan on research of potable water.

The Pollution Research Group of the Chemical Engineering Department of the University of Natal and Umgeni Water realised that package and preconstructed plants have a major role to play in the provision of water to remote rural areas. Package water treatment plants also form a component of Umgeni Water's strategy in providing a cost-effective supply of purified water to regions where the population does not have a reliable supply. However, there is a dearth of information in South Africa on package plants for water treatment under local conditions, and no formal testing programme or evaluation criteria have been developed.

Hence, it was recognised that in order to assist smaller organisations and consulting firms and to provide positive feedback to the designers and vendors of such equipment, there was a dire need to develop formal testing procedures in conjunction with all the classes of users and taking into account the range of capacities and the degree of sophistication required.

A joint submission was made to the WRC in 1991 for a project entitled "Performance Criteria for Package Water Treatment Plants" to address the inadequacies highlighted in the previous paragraphs. The project was approved and commenced in January 1992 at Umgeni Water's Process Evaluation Facility at the Wiggins Water Treatment Plant.

Objectives

The objectives of the project, as set out in the official WRC documentation, were to:

- Determine the performance objectives by interviewing end users, water supply organisations, consultants, funding bodies, local, regional and governmental organisations.
- Set performance criteria for package water treatment plants.
- Evaluate a number of package water treatment plants against the performance criteria.

  Since there are a variety of performance objectives for package water treatment plant these had to be codified and ordered. Examples of the performance objectives are:

  - Raw water characteristics and availability;
  - Volume of water required and demand elasticity;
  - Sophistication of operating staff;

  - Source of power;
  - Required plant life; and
  - Service frequency.
- Disseminate information in the form of guidelines on the performance of package water treatment plants.

Evaluation Criteria and Postal Survey

A list of evalution criteria based on the engineering experiences of members of Umgeni Water and the Pollution Research Group was prepared by the project researchers. A postal survey was conducted in which various consultants, research institutions and Southern African government institutions were requested to comment on the proposed list of evaluation criteria. A number of useful comments were received and incorporated into the evaluation criteria. The criteria were then used to establish an evaluation methodology for package water treatment plants. The importance of having operating manuals written in the operator's home language was stressed by several respondents to the postal survey.

Package Plants Evaluated

Ten package water treatment plants comprising of a range of different turbidity removal and disinfection technologies were evaluated during the experimental phase of the project. The evaluations were carried out from October 1992 to July 1994 and the plants were evaluated as supplied. Minor modifications were carried out on some of the systems to improve performance and these modifications are documented in the reports on the individual plants.

The Ten Package Water Treatment Plants were:

	SUPPLIER	PROCESS TECHNOLOGY
1)	Atomic Energy Corporation (AEC)	: Ceramic microfiltration
2)	Aquatek (Pty) Ltd	: Dual media direct pressure filtration with chlorination
3)	In-house design	: Diatomaceous earth filtration
4)	Explochem Water Treatment (Pty) Ltd	: Crossflow microfiltration
5)	Division of Water Technology, CSIR	: Conventional* with optional UV disinfection
6)	Explochem Water Treatment Pty (Ltd)	: Direct upflow filtration
7)	Johnson's cc.	: Solar powered UV disinfection with cartridge filtration
8)	Select Water & Engineering Services	: Batch settling and filtration with chlorination
9)	Vector Environmental Technologies Inc.	: GAC series filtration with iodine disinfection
10)	In-house design	: Slow sand filtration

* The package plant consisted of sequential coagulation/flocculation, sedimentation, filtration and disinfection.

The range of technologies varied from simple (e.g. slow sand filtration) to sophisticated (e.g. GAC series filtration with iodine disinfection)

Water Quality Guidelines

The quality of treated water produced by the plants was assessed in terms of the 1994 draft guidelines for potable water quality produced by the Department of National Health and Population Development.

Package Plant Evaluation Results

The package plants were all evaluated according to the evaluation methodology and detailed reports on their design and performance are provided. A summary of the most pertinent results is given in the following paragraphs.

Water Treatment Performance

- **Disinfection :** The diatomaceous earth filter and the upflow filter unit were development prototypes and were not fitted with disinfection systems. The eight remaining units were able to remove or destroy faecal microorganisms satisfactorily. In the batch settling and filtration unit adequate chlorine residuals were obtained but poor disinfection results were recorded because there there was insufficient chlorine contact time between the point of chlorine addition and the sampling point. In practice, when used with a treated water reservoir, adequate contact time will occur and satisfactory disinfection results should be obtained.

- **Turbidity and Aesthetics :** Excellent turbidity removal, beyond that required for potable water was achieved with the two microfiltration units. The dual media and upflow filter systems produced water with a turbidity well below 1 NTU for most of the evaluation period. Poor turbidity removal was obtained with the diatomaceous earth filtration unit due to problems with the filter bags. The cartridge filter system used for the solar powered UV unit removed only 30% of the influent turbidity.

- **Micro Pollutant Removal :** Three of the systems exhibited undesirable breakthrough of chemicals used in the treatment process:

  - Occasional iodide ion breakthrough occurred with the GAC series filtration unit when the resin in the ion exchanger cartridge became saturated with respect to iodide.

  - Total aluminium concentrations in excess of 0,7 mg/l were consistently detected in the treated water from the batch settling and filtration system. Investigations showed that this was due to micro colloidal aluminium hydroxide passing through the filter.

  - Inefficient rinsing of the ceramic microfiltration unit during the acid/alkali wash procedure could produce concentrations of nitrates well above the guideline limits in the treated water.

  The GAC series filtration system is capable of removing many organic and certain inorganic micropollutants. None of the other plants evaluated had this capability.

- **Sludges and Effluents :** Two of the plants, the slow sand filter and the solar powered UV unit produced negligible quantities of effluent, while the rest all produced effluents containing various combinations of suspended solids, water treatment chemicals, filter media and cleaning chemicals. Provision for handling and disposal of these waste products must therefore be included in the design phase of water supply schemes where package water treatment plants will be used.

- **Robustness and Reliability** : In general, the choice of materials in all plants was satisfactory and no failures due to inappropriate materials occurred during the evaluation period.
- **Potential for upgrading capacity** : The only system in which significant potential for increasing the treatment capacity exists is the crossflow microfiltration unit. The purchase and installation of additional crossflow modules represents a relatively inexpensive method of increasing plant capacity. In all the other systems, significant capacity increases require the purchase of additional package units.
- **Control systems** : Six of the systems were manually controlled, two were partially automated and two were fully automated. On the whole, the control systems were effective but in many cases, inexpensive modifications were required to improve the overall reliability of the process and reduce the operating workload. Since most manufacturers have attempted to minimize the capital costs, there is a lack of alarm systems or automated cut-outs which shut off the plants when an alarm condition arises. The addition of automated cut-outs for high filter pressures or low chemical tanks levels will remove the requirement for the plant to be continually manned while in operation and will decrease the risk of mechanical failures or contamination of the treated water supply.

Maintenance Requirements

Regular maintenance is essential to ensuring that package water treatment systems function correctly. Most of the spares and consumables required for the units that were evaluated are available locally. However, the thread used for the pipe fittings on the GAC series filtration unit was not compatible with locally available metric and British Standard fittings. The availablility of proprietary chemical formulations and filter media for this unit was also limited to the local distributor who, at the time of the evaluation, had a single agency in the PWV region.

Operation and Operator Training Requirements

Proper operation of package water treatment plants is essential if a reliable supply of potable quality water is required. The ten systems under investigation were rated in terms of complexity of operation on a scale which varied from simple to expert. Recommendations are made for each system with respect to the skills and training that an operator would require. This is an important aspect that will provide a guide as to the level of operator skill required for any of the systems. Recommendations for the content of package plant operating manauals are also provided.

The manuals supplied with the GAC series filtration system and the conventional process were comprehensive, including instructions for installation, commissioning, operation, maintenance and trouble shooting. Both these manuals were well illustrated and cross referenced. Plant operating manuals were not supplied for the prototype slow sand filter, upflow filter and crossflow microfiltration units. The manuals for the remaining five plants were rudimentary, generally only providing basic operating and maintenance notes.

None of the operating manuals for the systems under investigation were available in any of the indigenous African languages. Since these systems are likely to be used in rural areas, it is essential that operating manuals are made available in languages that are familiar to the community being served.

Capital and Operating Costs

The capital costs quoted in this study are based on the manufacturer's 1994 ex-factory price, excluding VAT. The cost of delivery, raw water provision, electricity supply and civil work at the treatment plant site is not included. The considerable variations in the capital costs of the package plants are mainly due to variations in capacity (11 m^3/d to 240 m^3/d) and variations in the water treatment technology. When the capital costs are normalised for plant capacity, they range from R 6000 /(m^3/d) for the smaller capacity, high technology units to approximately R 200 /(m^3/d) for the larger capacity, lower technology processes. The additional cost of delivery, establishment of site infrastructure and engineering fees can effectively double these ex-factory costs. By comparison, the normalised capital cost of Umgeni Water's new 250 Mℓ/d Midmar plant will be approximately 460 R/(m^3/d) (including entire water treatment plant, sludge treatment plant and engineering fees but excluding the raw water pumpstation and the treated water storage).

Operating costs were estimated from the sum of the energy, labour, chemical and maintenance costs. Capital redemption costs and depreciation are not included. Labour costs were estimated at a rate of R 7,00 /h while actual costs were used wherever possible to estimate the energy, chemical and maintenance costs.

Operating costs varied from R 0,11 /m^3 for a 24 m^3/d slow sand filter to R 6,98 /m^3 for the high technology GAC series filtration unit (11 m^3/d). In plants with capacities up to approximately 240 m^3/d, the operating workload is not particularly sensitive to the plant capacity and labour costs therefore contribute significantly to the operating costs of smaller systems. Operating costs less than R 2,00 /m^3 are not likely to be achieved with any package plant smaller than 10 m^3/d in capacity.

These costs must be interpreted with caution. The 24 m^3/d slow sand filter system (which had the lowest estimated operating cost of R 0,11 /m^3) will only function well at turbidities up to 10 NTU and will not be able to deal with algae and algal by-products. On the other hand, the GAC series filtration unit can handle a wider range of turbidities, and is also able to remove organic and inorganic micropollutants.

All of the systems were evaluated as they were supplied and it was expected that there would be a wide range of operating costs. However, it must be stressed that each system has its niche in the market and will have an application depending on a variety of factors that have been detailed in the main report.

Technology Transfer Actions

- A set of guidelines for the selection and specification of package plants has been produced.
- Each Supplier was supplied with a detailed report on the performance of their respective units prior to the finalisation of the report. All of the comments received were very favourable and complimentary on the quality and standard of the work undertaken.

- Mr Voortman made a presentation to the WISA bimonthly meeting held in March 1995 in Pinetown on the subject of water treatment package plants. This presentation led to much discussion, and has resulted in many enquiries being directed to him on the subject matter and the future availability of the WRC report.
- Mr Voortman presented a paper entitled "Disinfection Methods for Package Water Treatment Plants" to the IWSA's International Specialised Conference on Disinfection of Potable Water held at the Kruger National Park in March 1994.

This draft report is intended as a basis for a guide that will allow consultants and water authorities to make an informed choice when selecting package water treatment plants. The following additional technology transfer actions are recommended:

- Continuous exhibition of various units at the PEF or other Umgeni Water sites.
- Compilation of a Register of package and small-scale water treatment plants installed in Southern Africa.
- Presentations at conferences and publishing of information in local and national water treatment journals.

……

It should be noted that the assessments presented in the main report consisting of Part I and Part II as well as the attachments do not in any way reflect an endorsement or rejection of any of the systems that were evaluated.

Acknowledgements

The research in this report emanates from a project funded jointly by the Water Research Commission and Umgeni Water and entitled :

"Performance Criteria for Package Water Treatment Plants".

The Steering Committee responsible for this project consisted of the following persons:

Mr G Offringa	Water Research Commission (Chairman)
Mr P Smit/ A Fritz	Water Research Commission (Secretary)
Dr TC Erasmus	Water Research Commission
Prof CA Buckley	University of Natal, Durban
Prof J Haarhof	Randse Afrikaanse Universiteit
Mr BM Jackson	Development Bank of Southern Africa
Prof WA Pretorius	University of Pretoria
Dr M Starzak	University of Natal, Durban
Mr RB Townsend	University of Natal, Durban
Mr PJ van der Merwe	GFJ Engineering
Mr JS Wium	Watertek, CSIR

The financing of the project by the Water Research Commission, the provision of laboratory and office facilities by Umgeni Water and the contribution of the members of the Steering Committee is gratefully acknowledged.

The various package plants evaluated as part of this project were donated free of charge for the duration of the evaluation by the manufacturers and vendors of the plants. Sincere thanks are therefore due to these companies and their representatives who were helpful at all times:

Mr K Treffry-Goatley	Explochem Water Treatment (Pty) Ltd
Messrs. J v.d.Mescht & D.Duane Dunk	Vector Environmental Technologies Inc.
Mr P Mossner	Select Water and Engineering Services (Pty) Ltd
Dr L Buchan	Control Chemicals (Pty) Ltd
Messrs. J Schewitz & R Claasens	Atlas Filter Co. (Pty) Ltd
Mr R Starke	Aquatek (Pty) Ltd
Messrs. B Johnson & C Johnson	Johnson's cc.
Mr M Gioia	UV Water Systems (Pty) Ltd
Messrs. C Swartz & D Whyte	Watertek, CSIR
Messrs. F Coetzer & A Posthumus	Atomic Energy Corporation

In addition, the authors would like to express their gratitude to the following people for their co-operation and assistance with the project:

Dr G.E. Rencken and Mr D Kerdachi for advice and guidance in the former and latter stages of the project respectively.

Prof CA Buckley of the Department of Chemical Engineering for inspiration and access to his personal library.

Mrs. A Marais of Umgeni Water's Library for help with literature searches and obtaining copies of various journal articles.

Dr B Rae, Mr I Bailey, Mrs J Abbot, Mr P Jonas and Ms J Govender and other staff of Umgeni Water's Scientific Services Laboratory in Pietermaritzburg for analysing nearly two thousand samples over the duration of the project.

Mr R Rajagopaul (Chief Technician), Messrs E N Luthuli, V Mhlongo, R Msweli, T Nyawose and Ms N Shange (Trainee Technicians) for their assistance in operating and maintaining the package plants during the course of the evaluations.

Table of Contents

Section Title **Page**

Part 1 : Guidelines

Executive Summary i
Acknowledgements viii
Table of Contents x
List of Tables xiii
List of Figures xv
List of Symbols xvii
1 **Introduction** 1
1.1 **WRC Package Plant Project** 1
1.2 **Umgeni Water's Process Evaluation Facility (PEF)** 2
1.2.1 Facilities and analytical services at the PEF 2
1.2.2 PEF raw water quality 2
1.3 **Evaluation criteria and methodology** 3
1.4 **Water treatment processes** 4
1.4.1 Characteristics of typical water treatment processes 4
1.4.2 Water Quality Guidelines 5
2 **Review of Water Treatment Technologies used in Packaged Water Treatment Systems** 7
2.1 **Water treatment chemical dosing** 7
2.1.1 Dosing equipment 7
2.1.2 Chemical preparation 8
2.1.3 Dose control 8
2.2 **Coagulation and flocculation** 9
2.2.1 Coagulant mixing in package plants 10
2.3 **Clarification and sedimentation processes** 11
2.3.1 Inclined tube settlers 11
2.3.2 Batch Sedimentation 12
2.3.3 Adsorption Clarifiers 13
2.4 **Filtration processes** 13
2.4.1 Depth filtration processes used in package plants 13
2.4.2 Cake filtration processes used in package plants 15
2.4.3 Slow sand filtration 19
2.4.4 Summary of typical Design parameters 20
2.5 **Disinfection and micro-organism removal** 20
2.5.1 Chemical disinfection processes 21
2.5.1.1 Chlorination 21
2.5.1.2 Iodination 23
2.5.1.3 Other biocides 23
2.5.2 Physical barrier processes 24

2.5.2.1 Slow sand filtration ... 24
2.5.2.2 Precoat (Crossflow) Microfiltration ... 24
2.5.2.3 Membrane microfiltration and ultrafiltration ... 25
2.5.3 Energy processes ... 25
2.5.4 Positioning of disinfectant dosing points ... 26

3 Guidelines for the Selection of Package Plants ... 27

3.1 Estimating the required plant capacity ... 27

3.2 Recommendations for the specification of plant components ... 28
3.2.1 Control systems ... 28
3.2.2 Chemical dosing ... 29
3.2.3 Filtration systems ... 31
3.2.3.1 Pressure sand filters ... 31
3.2.3.2 Slow sand filters ... 32
3.2.3.3 Precoat filtration systems ... 33
3.2.3.4 Membrane ultrafiltration and microfiltration systems ... 33
3.2.3.5 Cartridge filtration ... 33
3.2.4 Disinfection systems ... 34
3.2.4.1 UV disinfection ... 34
3.2.4.2 Chlorination systems ... 35
3.2.4.3 Other biocides ... 36
3.2.5 Micropollutant removal ... 36
3.2.6 Pumps ... 37
3.2.7 Tanks ... 37

3.3 Additional infrastructure requirements ... 37
3.3.1 Site preparation requirements ... 38
3.3.2 Additional equipment required for optimising and monitoring plant performance 38

3.4 Operation and maintenance of package plants in South Africa ... 39
3.4.1 Personnel requirements ... 39
3.4.1.1 Training ... 39
3.4.1.2 Plant operating manuals ... 39
3.4.2 Maintenance requirements ... 40
3.4.3 Availability of spares and consumables ... 41

3.5 Effluent handling ... 42
3.5.1 Effluent standards and legislation ... 42
3.5.2 Types of effluents and options for treating them ... 43

3.6 Effects of plant capacity on capital and operating costs ... 44
3.6.1 Capital cost ... 44
3.6.2 Operating cost ... 45

4 Future Research and Technology Transfer ... 47

Part 2 : Limited Comparative Performance Study

5 Summary of Package Plant Evaluations ... 50

5.1 Process Descriptions ... 51

5.2 Site preparation requirements ... 54

5.3 Personnel requirements ... 55
5.3.1 Operating and maintenance personnel requirements ... 55
5.3.2 Plant operating manuals ... 55

5.4 **Control systems** 56
5.4.1 Additional equipment for optimising and monitoring plant performance 57

5.5 **Water treatment performance** 57
5.5.1 Disinfection 57
5.5.2 Turbidity and Aesthetics 58
5.5.3 Micropollutant removal 58
5.5.4 Consumption of chemicals and other consumable items 59
5.5.4.1 Chemical economy 59
5.5.5 Sludges and effluents 62

5.6 **Robustness and reliability** 63
5.6.1 Materials of construction 63
5.6.2 Component failures 63
5.6.3 Reliability of processes and the consequences of component failures 63
5.6.4 Potential for expansion of capacity 64

5.7 **Maintenance and servicing** 64

5.8 **Capital and operating costs** 65
5.8.1 Capital cost 65
5.8.2 Operating cost 65
6 **AEC Ceramic Microfiltration Package Plant *** **68**
7 **Aquasprite Dual Media Pressure Filter *** **83**
8 **Diatomaceous Earth Filter *** **99**
9 **Crossflow Microfiltration Unit *** **117**
10 **CSIR Package Water Treatment Plant *** **131**
11 **Filtrex Direct Upflow Filter *** **151**
12 **Eliminator UV Unit *** **164**
13 **Watermaker Package Plant *** **181**
14 **Diamond Rain Water Purification Plant *** **202**
15 **Slow Sand Filter *** **219**
16 **References** **232**
Appendix 1 Evaluation testing methodology checklist .... **A1 - 1**
Appendix 2 Dept. of Health, 1994 Draft guidelines for drinking water quality .. **A2 - 1**

* **Note :** These sections comprise package plant evaluation reports which are structured according to the methodology checklist (**Appendix 1**). In order to avoid repetition, their sub-sections have not been included in the contents list.

List of Tables

Table .... **Page**

Section 1

Table 1.1 Typical raw water quality at the PEF 3
Table 1.2 Department of Health guidelines for potable water quality (abbreviated) .. 6

Section 2

Table 2.1 Operating and design parameters for package plant filter systems 20
Table 2.2 Advantages and disadvantages of various forms of chlorine 21
Table 2.3 Summarised comments on use of selected biocides 24

Section 5

Table 5.1 Manuafucturers and Plant Capacities 50
Table 5.2 Package Plant Diagrams 51
Table 5.3 Additional infrastructure required by various package plants 54
Table 5.4 Operating and maintenance workload 55
Table 5.5 Control Philosophies 56
Table 5.6 Additional equipment required for effective control of package plants 57
Table 5.7 Treatment system operating parameters 58
Table 5.8 Consumption of chemicals and consumables 60
Table 5.9 Summary of treated water quality achieved with the units tested 61
Table 5.10 Effluents produced by the package units 62
Table 5.11 Summary of materials of construction 63
Table 5.12 Spares and consumables with limited availability 65
Table 5.13 Capital cost of package plants 66
Table 5.14 Breakdown of estimated package plant operating costs 66

Section 6

Table 6.1 AEC package plant range 68
Table 6.2 Summary of components fitted to AEC pilot plant 70
Table 6.3 Microbiological results 75
Table 6.4 Algae removal for 100 nm module 75
Table 6.5 Water recovery 77
Table 6.6 Materials used 78
Table 6.7 Summary of operating costs 81

Section 7

Table 7.1 Aquasprite component list 84
Table 7.2 Monitoring of process operating parameters 86
Table 7.3 Disinfection results 91
Table 7.4 Summary of the materials of construction 94
Table 7.5 Expansion potential of the plant components 95
Table 7.6 Summary of operating costs 97

Section 8

Table 8.1 Manufacturer's specifications 99
Table 8.2 List of Process Components 100
Table 8.3 Comparison of operating parameters 112
Table 8.4 Consequences of filter component failures 113
Table 8.5 Capital cost 115
Table 8.6 Operating costs 116

Section 9

Table 9.1 Component list 118
Table 9.2 Monitoring of operating parameters 120
Table 9.3 Description of the workload requirements 122
Table 9.4 Microbiological removal 124
Table 9.5 Description of major materials of construction 127

Table 9.6 Expansion potential of the CFMF 128
Table 9.7 Maintenance problems encountered with the Exxflow unit 128
Table 9.8 Operating costs for the Exxflow plant 130

Section 10

Table 10.1 Summary of CSIR Package Plant Components 133
Table 10.2 Disinfection results for the treated water 141
Table 10.3 Summary of operating costs for CSIR package plant 149

Section 11

Table 11.1 Summary of installed equipment in the Filtrex pilot plant 152
Table 11.2 Filtrex design and operating parameters 153
Table 11.3 Monitoring of process parameters 154
Table 11.4 Microbiogical removal achieved with Filtrex process 158
Table 11.5 Materials of construction 160
Table 11.6 Estimated operating costs 163

Section 12

Table 12.1 Summary of Eliminator process components 165
Table 12.2 Disinfection results 173
Table 12.3 Typical disinfection efficiency at various flowrates 173
Table 12.4 A summary of the consequences of component failures 177
Table 12.5 Summary of operating costs 179

Section 13

Table 13.1 Summary of process components 183
Table 13.2 Disinfection results 191
Table 13.3 Summary of the consequences of component failures 197
Table 13.4 Estimated operating costs 200

Section 14

Table 14.1 Summary of installed equipment 203
Table 14.2 Microbiological results for samples of raw and treated water 208
Table 14.3 Turbidity removal across process components 210
Table 14.4 Micro-pollutant removal 213
Table 14.5 Approximate service life of cartridge filters and other media 214
Table 14.6 Estimated operating cost for DRWP2 plant 217
Table 14.7 Estimated cost of consumables for DRWP2 plant 218

Section 15

Table 15.1 Design parameters 220
Table 15.2 Summary of slow sand filter components 221
Table 15.3 Micro-organism removal 225
Table 15.4 Summary of turbidity removal 227
Table 15.5 Estimated operating cost 230

Appendix 2

Table A2-1 Guideline values for microbiological and biological quality of drinking water .... A2 - 1
Table A2-2 Guideline values for substances affecting the aesthetic quality of drinking water .... A2 - 2
Table A2-3 Guideline values for inorganic and radioactive substances of health significance in drinking water .... A2 - 3
Table A2-4 Guideline values for organic substances of health significance in drinking water .... A2 - 4
Table A2-5 Recommended frequency for the testing of inorganic determinands in drinking water supplies .... A2 - 5
Table A2-6 Recommended frequency for the microbiological testing of drinking water supplies .... A2 - 5

Figure 12.2 Relationship between raw and filtered water turbidity 175

Section 13

Figure 13.1 Batch process flowchart 182
Figure 13.2 Control system 186
Figure 13.3 In-line chlorine dispensing system 191
Figure 13.4 Variation of chlorine residual during batch filtration 192
Figure 13.5 Turbidity removal 193
Figure 13.6 Raw vs Final turbidity showing effects of plant modifications 194

Section 14

Figure 14.1 Process flow diagram 203
Figure 14.2 Turbidity removal 211

Section 15

Figure 15.1 Slow sand filter process flow diagram 220
Figure 15.2 Turbidity trends for pilot slow sand filters 226

List of Figures

Figure .... **Page**

Section 1

Figure 1.1 A typical conventional water treatment process 4

Section 2

Figure 2.1 Conventional package plant with inclined tube settler 12
Figure 2.2 Batch sedimentation and filtration system 12
Figure 2.3 Dual media direct pressure filter 14
Figure 2.4 Direct upflow filter 15
Figure 2.5 Diatomaceous earth filter 16
Figure 2.6 Crossflow microfiltration process 16
Figure 2.7 Prototype ceramic microfiltration process 17
Figure 2.8 Multiple cartridge and GAC filtration with iodination 18
Figure 2.9 Slow Sand Filter 19
Figure 2.10 Solar powered UV disinfection system 26

Section 5

Figure 3.1 Effect of capacity on normalised capital cost 44
Figure 3.2 Effect of capacity on operating cost for various package plants 45

Section 6

Figure 6.1 Ceramic microfilter process flow diagram 69
Figure 6.2a Turbidity removal and flux variation for the 50 nm module 76
Figure 6.2b Turbidity removal and flux variation for the 100 nm module 76
Figure 6.2c Turbidity removal and flux variation for the 200 nm module 77

Section 7

Figure 7.1 Dual-media pressure filter process flow diagram 83
Figure 7.2 Filter feedwater pressure fluctuations 87
Figure 7.3 Turbidity removal 92

Section 8

Figure 8.1 Diatomaceous earth filter process flow diagram 100
Figure 8.2 Permeate flow in filter cores during filtration and backwash 101
Figure 8.3 Turbidity removal 109
Figure 8.4 Relationship between raw and filtered water turbidity 109
Figure 8.5 Effect of pressure drop on turbidity removal 110
Figure 8.6 Pressure drop and flowrate variations during Run 2 110

Section 9

Figure 9.1 Cross-flow microfilter process flow diagram 118
Figure 9.2 Permeate flux for various operating conditions 126
Figure 9.3 Cross-flow microfilter turbidity removal 126

Section 10

Figure 10.1 CSIR package plant flowchart 132
Figure 10.2 Physical layout of plant 132
Figure 10.3 Turbidity removal 143
Figure 10.4 Raw water vs treated water turbidity 143

Section 11

Figure 11.1 Upflow filter process flow diagram 152
Figure 11.2 Solids loading and pressure drop for a specific run 155
Figure 11.3 Turbidity removal 158
Figure 11.4 Treated water turbidity as a function of raw water turbidity 159

Section 12

Figure 12.1 UV unit process flow diagram 165

List of Symbols

a.c.	alternating current
AEC	Atomic Energy Corporation
CFMF	cross-flow microfiltration
CSIR	Council for Scientific and Industrial Research
d.c.	direct current
DE	diatomaceous earth
DWA	Department of Water Affairs (South Africa, see DWA&F)
DWA&F	Department of Water Affairs and Forestry (South Africa) formerly known as Department of Water Affairs (see DWA)
EPA	Environmental Protection Agency (United States of America)
GAC	granular activated carbon
HPC	heterotrophic plate counts
NTU	Nephelometric Turbidity Units
MF	microfiltration
PAC	powdered activated carbon
PACl	polyaluminium chloride
PEF	Process Evaluation Facility (Umgeni Water)
RDP	Reconstruction and Develpment Program (South Africa)
RWQO	receiving water quality objectives
SABS	South African Bureau of Standards
SSF	slow sand filter
TDS	total dissolved solids
UF	ultrafiltration
USA	United States of America
USEPA	see EPA

1 Introduction

The supply of potable water to rural and Peri-urban areas in South Africa is a national development priority and is being addressed by the South African Government's Reconstruction and Development Programme (RDP). Prefabricated package water treatment plants have considerable potential for addressing this need. Some of their perceived advantages include:

- **Suitable capacity** for small and isolated settlements in rural areas.
- **Rapid deployment.** Most package plants are compact, can be transported by road and can be operating at full capacity within days of delivery.
- **Mobility.** Many package plant systems are suitable for dismantling, relocation and installation within a short time period.
- **Lower capital costs** than fixed structures or processes of similar capacity.
- **Simplified operation** and maintenance procedures in comparison with conventional water treatment processes.

There has been a reluctance by consultants, development agencies and smaller local authorities to specify package plants for use in their water supply schemes. This reluctance stems from:

- the lack of a formal evaluation methodology by which comparisons of plant performance may be made. *Ad hoc* evaluations of individual plants in the past by various organisations have not produced comparable results.
- uncertainty about the long term operating costs and performance of package water treatment plants which has arisen from the lack of a formal evaluation methodology.

1.1 WRC Package Plant Project

A joint project, funded by the Water Research Commission and conducted by Umgeni Water in conjunction with the Pollution Research Group (University of Natal) , was initiated in January 1992. The objectives of this project were to:

- Establish a set of **performance criteria** for package water treatment plants.
- Develop a **testing methodology** for evaluating package plants from these criteria.
- **Evaluate** a number of **plants** against these criteria using the methodology.
- **Disseminate information** on the performance of the tested plants so as to enable consultants or other interested bodies to make an informed choice of plant for any particular application.
- **Provide feedback** on plant performance **to the manufacturers** or vendors that will allow them to improve their products.

Performance criteria were compiled and circulated for comment (see **Section 1.3**). An evaluation methodology incorporating the performance criteria was prepared and used for the evaluation of a number of package water treatment plants and prototypes during the period from September 1992 to September 1994. These evaluations culminated in the production of this report which is issued in two parts:

Part 1 : Consisting of **Sections 1 to 4**, this is a generalised document which provides performance and selection criteria as guidelines for the design, selection and implementation of package water treatment plants.

Part 2 : Consisting of **Sections 5 to 15** and **Appendices 1 and 2**, this is a limited comparative performance study in which the actual performance of the evaluated package plants is discussed in terms of the evaluation methodology (see **Section 1.3**).

The use of trade names in connection with various products in Part 2 of this report does not constitute an endorsement of those products by the Water Research Commission, Umgeni Water or the University of Natal.

1.2 Umgeni Water's Process Evaluation Facility

The evaluations were carried out at Umgeni Water's Process Evaluation Facility (PEF) situated at the Wiggins water treatment plant site in Durban. The PEF is used for pilot plant studies to evaluate water treatment processes. Raw and domestic (treated) water is available from manifolds in the main laboratory and the raw water was used for the package plant evaluations. The plants were not evaluated under field conditions.

1.2.1 Facilities and analytical services at the PEF

A pipeline from the surge tower at the head of the Wiggins plant provides a flow of up to 100 m^3/h of raw water. Single phase (220 V) and three-phase (380 V) electrical power, a sludge capture system and basic analytical facilities are available. Umgeni Water's central Scientific Services laboratory (SABS accredited) in Pietermaritzburg provided the facilities for the analysis of microbiological and micropollutant contamination in raw and treated waters.

1.2.2 PEF raw water quality

The raw water source varied during the evaluation period. From the beginning of the project until July 1994, raw water was sourced from the Clermont pump station on the Umgeni River. The Inanda Wiggins tunnel was commissioned in July 1994 and from then until the end of the project, raw water was sourced from the Inanda dam. The Inanda dam water was characterised by low turbidity (typically less than 3,5 NTU) and significantly lower microbiological contamination. The quality of the raw water during the evaluation period is summarised in **Table 1.1**.

Table 1.1 : Typical raw water quality at the PEF

Determinand	Units	Average	Range
Chlorophyll a	µg/ℓ	2,3	0,30 - 5,35
pH	pH units	7,6	6,90 - 8,40
Colour	Hazen units	9,3	2,2 - 33,9
Turbidity	NTU	14,8	1,86 - 4000
Conductivity	mS/m @ 20°C	19,5	7,3 - 35,1
Total Aluminium	µg/ℓ	206	10 - 4099
Alkalinity	mg/ℓ as $CaCO_3$	50,5	25 - 71
Total Hardness	mg/ℓ as $CaCO_3$	58,8	35 - 69
Calcium	mg/ℓ	9,8	5,0 - 13,5
Magnesium	mg/ℓ	5,8	3,2 - 8,6
Sodium	mg/ℓ	20,1	5,1 - 35,8
Potassium	mg/ℓ	2,5	1,2 - 5,0
Iron	µg/ℓ	400	20 - 1510
Manganese	µg/ℓ	80	10 - 310
Silica	mg/ℓ	2,9	1,2 - 5,8
Nitrate	mg/ℓ as N	0,3	0,1 - 0,84
Nitrite	mg/ℓ as N	0,05	0,05
Chloride	mg/ℓ	25,5	6,3 - 43,7
Fluoride	µg/ℓ	75,0	75
Sulphate	mg/ℓ as SO_4	10,5	3,4 - 18,5
Total Dissolved Solids	mg/ℓ	140	75 - 204
Suspended Solids	mg/ℓ	17,2	4 - 88
Total Organic Carbon	mg/ℓ as C	2,6	0,9 - 5,9
Trihalomethanes (total)	µg/ℓ	1,6	0,47 - 6,62

1.3 Evaluation Criteria and Methodology

It was necessary to develop an evaluation methodology derived from relevant process performance criteria. In this way the performance of the plants evaluated at the PEF could be directly compared. These criteria also provide a basis for the future evaluation and comparison of plants that were not tested during this project.

A list of **performance criteria** relevant to package plant operation was formulated at the inaugural steering committee meeting for the project. The criteria were grouped into the following main categories:

- Technological sophistication
- Personnel requirements
- Chemical dosing
- Reliability and plant life
- Servicing, maintenance and repair
- Transportation, installation and commissioning
- Process control and automation
- Infrastructure requirements
- Raw water quality
- Final water quality
- Expansion
- Costs and financing

This list was circulated for comment to steering committee members, the Department of Water Affairs, Regional Services Councils, consultants, foreign aid organisations, research organisations and water authorities.

A detailed list of criteria based on common sense, published literature and replies to the postal survey was drawn up and an evaluation methodology comprising some 170 quantitative and qualitative criteria was developed. This methodology was continually refined during the first year of the evaluations to enhance its relevance and culminated in the Evaluation Methodology Checklist presented in **Appendix 1 (Part 2)**.

1.4 Water treatment processes

The objective of treating raw waters to be used for human consumption is to render the water aesthetically acceptable and to remove contaminants, pathogens in particular, to the extent that negligible health risk is posed to the consumers. Contaminants in raw waters may be dissolved (salts and soluble organic compounds) or suspended (mineral and inorganic particles, insoluble organics and micro-organisms). The suspended matter may range in size from coarse (such as leaves, sticks, stones and floating matter) to colloidal (< 1 μm). The removal or inactivation of pathogenic micro-organisms is of prime importance in the treatment of water for human consumption.

1.4.1 Characteristics of typical water treatment processes

Typical water treatment processes are designed to remove turbidity to aesthetically acceptable levels and to disinfect the water so that consumers are not exposed to pathogenic micro-organisms. Dissolved solids are not normally affected by conventional treatment processes. The removal of specific dissolved contaminants that constitute a health risk or aesthetic problem will require the addition of one or more treatment steps to a water treatment process.

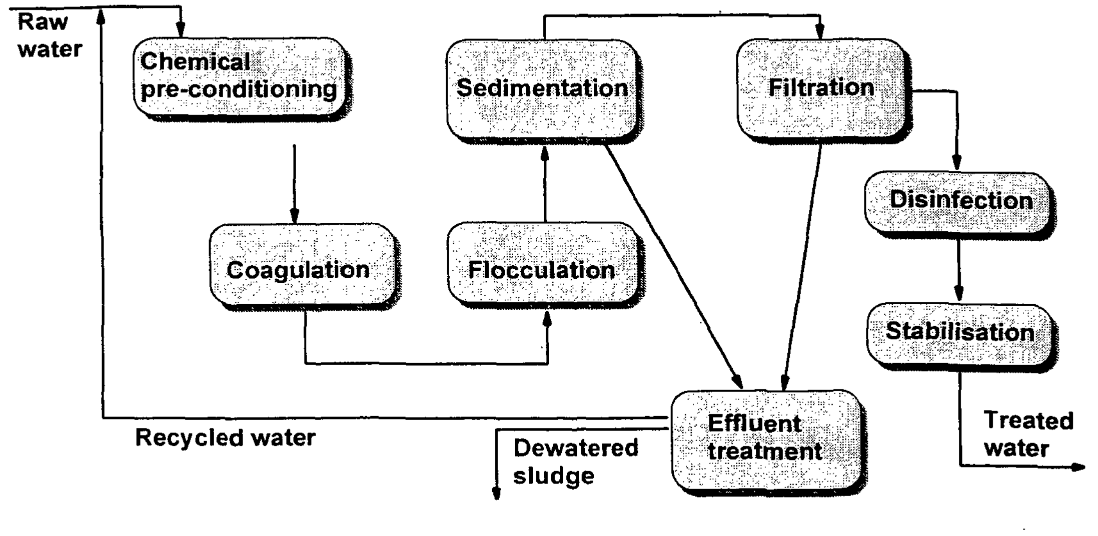


Figure 1.1 : A typical conventional water treatment process

A typical conventional large-scale water treatment process is depicted in **Figure 1.1**. The functions of the individual stages depicted in **Figure 1.1** are as follows:

- **Chemical pre-conditioning** may include:
    - i) pH correction to enhance the efficiency of coagulation.
    - ii) Oxidation of contaminants or micro-organisms by, for example, ozonation or chlorination.
    - iii) Powdered activated carbon (PAC) dosing for the removal of organoleptic compounds.
- **Coagulation** refers to the dosing and rapid mixing of chemicals (such as alum, lime, ferric chloride or polymers) which destabilise suspensions of colloidal particles thus permitting subsequent aggregation.
- **Flocculation** refers to the agitation and mixing of coagulated waters to cause gentle inter-particle collisions which promote the formation and growth of aggregates of destabilised colloidal particles (flocs). Flocs are more easily removed from the water by flotation, sedimentation or filtration than individual colloidal particles.
- **Sedimentation** is used to remove the bulk of the flocs from the water prior to filtration although flotation and direct filtration of flocculated waters may be feasible with some waters. The flocculation and sedimentation stages are frequently incorporated in a single process unit such as an upflow clarifier.
- **Filtration** is used as a 'polishing' stage to remove fine suspended matter that was not effectively removed by the sedimentation (or equivalent) process. Rapid gravity sand filtration is typically used on large-scale plants but various forms of pressure filtration may also be used, especially on smaller plants.
- **Chemical post-treatment** includes the addition of a disinfectant for the inactivation of micro-organisms that were not removed in the preceding treatment stages and stabilisation of chemically 'aggressive' waters to prevent attack of concrete and steel structures in the storage and reticulation system. Neither the disinfection nor stabilisation procedures are limited to this position in the process.
- **Effluent treatment** is frequently required to reduce the volume of the dilute sludges produced by clarifier draining and filter washing. The water recovered from the sludge treatment process is recycled and the sludges are dewatered and disposed of in landfill sites.

Package plants do not use all of the treatment stages discussed here and many of the package plants that were evaluated used novel or non conventional processes. Detailed reports on the various package plants that were evaluated are given in **Sections 6 to 15 (Part 2)** while the operating parameters are discussed in **Section 2 (Part 1)**.

1.4.2 Water Quality Guidelines

Water quality was assessed in terms of the 1994 draft guidelines of the Department of Health. The criteria are based on the aesthetic quality and health risks and are illustrated in **Appendix 2**.

Appendix 2 contains a complete list of the contaminants for which guidelines are defined. An abbreviated list showing the guideline values for the contaminants that were regularly monitored during the package plant evaluations is given in **Table 1.2.**

Table 1.2 : Department of Health guidelines for potable water quality (abbreviated, see Appendix 2 for complete list)

Determinands	Units	Health (* Aesthetic) risk ranges			
		None	Insignificant	Low	Greater
Standard plate count	/mℓ	<100	1000	10000	
Total Coliforms	/100 mℓ	0	5	10	
E. Coli	/100 mℓ	0	1	10	
* pH	pH units	6 to 9	>5,5 or <9,5	>4 or <11	
* Turbidity	NTU	1	5	10	
* Colour	mg/ℓ Pt	20			
* Conductivity	mS/m @ 20°C	70	300	400	
Aluminium	µg/ℓ Al	150	500	1000	
Chloride	mg/ℓ Cl	250	600	1200	
Chlorine (free residual)	mg/ℓ as Cl	0,2 to 5	<0,2 or >5		
Total hardness	mg/ℓ $CaCO_3$	200 to 300	650	1300	
Calcium	mg/ℓ Ca	150	200	400	
Magnesium	mg/ℓ Mg	70	100	200	
* Iron	µg/ℓ Fe	100	1000	2000	
* Manganese	µg/ℓ Mn	50	1000	2000	
Nitrates	mg/ℓ as N	6	10	20	
Sodium	mg/ℓ Na	100	400	800	
Sulphate	mg/ℓ as SO_4	200	600	1200	
Trihalomethanes (total)	µg/ℓ	100			

2 Review of Water Treatment Technologies used in Packaged Water Treatment Systems

The characteristics and operating requirements of package plants differ from large-scale water treatment plants in the following ways:

- The capacity of most package plant systems available in South Africa is less than 1 Mℓ/d and the capacity of the largest plant evaluated during this project was 0,24 Mℓ/d.
- Many plants are designed for operation in remote and rural areas where the technical support required for sophisticated modern technologies is not available.
- Plants are required to have a low workload and be able to operate unattended for much of the time
- Operation and maintenance should be simple because unskilled operators may be used.
- There is a need to minimise the capital cost of small scale plants because the cost per unit of installed capacity is typically higher than that for large-scale plants.

In this section, the various unit operations used in water treatment systems are discussed with emphasis on the technologies incorporated into the plants that were evaluated and the design differences that apply to package plants. Simplified diagrams of the processes that were evaluated are given to demonstrate practical applications of the various unit operations in water treatment. Full descriptions of these plants are given in **Sections 6 to 15** of the limited comparative performance study **(Part 2)**.

Extensive use has been made of information from *Water Quality and Treatment*, 4 ed, 1990; Degrémont's *Water Treatment Handbook*, 6 ed, 1991; *Water Treatment Plant Design*, 1978, *The Handbook of Water Purification*, 2 ed, 1987 and *The Handbook of Chlorination and Alternative Disinfectants*, 3 ed, 1992. Information obtained from other sources is specifically referenced in the text.

2.1 Water treatment chemical dosing

The objectives of chemical dosing in water treatment processes is to destabilise the suspended particulate (colloidal) matter and to disinfect the water. To ensure the efficiency of the destabilisation process in particular, adequate mixing and control of the dose is required. In an ideal system, the dose will vary automatically in response to changes in the water flowrate or quality. In package plants this degree of sophistication is usually not feasible because of the need to contain capital costs and simpler dosing systems are frequently used.

2.1.1 Dosing equipment

When water flows in an open channel or has a free surface, chemical dosing may be achieved with simple dosing apparatus that does not require electrical power or pressurisation of the dosing system.

Examples include drip feeders, siphons, mechanical screw-feeders and saturators (Schulz & Okun, 1984). Where mechanical devices are used it may be feasible to power them with the momentum of the water being treated.

If chemical solutions are dosed into water that flows in pipes, sufficient pressure will be required to overcome the pressure in the pipe and the flowrate of the solution should be independent of the pressure difference. Positive displacement dosing pumps powered either by electricity or by the water stream itself will be required for liquid solutions. It is difficult to dose dry solids directly into a pressurised line but these chemicals may be dosed as liquid solutions by controlling the flowrate of a side-stream through a saturator device in which the solid chemical continuously dissolves.

2.1.2 Chemical preparation

Chemical coagulants and disinfectants used in package plants are often supplied in concentrated form and require dilution prior to use. Typical doses of water treatment chemicals fall in the range from 0,5 to 50 mg/ℓ. In package plants where the water flowrate may be between 1 and 10 m^3/h this means that a chemical mass flow rate less than 500 g/h and usually between 0,5 and 50 g/h is required. The smallest available diaphragm dosing pumps are able to provide reasonably accurate control of chemical solution flowrates from 100 to 1000 mℓ/h. If chemical solutions are dosed in their concentrated form, these pumps are not able to accurately provide the small flowrates that are required. Dilution of chemicals such as sodium hypochlorite and polyelectrolytes to concentrations between 5 and 50 g/ℓ is therefore required. Dilution permits more accurate dosing but increases the complexity of the operator's tasks.

Dilution of chemicals may affect their stability. Sodium hypochlorite solutions in particular decompose within days when exposed to heat and light or when diluted with water that contains impurities (White, 1992). Polyelectrolytes may also become less stable when diluted with water and excessive dilution of aluminium or iron (ferric) based coagulants will cause them to hydrolyse. When it is necessary to dilute chemicals before use, appropriate quantities of clean treated water should therefore be used.

2.1.3 Dose control

On large-scale plants a feedback control loop that continuously monitors flowrate or streaming current is commonly used to control the coagulant dose. Feedback control based on flowrate measurement will compensate for variations in the flowrate. Feedback control based on a streaming current setpoint will compensate for variations in both the flowrate and water quality. Similar considerations apply to the control of disinfectant dosage by measurement of the treated water's flowrate or disinfectant residual.

The expense and complexity of these active control methods generally precludes them from use in package plants and none of the ten package plants that were evaluated made use of such control loops.

Three of the plants made use of manually controlled diaphragm dosing pumps which are unable to respond to changes in the water flowrate or quality. If the water flowrate remains constant, adequate dosing can be achieved with such a system but manual adjustments will be required to compensate for water quality fluctuations.

In direct filtration systems, the initial flowrate may decrease by more than 50 % during a filter run because the delivery flowrate of the centrifugal pumps often used with these systems decreases as the filter bed pressure drop increases (see **Sections 6, 7, 8** and **11**). If the chemical flowrate remains constant while the water flowrate decreases during filtration, the chemical dose effectively increases during the filter run unless the operator frequently adjusts the dosing pump. Coagulant wastage and inefficient coagulation may result from the continual overdosing that will occur with such dosing systems.

Positive displacement pumps (helical rotor type) can be used instead of centrifugal pumps to ensure that the water flowrate remains constant. However, these pumps are better suited to high pressure, low flowrate applications (Perry & Chilton, 1983) and where they are used for filtration applications, a pressure relief valve and high pressure cut-off switch will also be required. The capital, operating and maintenance costs are higher for helical rotor pumps than for centrifugal pumps of equivalent capacity and it may be cheaper to upgrade the dosing system than to select a more expensive feed pump.

A practical form of proportional dosing control for package plants is to use a mechanical water meter fitted with a pulse output (magnetic reed switch activated by the rotor). Pulse controlled dosing pumps are available and may be set to give a certain number of pump strokes per pulse. In addition, they usually have a manually adjustable stroke length. Proportional dosing by means of pulse control is cheaper and has lower maintenance requirements than sophisticated electronic flow control systems. Multiple dosing pumps may be operated from a single pulse meter if appropriate signal isolation is incorporated. A pulse operated dosing system may cost twice as much as a manual constant-rate pump but the advantages include reduced operating workload, reduced chemical consumption and improved water quality.

2.2 Coagulation and Flocculation

The terms coagulation and flocculation are often used interchangeably. In water treatment practice they frequently occur in close proximity to each other. In this document the following definitions are used.

Coagulation : This term refers to the process of chemical mixing, chemical particle destabilisation and physical inter-particle contacts which occur under the influence of Brownian motion prior to floc growth.

Flocculation : This term refers to the physical process of promoting inter-particle contacts that result in the formation and growth of flocs.

Four of the package plants that were evaluated used coagulation and flocculation processes to enhance the removal of turbidity from the raw water. One plant used a powdered coagulant which incorporates a flocculation aid and a pH buffer while the other three plants used liquid coagulants administered by dosing pumps.

2.2.1 Coagulant mixing in package plants

Flashmixing or rapid mixing : Coagulant chemicals must be brought into contact with the suspended solid matter in a raw water in order for particle destabilisation to occur. Inorganic metallic coagulants such as alum tend to hydrolyse within a second of dilution after dosing. Neutralisation of charges on colloidal suspended matter (destabilisation) requires mixing that is sufficiently rapid to allow the hydrolysis product to make contact and be adsorbed onto these particles before precipitation occurs. In theory, organic polyelectrolytes do not require to be as rapidly dispersed as the inorganic metallic coagulants.

Typically, velocity gradients with a G-value between 300 and 5000 s^{-1} and residence times from 1 s to 2 min are required for flash-mixing (Pontius, 1990; Sanks, 1978; Degrémont, 1991). The G-value is a function of the temperature, mixing vessel volume and the rate of energy dissipation (power consumption) in the mixer. The optimum G-value for a given application will depend on the coagulant being used, the type of mixer and the characteristics of the water being treated.

The provision of a separate stirred vessel or in-line static mixer for flash-mixing is typically too expensive for package plant systems that use coagulants. However, components of the process in which turbulence occurs may be successfully used for flash-mixing. These components include active devices such as pumps in which energy is imparted to the water and passive devices such as valves, rotameters and orifice plates where momentum changes result in turbulence and energy dissipation. In passive mixing devices, the G-value is a strong function of the flowrate and effective coagulation may only be achieved within a narrow range of flowrates. In active devices, the G-value (for instance in a pump volute casing) is less sensitive to the flowrate and although the residence time in the casing is inversely proportional to the flowrate, effective mixing can be achieved with a wide range of flowrates.

Flocculators : The objective of a flocculator is to increase the number of inter-particle collisions that result in aggregation of the colliding particles to form flocs that settle more rapidly or filter out more readily. Energetic mixing will obviously increase the rate and force of the collisions but it follows that velocity gradients in the fluid should not be high enough to erode or fragment the developing flocs. Typically, where separate flocculators are used in large scale plants, G-values between 20 and 60 s^{-1} are used and the Gt-value (dimensionless product of G-value and flocculator residence time) is typically between 10^4 and 10^5 (Pontius, 1990; Sanks, 1978; Degrémont, 1991). Similar G and Gt values are required in package plant systems that use sedimentation for floc removal.

Some package plants incorporate flocculation as a discrete stage in the process. In the batch treatment plant described in **Section 13**, flash-mixing occurs in the short period following start-up of the mixer.

The estimated G-value at start-up is approximately 680 s^{-1} and decreases significantly as the fluid in the tank accelerates to approach the rotational speed of the impeller. The mixer operates for a pre-set time during which the estimated G-value is relatively high for flocculation (100 to 200 s^{-1}). When the mixer stops, considerable floc growth occurs while the rotating mass of water in the tank decelerates and the G-value gradually decreases to zero. There is a gradual decrease in G-value throughout the batch and the flash-mixing, flocculation and sedimentation stages overlap considerably. The flocculation time could not be exactly determined but was approximately 15 minutes.

In the continuous process described in Section 10 a heliocoidal flocculator (Schulz & Okun, 1992) was initially used. Rapid-mixed water entered tangentially into the base of a 2 m^3 tank. Agitation was provided by the inlet jet and side wall friction as the water 'spiralled' up to the outlet. Flocculator residence times varied from 12 min at full capacity to 1 h at low flowrates. A G-value of approximately 10 s^{-1} was estimated for this system and little visible flocculation occurred. The degree of bypassing was not investigated. The flocculator was modified by fitting a vane impeller which operated at a speed of 10 min^{-1} and significantly increased the average floc size at the outlet.

In direct filtration processes such as dual-media filters or multimedia upflow filters, flocculation may occur in a pipe flocculator or directly in the coarse media with which the process stream first makes contact. Higher G-values and shorter residence times are typically used in these direct filtration systems because large, rapid settling, flocs are not required. Dual media filtration plants fitted with pipe flocculators are available in South Africa but were not evaluated during this project.

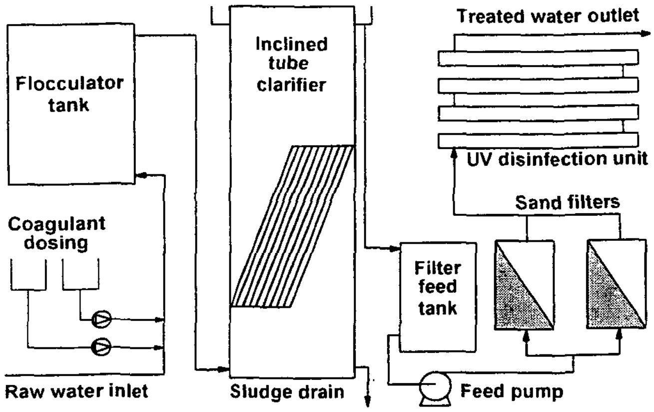
2.3 Clarification and sedimentation processes

When sedimentation processes are used in package plants, designs that allow the highest possible loading rates are usually specified in order to reduce size and capital cost. Examples of clarifiers used in package plants include:

- Upflow and horizontal flow clarifiers fitted with **inclined tubes or plates**
- **Adsorption** clarifiers.
- **Batch sedimentation** tanks

2.3.1 Inclined tube settlers

Inclined tubes or plates of 1 to 2 m in length can be retrofitted to most conventional clarifiers to enhance the separation of flocs from the water. The tubes or plates are generally self cleaning when inclined at angles greater than 50 to 60°. Upflow rates (surface loadings) of up to 8 m/h have been reported (Pontius 1990). This is approximately double the maximum loading achieved with conventional upflow clarifiers. One disadvantage is that the inclination of the tube bundle renders part of the clarifier's horizontal area inactive. This area can be a significant portion of the total area in small clarifier systems. Care is required when designing the inlet distribution system that an even upflow velocity is achieved over the entire horizontal cross-section of the bed. An example of a package plant that uses an inclined tube settler is given in **Figure 2.1**.

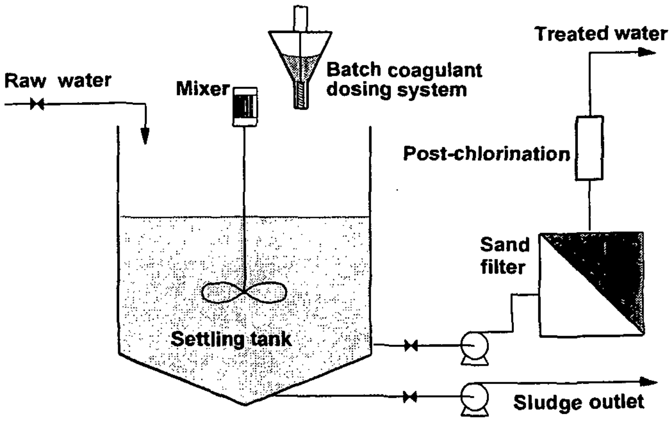


Raw water is coagulated, flashmixed and flocculated. Sedimentation occurs in a rectangular upflow clarifier fitted with inclined tubes. The clarifier overflows to a filter feed tank from which clarified water is pumped to a pair of pressure sand filters. UV disinfection was used on the plant that was evaluated but post chlorination is conventionally used.

Figure 2.1 : Conventional package plant with inclined tube settler

2.3.2 Batch Sedimentation

Some plants operate on a batch principle (see **Section 13** and **Figure 2.2**) for dosing, mixing, flocculation and sedimentation of the raw water. In batch sedimentation systems it is important to be able to remove as much sediment as possible during each cycle without entraining the supernatant water. A plant of this type that had a settling tank with a 30° conical base was evaluated. This was insufficient for self cleaning because only a small proportion of the settled sludge accumulated at the base of the cone. Self cleaning will probably require a 50 to 60° conical base and although this will increase the capital cost, smaller quantities of a more concentrated sludge will be produced.



A batch of raw water is dosed with a coagulant and thoroughly mixed. Sedimentation occurs after mixing. The supernatant water is filtered by pressure sand filtration. The filtered water is chlorinated by a proprietary in-line dosing device after which it is sent to storage. Sediment is pumped out of the tank by a separate pump at the end of each batch.

Figure 2.2 : Batch sedimentation and filtration system

The settling tank fulfils multiple roles (flash-mixer, flocculator, sedimentation tank, filter feed tank) as the cycle progresses. This permits a capital cost saving since, in a continuous system, an individual item of equipment may be required for each of these roles. Comparison of the processes depicted in **Figures 2.1** and **2.2** illustrate this point.

2.3.3 Adsorption Clarifiers

Adsorption clarifiers consist of an upflow bed filled with coarse plastic beads. The beads are coated with coagulant prior to the onset of clarification and the raw water is also dosed with coagulant and mixed in the normal way. Suspended matter and flocs adhere to the beads as they pass through the bed. Removal of more than 95 % of influent suspended solids at loading rates up to 22 m/h are reported in the literature (Clark *et al*, 1994). The need for frequent cleaning (4 to 8 hourly intervals) is a disadvantage. These clarifiers have been used on package plants in the USA but are not known to be available in South Africa at present.

2.4 Filtration processes

Filtration refers to the removal of suspended matter from a process stream by the passage of the stream through a porous barrier. A number of mechanisms for particle removal have been proposed and particles considerably smaller than the average pore size can be removed. Filtration processes may be classified as cake or depth filtration processes. Slow sand filters appear to operate as cake filtration processes but do not fall readily into either category because biological activity within the filter bed also plays a significant role in the operation of these filters.

In **cake filtration processes** the particles in the water are either screened out by the filter media due to the pores being smaller than the particles or the particles initially penetrate the filter but eventually bridge around the pores in the filter media. In both cases, a cake of particulate matter builds up on the clean porous surface and subsequent filtration takes place through this porous cake. Operating pressures are typically higher and filtration rates lower than for depth filtration.

Depth filtration processes are those in which the pores in the filter media are considerably larger than the particles to be removed. Particles enter the media and are trapped in the filter bed. Chemical pretreatment of either the filter media or the water being processed is essential for particulate removal by depth filtration As the filter bed becomes loaded with trapped particles the voidage of the bed is reduced. This results in a pressure drop increase and , ultimately, in turbidity breakthrough because the increased velocity of flow either strips attached particles from the bed or prevents incoming particles from being trapped.

2.4.1 Depth filtration processes used in package plants

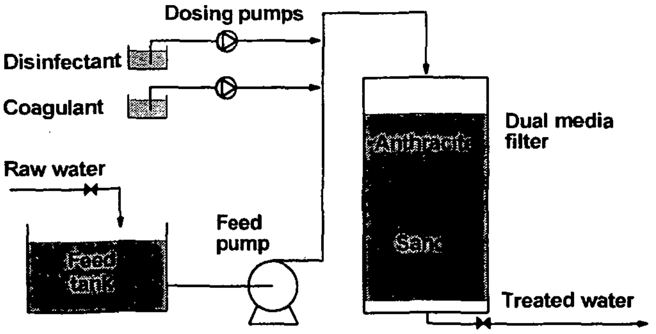
Conventional rapid gravity filters : Although none of the plants evaluated use rapid gravity sand filters, these are widely used in large scale plants and performance criteria are stated in **Table 2.1** for comparison purposes. On large scale plants, rapid gravity filters are usually of concrete construction. The depth of water above the sand bed is 0,5 to 2 m and this provides the driving force for gravity filtration. Constant-head or constant-rate control strategies can be used (Degrémont Handbook, 1991; Pontius, 1990).

Pressure sand filters : Pressure sand filters generally have similar media and bed depth specifications to rapid gravity filters. Pressure sand filters are frequently used in locally designed package water treatment plants because:

- Small pressure sand filters operated by single multiport valves are popular for domestic swimming pool filtration in South Africa. They are reliable and easy to operate.
- Several local companies manufacture filter vessels, pumps and the multiport filter control valves.
- Spare parts are available from retail outlets throughout South Africa.
- These filter systems are compact, robust and transportable.

Figures 2.1 and 2.2 depict package plants in which pressure sand filtration is used.

Dual media pressure filtration : A variation of conventional single media filtration, dual-media filters use media of two different sizes with the larger, less dense particles in the upper layer. The greater solids loading capacity renders dual media pressure filters suitable for direct filtration plants in which flocculation and the bulk of the floc removal occur in the coarse (upper) media layer (Pontius, 1990; Oeben *et al* 1968). This allows very compact, cost-effective package plants to be produced because the inclusion of separate flocculation and sedimentation stages can be avoided. A simple process flow diagram for a direct filtration process using a dual media pressure filter is shown in **Figure 2.3**.



Raw water is dosed with a coagulant and a disinfectant solution and pumped directly to the dual media pressure sand filter. The processes of flocculation and roughing filtration are combined in the upper anthracite layer and filtration of the remaining suspended matter occurs in the finer sand layer. Treated water is pumped to storage.

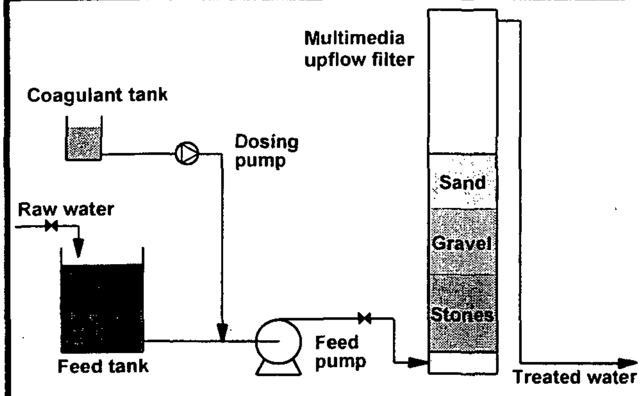
Figure 2.3 : Dual media direct pressure filter

At least three local package plant manufacturers use this technology and some offer sedimentation based pretreatment systems for installations where high raw water turbidities (unsuitable for direct filtration) are experienced.

Direct upflow and upflow-downflow filtration : Package plants utilising this technology are currently available from a number of engineering consultants in South Africa and plants are usually designed for individual applications. Upflow filters have many industrial uses and a number of design variations exist in practice.

In direct upflow filters, layers of graded media are arranged with the coarsest media at the bottom ranging through to fine media at the top (see general process flow diagram in **Figure 2.4**). Since filtration occurs in the upflow direction, there is no need to use media of different densities to retain the vertical classification of media sizes. The direct upflow filter is a variation of the upflow-downflow filter in which the upflow section is used only as a roughing filter containing relatively coarse media.

Upflow washing is used at rates from 30 to 70 m/h (depending on media size) and untreated water may be used (Hamann & McKinney, 1968; Haney & Steimle). Washing rates are high in comparison with rapid gravity or pressure sand filters and an air scour must be used because violent agitation of the bed is required to transport all of the captured solids through the finer upper layers of filter media.



Raw water is dosed with a coagulant and pumped to the multimedia upflow filter. Flocculation and roughing filtration take place in the coarse (lowest) layer. Filtration of finer suspended matter occurs in the progressively finer layers of media above. The overflow is usually disinfected and drained or pumped to storage. Many design variations exist in practice.

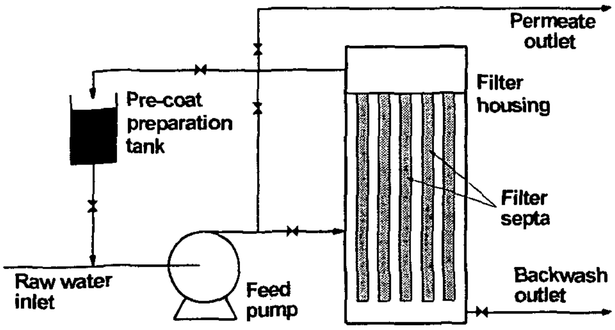
Figure 2.4 : Direct upflow filter

Filtration rates vary between 4,8 and 14 m/h (Hamann & McKinney, 1968; Haney & Steimle). Higher rates may be used in upflow roughing filters. Depending on the materials used, prefabricated package plants using this technology can be feasibly produced in diameters from 0,4 m to 3 m (Treffry-Goatley, 1994, Buchanan, 1994). Vessels of larger diameter can also be manufactured but are more difficult to transport. Lower coagulant doses can be used than in conventional plants because there is no need to form large settleable flocs. Multiple filter beds can be used to provide larger treatment capacity. Concrete construction has also been used for fixed plants of larger capacity. The smaller units (diameter < 0,7m) use a single pump, sized appropriately for backwashing and throttled during normal filtration. In units where the bed diameter exceeds 0,7 m or where multiple filter beds are installed, the use of separate filtration and backwash pumps may become feasible.

2.4.2 Cake filtration processes used in package plants

Precoat filtration : Prior to the onset of filtration, a septum covered with a steel or textile filter fabric is precoated with a filter medium such as **diatomaceous earth** (DE) or limestone which forms a porous cake on the support fabric. A simple DE precoat filtration process is depicted in **Figure 2.5**. A precoat density of 1 to 2 kg/m^2, giving a precoat thickness of approximately 3 mm is used. The process stream is then introduced and cake filtration occurs with suspended matter being strained by the precoat. The cake of trapped matter that builds up on the precoat frequently has smaller pores than the precoat layer and resistance to flow can build up, ultimately clogging the filter. To overcome this, additional precoat media (called body feed) can be dosed continuously into the filter feed line at concentrations up to 80 mg/ℓ to maintain the porosity of the developing cake layer (Baumann *et al*, 1962). The maximum operating pressure is usually determined by the strength of either the fabric support or the filter vessel and is typically 200 kPa.

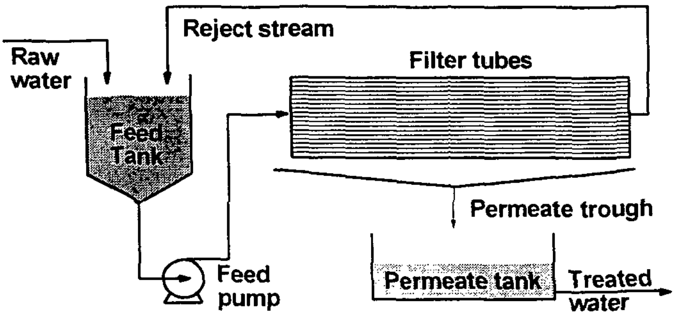
In this type of precoat filtration, the cake layer continues to grow throughout the filter cycle. Eventually, the process must be stopped so that the filters can be washed and precoated with fresh media prior to the start of a new cycle. There is considerable flexibility in the operation of diatomaceous earth filters. They can be optimised for maximum cost efficiency, permeate quality or volumetric throughput by juggling operating parameters such as cycle time, precoat thickness, body feed rate and filtration rate (LaFrenz and Baumann, 1962).



Fabric covered septa are precoated with diatomaceous earth prior to each filter cycle. Suspended matter in the raw water is filtered out by the precoat, forming a cake through which subsequent filtration takes place. The filter cycle is terminated when the pressure reaches about 150 to 200 kPa. The filter is washed by reversing the flow to eject the filter cake and used media.

Figure 2.5 : Diatomaceous earth filter

Another precoat filtration process is **Crossflow microfiltration** (CFMF). This is a novel technology that has considerable potential for potable water treatment as well as sludge thickening and sludge dewatering in the water and wastewater industries (see **Section 9**). When used for potable water production, raw water is pumped along the inside of a permeable fabric tube through which filtration occurs. The tube may be precoated with limestone or other precoat media. In practice, a custom woven curtain consisting of 20 to 40 tubes is used. The entire process can be fully automated and a simplified process flow diagram is given in **Figure 2.6**.



Feed water is pumped into a system of hollow fabric tubes precoated with limestone. Filtration occurs through a cake of suspended matter that builds up on the precoat. By maintaining a high cross-flow velocity, headloss development is retarded and long filter cycles are possible. The reject stream is recycled and the water lost as permeate is made up with raw water.

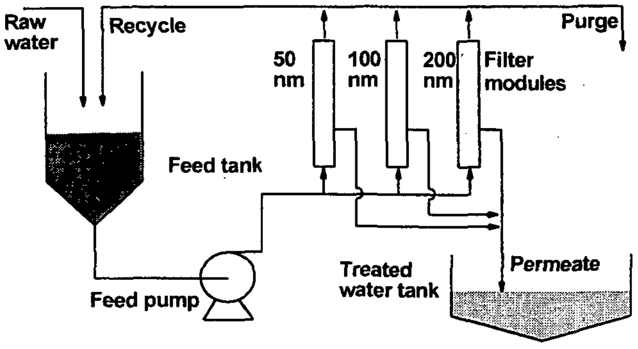
Figure 2.6 : Crossflow microfiltration process

As the filter cake builds up, the tube narrows and the velocity of flow increases until a state of dynamic equilibrium is achieved where the rate of deposition of particles is matched by the rate of erosion of particles from the cake. The permeability and thickness of the cake are stabilised by this effect and long filter cycles with relatively constant fluxes (filtration rates) can be achieved. At the end of a cycle, the curtain is washed by flushing the tubes at high velocity and spraying them from the outside with a high velocity spray. Both DE and CFMF processes are capable of removing certain bacteria and cysts from water although potential for micro-organism breakthrough exists during cleaning and precoating. The use of DE filtration for removal of chlorine resistant *Giardia Lamblia* cysts from potable waters has been reported (Lange *et al*, 1986).

Membrane Microfiltration and Ultrafiltration : This refers to membranes with pore sizes ranging from 100 to 3000 nm for microfiltration (MF) and 0,1 to 20 nm for ultrafiltration (UF). These processes are gaining acceptance in the following industries:

- Dairy and fruit juice processing.
- Industrial effluent treatment
- Supplementary water purification for the electronics, pharmaceutical and biochemical industries.

Membrane modules used for MF and UF may consist of hollow synthetic fibres, porous ceramic monoliths or spiral wrapped cartridges into which the raw water is pumped . The raw water may be pumped into these modules at pressures up to 4 000 kPa (but typically 500 kPa) and the rejected matter can be discarded (once through) or recycled with periodic concentrate purging (Lorch, 1987). A process flow diagram for a prototype ceramic microfiltration system is shown in **Figure 2.7**



Water is pumped from the feed tank to the membrane modules. The clear permeate is collected and flows to a permeate storage tank. The retentate stream is recycled to the feed tank and the water lost from the system as permeate is made up by inflow of raw water. Periodic purging is required to reduce the concentration of rejected matter in the feed tank.

Figure 2.7 : Prototype ceramic microfiltration process

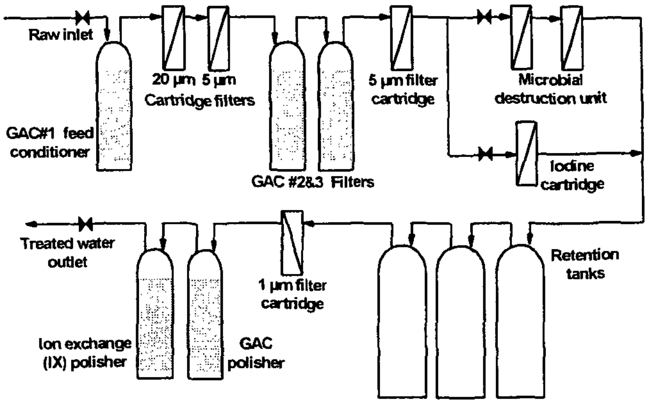
The ceramic MF modules that were evaluated had pore sizes between 50 and 200 nm and therefore fall into the lower end of the microfiltration bracket. The pore sizes of these MF membranes are of the same order of magnitude as the colloidal suspended solids in raw waters and limited penetration of the membranes by this colloidal matter occurs. In addition, the relatively smaller pores of UF membranes can remove certain dissolved macromolecules (depending on size) from the water. By maintaining sufficient cross-flow velocity in the membrane systems (regardless of configuration) most of the suspended matter screened by the membrane is kept in suspension and limited cake formation occurs (Goodrich *et al*, 1994). UF and MF membrane filtration may be considered non conventional processes for potable water production and have several distinguishing performance characteristics (Gandilhon and Tambo, 1992):

- Most micro-organisms are removed by ultrafiltration although high plate counts may occur in the treated water. Total removal of micro-organisms of faecal origin can be achieved.
- The more robust ceramic membranes are resistant to high pressures and erosion by abrasive suspended matter and a reliable seal can be obtained between the permeate and feed streams.
- Excellent permeate quality is possible and relatively small quantities of sludges are produced.
- Operation is chemical free although detergents and occasionally strong acids or alkalis may be required for membrane cleaning.
- Energy costs are higher than conventional systems because the operating pressure is higher.
- Installations can be compact and simple to operate; the plants can operate unattended for up to a week depending on the configuration of the process and the water quality.

Cartridge filtration : Pleated paper or fibre-wound filter cartridges are routinely used on process streams in industry for screening out particulates that might clog or damage equipment located downstream. Generally, the cartridges cannot be effectively washed and do not have a high solids capacity although they can be used to produce compact portable systems. Cartridges designed to screen particles ranging in size from 1 µm to 50 µm are available in South Africa. When used as the primary means of removing turbidity or suspended solids in packaged water treatment systems they may be ineffective for the following reasons:

- **Expense.** Although widely used in industry in South Africa, the low yield achieved with filter cartridges in potable water filtration service can make them uneconomical.
- **Water quality.** The colloidal matter which accounts for much of the turbidity in local raw waters is able to pass through the relatively coarse pores in the filter cartridges.
- **Fragility.** The pleated paper cartridges are easily damaged during transport and installation.

Figure 2.8 shows a process flow diagram for a package plant system that uses multiple stages of cartridge filtration in combination with other unit operations. Another portable cartridge filtration system is depicted in **Figure 2.10**.

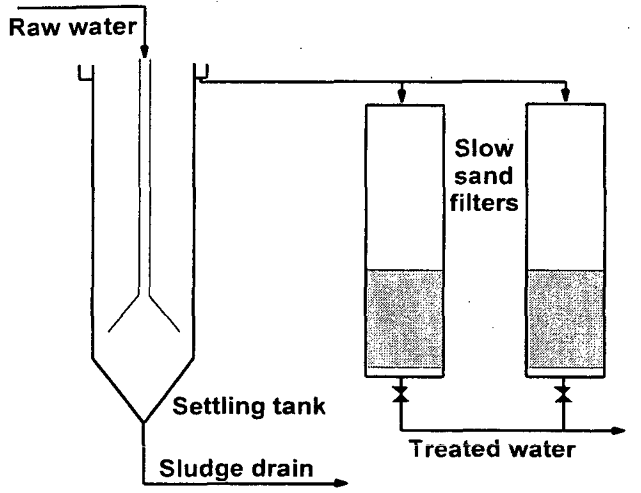


Raw water is passed sequentially through a series of GAC beds and cartridge filters to remove turbidity and organic contaminants. The filtered water is dosed with iodine and provided with sufficient contact time for proper disinfection. Iodine and iodide ion are then removed by sequential GAC and ion exchange treatment.

Figure 2.8 : Multiple cartridge and GAC filtration with iodination

2.4.3 Slow sand filtration

Slow sand filtration has been used throughout the world for the last 150 years and is well documented in the literature. The filters are easily constructed and the process is simple to operate. The process consumes no chemicals or electrical energy during normal operation. However, due to the low filtration rate, large areas of filter bed may be required. A process flow diagram for a pilot slow sand filter system with pretreatment is shown in **Figure 2.9**.



A pilot scale slow sand filtration plant was designed and commissioned by the project staff. A conical sedimentation tower with geometry as depicted was used for clarification of raw water prior to filtration by two slow sand filters connected in parallel. No disinfection or coagulant chemicals were used. The two filters were operated at different rates to assess the effect of filtration rate on water quality and frequency of filter scraping.

Figure 2.9 : Slow Sand Filter

Characterised by smaller sand particles (0,25 to 0,4 mm in diameter) and a lower filtration rate (0,1 to 0,3 m/h) than conventional rapid gravity filters, slow sand filtration is a biological filtration process in which turbidity, colour and microbiological contaminants can be removed to levels acceptable for potable water (Huisman & Wood, 1974). Slow sand filters operate best on raw waters that do not consistently exceed a turbidity of 10 NTU but this range may be considerably extended if appropriate pretreatments such as sedimentation (with or without coagulation) or roughing filtration are used (Graham, 1988 and USEPA, 1989).

Filtration occurs largely in the *schmutzdecke,* a biologically active skin or cake that develops on the surface of the sand bed and becomes gradually less permeable with time. Operating practice varies considerably but in general, slow sand filters are cleaned by scraping off the *schmutzdecke* and sand to a depth of 2 or 3 cm and refilling the filter with water. The sand that is removed during cleaning is either washed and replaced in the filter directly, or stored for use during periodic resanding of the filter. The filtrate is often discarded for three or four days after restarting the filters. This time is required for the new *schmutzdecke* and associated biological activity to develop. Filter scraping is required every three weeks to three months depending on raw water quality. When properly operated, disinfection of the filtrate should not be necessary but is typically practised to combat subsequent regrowth and contamination of the treated water.

2.4.4 Summary of typical Design parameters

Table 2.1 contains a summary of the typical operating and design parameters that apply to various types of filtration systems used in package plants. The data in this table is based on figures quoted in the literature and the actual design parameters of the plants that were evaluated.

Table 2.1 : Operating and design parameters for package plant filter systems

<table>
<tr><th colspan="5">Depth filters</th></tr>
<tr><th>Filter type</th><th>Rate
m/h</th><th>Bed depth
m</th><th>Media size
mm</th><th>Method of washing</th></tr>
<tr><td>Rapid sand filter</td><td>5 to 20</td><td>0,6 to 1</td><td>0,7 to 2</td><td>water only : 30 to 50 m/h
Water/air : water, 7 to 15 m/h
air, 50 to 60 m/h</td></tr>
<tr><td>Pressure sand filter</td><td>8 to 25</td><td>0,35 to 1</td><td>0,7 to 1,2</td><td>Water only : 30 to 50 m/h</td></tr>
<tr><td>Dual Media pressure filter</td><td>9 to 15</td><td>~0,5 (sand)
~0,4 (anth.)</td><td>0,5 to 0,7 (S)
0,8 to 1,6 (A)</td><td>Water only : 20 to 30 m/h</td></tr>
<tr><td>Direct upflow filter</td><td>5 to 10</td><td>1,2 (stones)
0,5 (gravel)
0,8 (sand)</td><td>10 to 12
3 to 5
1 to 1,5</td><td>Water/air : water at 70 m/h
: air at 35 m/h</td></tr>
<tr><td>Slow sand filter</td><td>0,1 to 0,3</td><td>0,5 to 1,5</td><td>0,15 to 0,4</td><td>Periodic *schmutzdecke* removal</td></tr>
<tr><th colspan="5">Cake filters</th></tr>
<tr><th>Filter type</th><th>Filtration rate (m/h)</th><th>Pressure (kPa)</th><th>Initial pore size</th><th>Method of washing</th></tr>
<tr><td>Ceramic UF</td><td>0,3 to 0,5</td><td>up to 600</td><td>50 to 200 nm</td><td>Detergent or acid/alkali rinse</td></tr>
<tr><td>CFMF</td><td>0,08 to 0,12</td><td>up to 400</td><td>up to 5 µm</td><td>Flush and spray tubes</td></tr>
<tr><td>Cartridge</td><td>0,9 to 1,2</td><td>up to 200</td><td>1 to 50 µm</td><td>Replace</td></tr>
<tr><td>DE</td><td>1 to 5</td><td>up to 250</td><td>2 to 17 µm</td><td>Backflush and rinse septa</td></tr>
</table>

2.5 Disinfection and micro-organism removal

The objective of disinfecting drinking water is to remove or inactivate to an acceptable degree:

- the pathogenic micro-organisms that pose a threat to the health of consumers.
- the micro-organisms that adversely affect the aesthetic quality of potable water.
- the micro-organisms that corrode or foul treatment and reticulation equipment.

The disinfection methods used in package water treatment plants can be classified into three generic types. These include:

- **Chemical addition**, where a substance that kills or inactivates micro-organisms is introduced to the water being treated. Examples include the addition of chlorine, chlorine dioxide, chloramines and iodine either singly or in combination with one another.
- **Energy addition**, where the addition of energy such as ultraviolet radiation inactivates micro-organisms.

- **Physical barrier processes**, where the water permeates through a barrier that retains some or all of the micro-organisms. Examples range from biological filtration to membrane filtration.

2.5.1 Chemical disinfection processes

Whatever type of disinfection system is used, the final water should be suitable for potable use when it reaches the first possible point of abstraction from the plant. This requirement can influence the design of the plant and the positioning of the disinfection system in the process. The following disinfection technologies were used in the package plants that were evaluated:

- Chlorination
- Iodination
- Slow sand filtration
- Ceramic Microfiltration
- Precoat Microfiltration
- Ultraviolet radiation

2.5.1.1 Chlorination

Chlorine is currently the most widely used disinfectant for potable water treatment processes. It is commonly dosed in gas, liquid and solid forms as chlorine gas, sodium hypochlorite solution and calcium hypochlorite granules (or tablets) respectively (White, 1992). The advantages and disadvantages of using each of these forms in package plant applications is summarised in **Table 2.2**.

Table 2.2 : Advantages and disadvantages of various forms of chlorine

Chlorine type	Advantages	Disadvantages
Chlorine gas	Most cost effective to transport Dry gas is non corrosive Can be stored for long periods	Hazardous due to toxicity Skilled operators required High capital cost of hardware (safety)
Sodium hypochlorite	Easily dosed and handled Low capital cost of hardware Moderate skill required	Least cost effective to transport Corrosive Short shelf life (up to 1 month)
Calcium hypochlorite	Long shelf life when sealed Widely available in S.A. Available as tablets or granules Easily transported	Can be confused with trichloroisocyanuric acid Corrosive Must be dissolved prior to dosing Most expensive form of chlorine

Chlorine gas reacts with water as follows:

$$Cl_2 + H_2O \Leftrightarrow HCl + HOCl \quad \text{.......} \quad 1$$

The hypochlorous acid (*HOCl*) will dissociate in water and this dissociation is pH dependent:

$$HOCl \Leftrightarrow OCl^- + H^+ \quad \text{.......} \quad 2$$

Hypochlorous acid is the most effective disinfecting form of chlorine in water. As pH increases, more hypochlorous acid dissociates to the hypochlorite ion form which is less effective for disinfection. At a pH of 7,5 approximately half of the hypochlorous acid is present in solution as the hypochlorite ion.

The reactions of sodium and calcium hypochlorite in water proceed as follows:

$$NaOCl + H_2O \Rightarrow HOCl + NaOH \quad \text{.......} \quad 3$$

$$Ca(OCl)_2 + 2H_2O \Rightarrow 2HOCl + Ca(OH)_2 \quad \text{.......} \quad 4$$

The hypochlorous acid produced by these reactions similarly dissociates according to the pH of the solution. Formation of calcium or sodium hydroxide occurs with these forms of chlorine and this can significantly elevate the pH of the water being treated, thereby reducing the concentration of hypochlorous acid in the undissociated (HOCl) form. pH correction may therefore be required for effective disinfection if the water has limited natural buffering capacity.

Chlorine gas is commonly used on large and medium scale plants. It is supplied as a liquid in pressurised cylinders and is evaporated prior to metering and injection into the water being treated. Due to the hazardous nature of the gas, appropriate safety measures are required. These safety requirements can considerably increase the capital cost of gaseous chlorine systems in comparison with the alternative liquid and solid based systems discussed in the following paragraphs.

Sodium hypochlorite is frequently used as the disinfectant in locally available package plants. In the package plants that were evaluated it typically required dilution to 1 % from the 13 to 15 % stock solution. Storage conditions are important as the hypochlorite solutions decompose on exposure to heat, light and impurities. The stock solution should not be stored for more than 1 month, even when sealed and stored under dark, cool conditions. The diluted dosing solution should be prepared in quantities sufficient for 1 to 3 days of operation.

Calcium hypochlorite can be dosed in a number of ways. Dosing of the dry granules or powder is not recommended since calcium hypochlorite is hygroscopic and decomposes in air to form chlorine gas. It can be dosed in the same way as sodium hypochlorite by dissolving the granules to create a solution of appropriate strength.. A number of proprietary in-line and free floating dispensers are available for industrial and swimming pool chlorination. These devices generally make use of tablets containing a mixture of calcium hypochlorite and calcium carbonate and they function as saturators from which the solution is gradually released into the line (in-line dispensers) or surrounding water (free floating dispensers). Similar dispensers containing trichloroisocyanuric acid (TCIA, also commonly known as 'stabilised chlorine') are available. Due to the relatively slow kinetics of dissolution and conversion of the chlorine content to hypochlorous acid (Baldwin 1981 and Carlsson, 1994), TCIA is not considered suitable for primary disinfection. The Department of Health does not recommend long term use of TCIA. However TCIA may be used in emergencies when calcium hypochlorite is not available. The use of longer contact and dissolution times is recommended when TCIA is used under these circumstances.

These chlorination devices provide only rudimentary control of the chlorine dose but are convenient to use since they require minimal calibration, adjustment or maintenance once they have been set up.

Due to the variety of dosing methods and its long shelf life, calcium hypochlorite is suitable for use as a backup disinfectant.

On-site generation of chlorine : Processes using membrane electrolysis and direct electrolysis are available for the small-scale generation of chlorine gas or sodium hypochlorite solutions on-site. Due to the low d.c. voltages required for electrolysis, these devices can be powered by solar panels. Table salt, which is cheap and widely available in South Africa, can be used as a raw material in most of the direct electrolysis systems but the membrane systems require high purity salt or extensive pretreatment of brines produced by poorer grades of salt.

The membrane electrolysis systems use a scaled down version of full-scale membrane cells that are now widely used in the chlor-alkali industry. The direct electrolysers use similar technology to the sea water electrolysers used for chlorine generation in ships (White 1992). Despite the obvious advantages, these systems have disadvantages which have frequently led to failures when used in developing areas of the world (Schulz and Okun, 1992). These disadvantages include:

- The coated electrodes and solar panels (where used) are fragile and extremely expensive.
- The membranes are particularly susceptible to damage by sparingly soluble metal hydroxides and carbonates produced by impurities such as magnesium and calcium in the brine solutions.
- The generation of hydrogen at the cathode can pose an explosion hazard.
- Skilled operators who understand the principle of operation are required. In developing countries, people with such skills can often command higher salaries in other positions.
- The direct electrolysers typically convert only 10 to 20 % of the sodium chloride in the brine to sodium hypochlorite. A maximum hypochlorite concentration of about 8 g/ℓ as Cl can be attained.

2.5.1.2 Iodination

A resin that releases iodine into water in a controlled manner was used by NASA in the space shuttle for disinfection of recycled water. This technology is now being commercially marketed and is locally available. It was incorporated into one of the plants that was evaluated (see **Section 14** and **Figure 2.8**). The resin causes iodine to be released into filtered and GAC pre-treated water at concentrations up to 4 mg/ℓ. After a contact period of approximately 20 minutes the excess iodine is removed by treatment with granular activated carbon and the associated iodide ion is removed by treatment with ion exchange resin. Due to the lack of a residual concentration of disinfectant, regrowth may occur in the distribution system and no protection is offered against subsequent contamination of the supply.

2.5.1.3 Other biocides

The use of chloramines, ozone, chlorine dioxide, silver, titanium dioxide (with UV irradiation), electrolytically generated mixed oxidant gases and hydrogen peroxide as disinfectants (either singly or in combination) for package plant and small water treatment systems is described in the literature

(Clark *et al*, 1994; Goodrich, 1994; Barrot *et al*, 1994; Shuval, 1994) but none of these biocides are known to be used in locally available package plants (see **Table 2.3**).

Table 2.3 : Summarised comments on use of selected biocides

Disinfectant	Comments on use
Ozone	Widely used in USA and Europe. Expensive for small systems. Little residual effect due to short half-life. By-product formation not well understood
Hydrogen peroxide	Limited use, can be used in combination with ozone (peroxone) , silver and UV light to enhance disinfection and advanced oxidation processes.
Chloramines	Not a strong primary disinfectant but long lasting, widely used for secondary disinfection of reticulation systems. Hazardous to dialysis patients.
Silver	Experimental, incorporated in some ceramic ultrafiltration modules. Used in very low doses (ppb).
Chlorine dioxide	Potentially hazardous, must be generated on site. Complex operation. Concern exists about chlorate by-products. Expensive for small systems

2.5.2 Physical barrier processes

Physical barrier processes (generally filtration processes) do not inactivate micro-organisms but physically separate them from the water being processed. In a sense, this does not amount to disinfection of the water and in some filtration processes, while efficient micro-organism removal occurs during filtration, there is potential for contamination during filter washing. Physical barrier processes do not leave a disinfectant residual in the treated water and therefore provide no protection against regrowth or subsequent contamination. The use of secondary disinfection systems is recommended with these processes.

2.5.2.1 Slow sand filtration

When the raw water turbidity is within the range given in **Section 2.4.3** slow sand filters can consistently produce treated waters of acceptable microbiological quality for potable use. However, they remain sensitive to fluctuations in raw water quality and sustained periods of poor water quality (Huisman and Wood, 1974; Galvis *et al*, 1993). Breakthrough of micro-organisms may also occur for a few days after filter scraping. In addition, the treated water, although biologically stabilised by the process contains no residual and a secondary disinfection system is recommended. Since slow sand filters are not pressurised, simple low-technology dosing systems using solutions of either sodium or calcium hypochlorite can be used. The use of pre-chlorination without disturbing the biological activity of the filter has been reported in the literature but due to the potential for accidental overdosing on small-scale plants, this is not recommended for slow sand filtration package plants.

2.5.2.2 Precoat (Crossflow) Microfiltration

Precoat microfiltration is described in **Section 2.4.2**. Total removal of plate count bacteria and faecal indicator organisms has been recorded in samples of permeate taken directly from the filter curtain but the washing process provides opportunities for contamination since the permeate tray is also used to capture washwater that permeates through the tubes during the cleaning cycle. It will be cheaper and more effective to provide a chlorination system than to re-engineer the process to eliminate this potential source of contamination.

2.5.2.3 Membrane microfiltration and ultrafiltration

These processes are described in **Section 2.4.2**. The removal of most micro-organisms, including viruses is possible but the risk of membrane perforation due to excessive pressure and erosion by solids in the feed stream exists with the polymer based membranes. The process leaves no residual and the treated water is therefore susceptible to regrowth and contamination.

2.5.3 Energy processes

Ultraviolet radiation is the only energy based disinfection process known to be used in packaged water treatment plants. Another well known energy based disinfection process is pasteurisation, used in the dairy industry. Experimental processes such as cavitation and high fluid shear are mentioned in the literature.

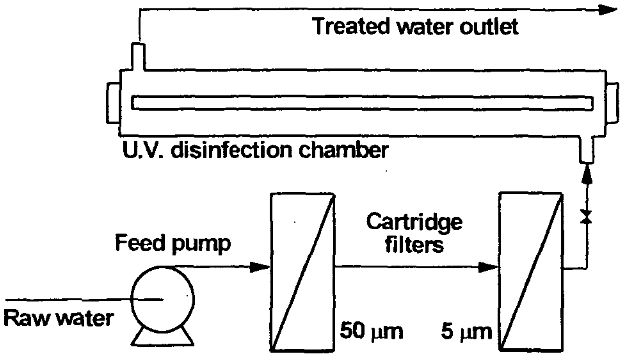
Ultraviolet (UV) radiation with a wavelength around 260 nm exerts a strong germicidal effect. In addition, it produces no known toxic by-products, is easy to operate and the required contact times are relatively short. Low pressure mercury vapour lamps that produce UV radiation with a wavelength of 254 nm are available from several manufacturers and are widely used for disinfection of water and to provide sterile spaces in the following industries:

- Potable water production
- Kidney dialysis water
- Wastewater treatment
- Fish hatcheries
- Dairy processing
- Pharmaceuticals
- Beverages
- Cosmetics
- Hospitals

The germicidal effect of UV radiation is thought to be due to absorption by organic molecular components essential to the functioning of cells. It follows that sufficient UV energy must actually strike a cell and be absorbed in order to inactivate the cell. Cells must therefore be exposed to the most diffuse and intense UV light possible. Turbidity, caused by particles which shield micro-organisms from radiation and the presence of soluble compounds which absorb UV radiation can therefore decrease the germicidal efficiency of a UV system.

The UV dose (***D***) received by the water being treated is calculated as the product of the radiation intensity (***I***) and the exposure time (***t***). There is currently no statutory minimum dose for UV treatment of potable water in South Africa but at least one local supplier uses the United States Environmental Protection Agency (USEPA) guideline minimum dose of 32 mWs/cm^2 which is sufficient for the inactivation of most pathogenic bacteria and many viruses.

The life of low-pressure UV lamps is typically 7 500 to 8 000 hours when operated in eight hour cycles. Lamp life is significantly reduced by frequent ignition and shut-down. Chambers can be positioned in parallel or in series but connection of at least two lamps in series is preferred because a degree of disinfection will still be achieved in the event of a lamp failure. A process flow diagram for a simple solar powered portable UV disinfection system is shown in **Figure 2.10**. **Figure 2.1** shows an example of a larger UV system used with a more conventional package plant process.



Raw water is pumped through two cartridge filters with pore sizes of 50 and 5 μm respectively. The filtered water then passes through a UV disinfection chamber where it is exposed to a dose of UV light. The treated water may be used directly or pumped to storage. The unit is solar powered and a 12 V car battery is used for electrical energy storage

Figure 2.10 : Solar powered UV disinfection system

2.5.4 Positioning of disinfectant dosing points

When a disinfectant such as chlorine is added to water being treated for potable use the point at which it is added will have consequences for the process, the treated water quality and the disinfectant consumption. Some advantages and disadvantages of the various options, with respect to the point of addition, are discussed in the following paragraphs.

Pre-chlorination of raw water prior to sedimentation and or filtration is useful in reducing the effects of algae which can cause clogging of filters. The growth, in pipes and filter vessels, of microbiological slimes that may cause taste and odour problems can also be controlled in this way. Due to subsequent passage of the chlorinated water through the process, a chlorine contact time equivalent to the residence time of water in the process is obtained and the water produced may be suitable for immediate consumption. However, many substances such as reduced inorganic compounds, THM precursors, algae and other micro-organisms that consume chlorine are partially removed by sedimentation and filtration processes. Pre-chlorination therefore has potential disadvantages:

- Overall chlorine consumption may be higher
- Increased THM formation may occur
- Increased taste and odour problems may arise from the action of chlorine on certain algae

Post-chlorination refers to chlorination of the treated water emanating from the process. Although post-chlorination addresses some of the disadvantages of pre-chlorination, adequate contact time must be built into the process to prevent water from being abstracted for use before adequate disinfection has occurred.

The most effective **UV disinfection** will be achieved if the water is exposed to UV at the end of the treatment process after the removal of as much turbidity and other impurities as possible.

3 Guidelines for the selection of package plants

3.1 Estimating the required plant capacity

The Water Supply and Sanitation Policy of the Department of Water Affairs and Forestry (as documented in the November 1994 White Paper and in full support of the government's Reconstruction and Development Program) is to provide all South Africans with access to **basic water supply** within seven years. In the White Paper, basic water supply is defined in terms of quantity, cartage, availability, assurance of supply and quality. These definitions are summarised below and represent the minimum level of supply on which planning should be based:

- **Quantity** : 25 ℓ per person per day. The minimum required for direct consumption, food preparation and personal hygiene.
- **Cartage** : The maximum distance that a person should have to cart water to their dwelling is 200 m and this figure should be reduced to compensate for steep terrain.
- **Availability** : Water should be regularly available at a flowrate of at least 5 ℓ/min.
- **Assurance** : Hydrological assurance of 98 %. Maintenance of the delivery systems is ultimately the joint responsibility of the regional water authority (DWA&F where no water authority exists) and the provincial governments.
- **Quality** : The following minimum quality guidelines are given:

  Microbiological quality .... max. 0 faecal coliforms/100 mℓ

  Total dissolved solids (TDS)* ..... Recommended 70 mS/m, max. 300 mS/m

  Taste, clarity and odour .... Acceptable to the majority

  * as measured indirectly in terms of conductivity

These **minimum** standards for basic water supply are not considered by DWA&F to be sufficient for a full, healthy and productive life.

The objectives of both the RDP and the Department is to ensure that recurring (operating) costs are borne by the consumers. In addition, consumers will expect to be able to progressively upgrade their supplies, ultimately providing house connections. At this level of supply, per capita consumption is typically in excess of 100 ℓ per person per day. These factors should be considered when planning water treatment and reticulation systems.

Every 1 m^3/day of plant capacity will therefore be sufficient for the supply of potable water to 40 people at the basic supply level or approximately 10 people if the reticulation system provides individual house connections.

3.2 Recommendations for the specification of plant components

3.2.1 Control systems

The objectives of a plant's control system, whether automated or manual is to provide adequate control of the quantity and quality of treated water produced by the plant. This requires the simplest and most inexpensively maintained control system that can provide the following:

- Adequate control of chemical dosages where chemicals are used (see **Section 2.1.3**).
- Adequate alarms or automatic cut-outs to prevent overloading of process components which may result in damage, clogging or treated water contamination
- Fail safe design to prevent contamination of treated water in the case of power failures, chemical depletion or component failure.
- Manual override of automated procedures.
- Sufficient ranges of adjustment for important control parameters such as surface loadings for filters and clarifiers, mixing energy, pressure and chemical dosages.

Instances where most of these criteria can be satisfied on the evaluated plants merely by installing a different type of valve or making an additional electrical connection at minimal expense have been recorded in **Sections 6** to **15 (Part 2)**.

Process control strategies are important on package water treatment plants. Due to the relatively small output of these plants, it is desirable for the plant to be able to operate reliably with as little supervision as possible. As can be seen in **Section 5.8.2** the specific labour cost was a significant proportion of the total specific operating cost for all of the plants evaluated.

While the operating labour rate of R 7,00 /h (in 1994) may not actually be paid to every operator, it represents a realistic cost for the operator's expertise and time. Okun and Shultz (1992) relate several instances in developing countries where trained water treatment plant operators were lost to higher paying jobs in industry and commerce. In small plants especially, additional capital expenditure on alarm and automatic cut-out systems may therefore be justifiable in terms of the reduced workload, enabling operation of the plant to become a part-time or after-hours job for a suitably qualified operator.

On the whole, the control systems used for the various package plants were effective but in many cases, inexpensive modifications were required to reduce the opportunity for contamination of the treated water during backwashing or power failures and in the event of chemical tanks running dry. In all processes where pressure filtration (cake or depth type) occurs, the addition of a head loss based cut-out will allow the plants to operate unattended for longer periods without filter clogging or damage to the filter internals.

3.2.2 Chemical dosing

Chemical dosing is usually the most complex of the tasks that must be performed by a package plant operator. Proper chemical dosing generally requires preparation of solutions to predetermined concentrations, choice of an appropriate dose, mass balance calculations to determine flowrates, calibration of the dosing equipment and monitoring of the results. Additional complications can arise from wear and tear of equipment, instability of chemicals and changing raw water conditions. The following recommendations are made to ensure proper specification and design of dosing equipment so that operating difficulties will be minimised :

Chemical tanks :

- Tanks fitted with drain taps, a sealed cap and a breather are easier to clean and stay clean longer.
- Sodium hypochlorite solutions will last longer if their tanks are screened from light and heat.
- Stickers displaying instructions for chemical dilution and pump settings can be attached to the tanks.
- The tanks should be appropriately sized for the plant and the shelf life of the diluted solution (see **Section 3.2.4.2**)

Diaphragm dosing pumps :

- Where they are used, water meters equipped with pulse outputs or magnetic reed switches should be fitted to the final treated water stream or the cleanest appropriate continuous stream to avoid fouling of the mechanism by suspended matter.
- The tubing used for the suction and delivery lines should have inelastic walls. This will minimise kinking, dilation or collapse of the tubing during suction and delivery strokes. Compressed air tubing is usually suitable.
- To prevent ingress of dirt (which will damage the one-way valves) and aid in the priming of the pump, a foot valve equipped with a filter can be fitted to the end of the suction line. A low level sensor (usually a reed switch in the foot valve actuated by a magnetic float) can be connected to the plant's control system so that the plant will trip if the chemical solution runs out. This will also prevent potentially damaging dry operation of the dosing pump.
- Manually adjusted fixed rate dosing pumps are most effective when a constant flow of water occurs at the dosing point and are not recommended for declining rate filtration processes.
- Volute casing turbulence provides 'free' flash-mixing when coagulants are dosed into the suction lines of process feed pumps. However, if this method of dosing is used, a discharge valve with sufficient spring tension to resist the pump suction will be required on the dosing line and the valve will require regular maintenance. Severe overdosing occurs when the coagulant is sucked through a faulty valve. At least one package plant manufacturer deliberately doses coagulant at the pump discharge outlet to avoid this potential problem.
- If dosing devices with periodic flow (such as drip feeders, peristaltic and diaphragm pumps) are used, the residence time in the flashmixer should considerably exceed the period between the

dosing strokes to ensure that the coagulant is homogeneously distributed in the water being treated. In-line mixing devices with short residence times and limited axial dispersion may not be suitable. These dosing devices should be adjusted to provide small volumes of the chemical at high frequency rather than less frequent injection of larger volumes.

Powder dosing systems : These may be used for dosing lime, powdered coagulants and flocculation aids like bentonite. The following considerations apply :

- Many hygroscopic powders will tend to coalesce in humid climates. Screw feeders with integral hopper scrapers work well with powders that arch or settle and do not flow easily.
- Clogging of the outlet port of powder dosing systems can be prevented if the clearance between the port and the receiving water is sufficient to prevent wetting of the port.
- Hoppers and powder storage facilities must be protected from wet weather.

Desorption and dissolution based dosing devices : Such devices may also be used to dose chemicals in the solid form into the water being treated. Examples include lime and alum saturators, iodinating cartridges and various types of calcium hypochlorite dispenser. A constant flow should be maintained through or past the device in order that a steady state and a relatively constant solution strength is achieved. This will reduce fluctuations in the administered chemical dose.

Slurry preparation and dosing : Various particulate solids used in water treatment may also be slurried prior to use. These include precoating materials such as diatomaceous earth or limestone, flocculant aids such as bentonite and slightly soluble substances such as lime.

- The pipes used for slurry transport or dosing should be large enough to prevent blockages from developing but small enough to ensure that relatively high flow velocities are maintained. The use of open channels with a steep gradient is recommended where possible.
- Facilities for flushing the slurry handling system with clean water are required.
- Stirred tanks will be required for slurry preparation and suspension of the slurry.
- The slurry should be continually recirculated through the dosing system with the shortest possible connections between the recirculation loop and the dosing point.

Gas dosing systems : Various gases including chlorine, ammonia, carbon dioxide, chlorine dioxide and ozone may be used for primary and secondary disinfection or pH adjustment in water treatment systems. The use of chlorine gas for chlorination of small water supplies in the USA is well documented in the literature. However, none of the package plants evaluated used gas dosing systems for chlorination, chloramination or recarbonation of water and the project staff are not aware of such equipment being fitted to package plants available in South Africa.

Where gases are used, suitable emergency breathing apparatus may be required. Operators must be properly trained in the operation of both the dosing and safety equipment. All equipment requires regular inspection and maintenance. A secure but well ventilated site for the equipment is also necessary. These factors can significantly increase the capital and operating cost in comparison with small-scale liquid and solid dosing systems.

3.2.3 Filtration systems

A summary of operating and design parameters for various types of filtration systems, summarised from the literature, is presented in **Table 2.1**. In the following paragraphs, recommendations are made for the successful integration of various filters into package water treatment plants. These recommendation have been based on operating experience and problems that occurred during the evaluations.

3.2.3.1 Pressure sand filters

A number of locally available package plants incorporate pressure sand filtration either for direct filtration of raw water or for filtration of clarified water from a roughing filter or sedimentation process. Single and dual-media filters are available in this form. Each of the following paragraphs discusses a problem that can arise and gives recommendations for preventing it:

- The single pump fitted to most filters resulted in either the **filtration rate** being too high, the **backwash rate** being too low or both of these effects. If the cost of separate pumps cannot be justified (small plants especially) several other options exist where centrifugal pumps are used :
    - i) An orifice or adjustable valve can be installed on the filter inlet or outlet to regulate the flowrate during filtration. During backwashing, this restriction is bypassed, permitting an increased flow of backwash water. The pump capacity must accommodate the backwash flowrate. However, this method will waste pumping energy because the pump must be throttled to operate at the normal filtration rate.
    - ii) The filtered water discharge can be elevated with respect to the backwash discharge. If the pump is appropriately sized, the lower pump head during backwashing will allow a higher flowrate to be achieved. An added advantage of elevating the treated water is that a greater pressure will be available for the reticulation system.
    - iii) If two separate filter vessels are used, they can be operated in parallel during filtration and backwashed separately to achieve a higher backwash flowrate. No energy is wasted and standby filtration capacity is available when one of the filters is off-line for repairs. A similar system was used on one of the package plants tested.
- Most of the pressure sand filters are fitted with **multiport valves** designed for swimming pool filters. These filters include a bypass option which, if accidentally selected, will allow unfiltered water to bypass the filter bed and enter the treated water storage. **Multiport valves are easily modified to disable the bypass option and this is recommended for potable water applications.**
- The head loss across the filter bed gives an accurate indication of the solids load and a given **terminal head loss** is the ideal criterion for initiating a backwash cycle. The filters are typically

provided with a single pressure gauge and a recommended backwash pressure. The pressure measured on the gauge is actually the sum of the head loss across the bed, the head loss in the subsequent piping and the static head between the gauge and the discharge end of the outlet pipe. In order to determine the true head loss across the filter bed, a second gauge fitted to the filter discharge is a minimum requirement. An adjustable differential pressure switch is more accurate and can be used to trip the filter pump or initiate an automated backwash cycle.

- **Clogging** occurred in **all** of the pressure sand filters that were evaluated. In every case, clogging was caused by a combination of ineffective backwashing due to low backwash rates and an inability to accurately determine filter head loss which resulted in overloading of the filters. The most severe clogging was typically found in the peripheral part of the bed (up to 15 cm from the sidewalls). The filtrate collection manifold at the bottom of the filter does not cover the entire cross-sectional area of the filter bed. This may cause a maldistribution of flow during either filtering or backwashing that results in the peripheral part of the filter bed becoming clogged.

  The tendency of a filter to clog can be reduced in the following ways:

  i) A suitable backwash rate can be obtained by one of the methods described above
  ii) The filter can be modified to include an air scour. This requires the installation of an air supply, filter floor and suitable nozzles since the underdrains used in conventional swimming pool filters will not work with an air scour. This feature is now offered by one manufacturer of a dual media pressure filter system (not evaluated during this project).
  iii) The filter can be operated to a lower terminal head loss or at a reduced rate.

3.2.3.2 Slow sand filters

Slow sand filtration is the only process that requires no chemicals or consumable items during normal operation. The results achieved with the pilot-scale slow sand filter corroborated findings reported extensively in the literature that continuous operation of slow sand filters with raw water turbidities exceeding 10 to 15 NTU is not feasible because:

- The frequency of filter scraping is increased significantly thereby increasing the operating workload and the frequency of sand replacement.
- Poor treated water quality is achieved with high raw water turbidities.

The simple sedimentation column that was used in conjunction with the pilot slow sand filters for this study was able to extend the range of raw water turbidities that could be effectively treated without significantly increasing the operating workload or complexity of the process. Pretreatment systems for slow sand filtration are discussed in the literature (Huisman & Wood, 1978; Graham, 1988; Galvis *et al*, 1993) and may consist of sedimentation or roughing filtration (both with or without coagulation). For the treatment of South African surface waters with slow sand filtration :

- Water abstracted from impoundments should be used wherever possible since a degree of natural sedimentation will have occurred.

- At least two separate filter beds should be installed to provide standby capacity during filter scraping and recovery.
- Post-disinfection is recommended, especially after filter scraping.
- A pre-clarification system is essential if raw water turbidities exceed 15 NTU for periods longer than 1 or 2 months per annum.

3.2.3.3 Precoat filtration systems

In their evaluated forms, neither of the two precoat filtration systems were suitable for use as package water treatment plants in rural areas, but may have application in peri-urban areas, holiday resorts and in industry. The CFMF unit (in spite of the excellent treated water quality and the potential for doubling capacity by adding two more filter modules) is technologically sophisticated and costly to build. It requires a well trained operator and frequent attention by artisans and technicians.

The diatomaceous earth filter that was evaluated gave unsatisfactory performance when fed with uncoagulated raw surface waters from the Umgeni river and the Inanda Dam. However this type of filter has potential for potable water treatment if it is modified to include the following essential components:

- A body feed system
- A disinfection system
- An adequate precoating system

Optimisation of such a modified system with respect to the most cost effective operating parameters should significantly reduce the estimated operating cost given in **Section 5.8.**

3.2.3.4 Membrane ultrafiltration and microfiltration systems

The occurrence of high plate counts in the treated water is mentioned in the literature for several ultrafiltration and microfiltration systems. The ultrafiltration process does not significantly remove nutrients and trace elements from the water. Regrowth of micro-organisms in a reticulation system fed by such a filter is likely to occur. The use of a secondary disinfection system that provides a disinfectant residual in the treated water is recommended.

3.2.3.5 Cartridge filtration

In-line cartridge filters of the type used in two of the package plants are designed for the removal of small quantities of particulates from industrial process streams, usually to protect downstream equipment from damage. They are not considered suitable for the removal of turbidity from raw waters for the following reasons:

- They have limited solids loading capacity and tend to clog rapidly. In both of the plants where they were used their average service life (expressed as the volume of water treated per cartridge) was less than 30 m^3.

- They are expensive to use because of the low service life. In the two plants that used them the specific cost of filter cartridges was greater than the total operating cost of the other processes evaluated.
- Their turbidity removal performance is relatively poor. The 50 and 5 µm series combination used in one unit typically removed less than 30 % of the influent turbidity.

The use of cartridge filters for primary particulate and turbidity removal in package plants is therefore not recommended.

3.2.4 Disinfection systems

In highly developed countries, chlorine is losing popularity because of the potential health risks from chlorine by-products, such as the trihalomethanes. Chlorine remains the most popular disinfectant for potable water treatment systems in developing countries because the health risk posed by consumption of untreated water in these areas is of more immediate concern than the risk posed by chlorine by-products. Some of the limitations of chlorine when used in developing areas include :

- Limited availability, especially in countries that have no local manufacturing capability and limited foreign exchange to pay for importation of chlorine.
- Concern about the health implications of chlorine by-products.
- Limited stability of sodium hypochlorite, the most easily dosed form of chlorine.
- The expense of chlorine dosing equipment, especially on small-scale plants.
- Limited success of on-site chlorine generation systems.
- The hazards associated with handling and transport of chlorine, particularly in gaseous form.
- Shortage of manpower with the necessary skills for handling, preparing and dosing chlorine.

These limitations have led some package plant manufacturers to search for disinfection systems that are not reliant on chlorine and five of the ten package plants evaluated were deliberately not equipped for routine chlorination.

Recommendations for the successful installation of both chlorination and other disinfection systems are given in the following sections

3.2.4.1 UV disinfection

Kruithof *et al* (1993) mention the successful application of UV for disinfection of extensively pre-treated water in the Netherlands. By removing assimilable organic carbon (AOC) and other trace elements required for microbial growth, the microbiological quality of water in the reticulation system was maintained without a disinfectant residual. The lesser degree of nutrient removal attainable with simple package plant processes and the higher ambient temperatures in South Africa are more conducive to regrowth in reticulation systems and indicate that UV disinfection may not be suitable for use in package plants. Nevertheless, acceptable disinfection results were achieved with both UV systems that were evaluated.

It should be noted that UV disinfection systems will not work effectively if attenuation of the UV light due to turbidity, fouling and UV absorbing contaminants is sufficient to reduce the UV dose below the guideline values. Doses of UV energy higher than the guideline value are required for the inactivation of organisms such as *Cryptosporidium* and *Giardia lamblia.* Reliable disinfection can be achieved with UV systems if the following guidelines are applied:

- The water to be treated should be examined for the presence of UV resistant micro-organisms of health significance. If such organisms are detected, it may be more economical to use other disinfection systems than to use a more powerful UV system.
- Where UV resistant organisms are not present, the UV system should be sized in accordance with the USEPA minimum UV dose guidelines (see below). The maximum flowrate and the transmittance of the water to be treated must be taken into account and the system design should prevent the maximum specified flowrate from being exceeded.
- The USEPA minimum UV dose guideline of 32 mWs/cm^2 is recommended for design purposes since South Africa has no statutory limit for the minimum intensity of UV radiation for potable water disinfection.
- Regular sleeve cleaning must be carried out until the effect of fouling is assessed and site specific cleaning instructions are issued.
- The elapsed operating time of each lamp must be recorded as a minimum requirement. (UV intensity monitoring is preferable).
- The reticulation system must be monitored for the build-up of micro-organisms in accordance with the guidelines issued by the Department of Health for the frequency of testing. Periodic flushing or disinfection with a hypochlorite solution is recommended as a minimum safeguard.
- A fail-safe emergency shut-down system must be provided to prevent flow through the system in the event of lamp or power failures.
- The lamps should be switched on and off as seldom as possible (by using long operating cycles) to extend lamp life.

3.2.4.2 Chlorination systems

Reliable service was obtained on several package plants by dosing **sodium hypochlorite** with various types of electronic dosing pump. The diaphragms and valves typically lasted in excess of two years before requiring replacement. Problems with decomposition of hypochlorite solutions did occur and apparent **chlorine doses of up to 25 mg/ℓ** (based on original solution strength of a three day old solution) were required to achieve residual chlorine concentrations less than 1 mg/ℓ.

Calcium hypochlorite can be reliably dosed by proprietary in-line devices. Although accurate adjustment of the dose may not be possible, the chlorine residual can be maintained between 0,3 and 1,0 mg/ℓ with a daily adjustment and residual monitoring. Calcium hypochlorite may also be dissolved to prepare a calcium hypochlorite solution that can be administered with a dosing pump.

The provision of adequate **contact time** prior to abstraction of water from the reticulation system is important. In normal practice, the treated water will flow to a storage reservoir prior to reticulation and adequate contact time will occur. **If sufficient contact time does not occur within the package plant process, the storage and reticulation system should be designed in such a manner that sufficient residence time exists (under maximum flow conditions) upstream of the first abstraction point.**

On site generation of chlorine or hypochlorite by direct electrolysis or membrane electrolysis of salt solutions is widely promoted by several manufacturers for the production of chlorine in remote and developing areas. The advantages and disadvantages of these systems are discussed in **Section 2.5.1.1**. None of the package plants evaluated incorporated one of these systems. However, a number of electrolytic chlorine generation systems are available in South Africa for both potable water treatment and swimming pool disinfection.

3.2.4.3 Other biocides

Alternative biocides to chlorine are discussed briefly in **Sections 2.5.1.2** and **2.5.1.3**. More detail is available in a number of authoritative texts (e.g. White, 1992). In order to be practical for a given application, alternative disinfectants should exhibit as many of the following characteristics as possible in relation to chlorine :

- Limited or no by-product formation.
- Greater availability.
- Easier to handle and dose.
- Greater stability and longer shelf life.
- Cheaper to purchase.
- Superior disinfection performance.

The **iodination system** used in one of the plants evaluated produced acceptable disinfection performance but the presence of high heterotrophic plate counts and the lack of a residual in the treated water were cause for concern. The aspects of the iodinated resin that are superior to chlorine include the ease of handling, shelf-life and by-products. However, the resin is more expensive than chlorine and it is currently scarce in South Africa.

3.2.5 Micropollutant removal

Some of the processes evaluated were unsuitable for the removal of various micropollutants that may occur in surface and ground waters in South Africa. While accurate predictions of the removal of particular micropollutants by these package plants will require appropriate site work, general guidelines are given here:

- **Chemical oxidation** processes are capable of converting reduced forms of iron and manganese to oxidised precipitates which are more easily removed by conventional treatment processes. In addition, chemical oxidation can be used for colour removal. Where chemical oxidation is not used in a package plant process, iron and manganese removal may be poor, especially when the raw water pH and dissolved oxygen content is low.

- **Activated carbon** treatment in the form of GAC beds is capable of removing many harmful organic compounds as well as certain inorganics. However, regular replacement or regeneration of the spent carbon will be required.
- **Ion Exchange** is suitable for the removal of ionic contaminants present in low concentrations but the regeneration of the resins will be necessary. If performed on site, suitable storage and disposal facilities for regeneration chemicals is required.
- None of the plants significantly reduced the **total dissolved solids** (TDS) concentration. The raw water at the PEF has a TDS of approximately 140 to 150 mg/ℓ which is low in comparison to ground and surface waters in many inland areas of South Africa.

3.2.6 Pumps

Most of the plants that used pumps were fitted with small centrifugal pumps (from 600 W to 2,2 kW). These typically provide flowrates between 2 and 20 m^3/h against discharge heads up to 20 m. Locally made pumps, typically used for domestic swimming pool filters are commonly used. These pumps have a tough nylon or plastic pump casing with an integral basket strainer and priming chamber. They are usually equipped with mechanical (carbon/ceramic) seals and proved to be very reliable in service. In over two years of operation with raw water, none of these pumps failed and no leakage from any of the pump seals was observed.

3.2.7 Tanks

The glass reinforced polyester (GRP) and rotomoulded polyethylene (PE) tanks that were used on many of the plants for chemical, raw and treated water storage are highly suited to package plants. The specification of chemical storage tanks was discussed in **Section 3.2.2**. The following design considerations apply to the use of tanks for raw and treated water storage:

- Stable foundations or supports are required, especially for elevated tanks.
- Scour valves and access for cleaning purposes should be provided. The normal safety procedures relating to work in confined spaces must apply during cleaning and the tank design should satisfy these safety requirements.
- All water storage tanks should be covered.
- If GRP tanks are used, flange ports or reinforced patches should be specified for pipe connections.
- Whether new or existing tanks are used for treated water storage, they should be protected from sources of contamination.

3.3 Additional infrastructure requirements

A water treatment and supply system consists of more than just the package plant itself. Additional equipment and infrastructure will be needed in order for the plant to operate reliably.

3.3.1 Site preparation requirements

Prior to the delivery and installation of a package plant, preparation of the proposed site will be required. This preparation may include the provision of :

- access to the site for the delivery or removal of the plant and supplies.
- a continuous supply of raw water to the plant.
- an adequate supply of electrical energy (where required) to the plant.
- adequate shelter and security for protection of the plant from the weather and vandalism or theft.
- adequate storage facilities for water treatment chemicals and filter media.
- a sludge treatment or disposal system.
- storage for backwash water and treated water with an appropriate reticulation system.

3.3.2 Additional equipment required for optimising and monitoring plant performance

Most package plants require additional analytical or volumetric equipment to enable the operator to properly monitor the treated water quality and prepare chemical solutions for dosing or cleaning purposes.

Volumetric equipment suitable for measuring flowrates and diluting chemicals that may be required includes:

- measuring cylinders, beakers and calibrated plastic buckets.
- funnels
- a stopwatch
- a scale (where measurement of solids is required)

Simple analytical equipment may be necessary for monitoring parameters such as pH, turbidity and chlorine residuals. While sophisticated portable electronic instruments are available for these purposes they are expensive and often require spare batteries, buffers, and calibration standards that will be difficult to obtain in rural areas. Simpler, far cheaper methods suitable for the control of small plants are available. For example:

- pH indicator strips with comparator charts are available that allow pH to be determined to within 0,2 pH units.
- comparator kits that use the **DPD method** (tablet form) can be used for monitoring chlorine residuals. **Inexpensive ortho-toluidine based comparator kits (swimming pool test kits) are available in South Africa but since the reagent is known to be carcinogenic, these kits should not be used for monitoring chlorine residuals in potable water.**
- comparator slides are available for estimating turbidity.
- comparator based kits for measuring a range of other contaminants are also available.

These methods, in conjunction with dosing charts, will probably be sufficient for most plants provided that the treated water quality is also monitored centrally in terms of the Department of Health guidelines.

3.4 Operation and maintenance of package plants in South Africa

3.4.1 Personnel requirements

The workload, training and skills requirements for the proper operation and maintenance of each package plant was estimated from operating experience gained during the evaluation period. The complexity of the operating tasks can be graded on a scale from simple to expert with terms defined as follows:

- **Simple** .... equivalent to or simpler than operating a domestic swimming pool filter
- **Moderate** ...... as for simple but requiring additional knowledge of dosing and dose adjustment.
- **Complex** .... equivalent to the operation of a small conventional water treatment plant
- **Expert** .... requires a qualified operator with a good understanding of the process.

In most cases, full-time operation (24 h/day) can be achieved without the need for shift operation and a single operator working for between 1 and 4 hours per day will suffice. In practice, the plant operator may also be responsible for maintaining the raw water supply system and the reticulation system. These additional responsibilities may entail significant extra work.

3.4.1.1 Training

The degree of training required is related to the complexity of operation. For plants that are **simple** to operate, training in the use of the plant can be imparted during commissioning and a literate operator should be capable of operating the plant with the aid of a manual. Plants that are rated **moderate** to **complex** to operate will require a literate operator with technical aptitude and a minimum Standard Eight qualification. Completion of a water care course at a technical high school and additional training specific to the operation of the plant should be considered essential. The operator of an **expert** rated system should be a fully qualified plant operator with an N4 certificate in water and wastewater treatment as a minimum requirement Further specific training related to the particular plant will also be required.

3.4.1.2 Plant operating manuals

The desirability of having manuals written in the operator's home language was stressed by a number of respondents to the postal survey (see **Section 1.3**) who work with developing communities. It is recommended that plant operating manuals should be properly bound and written in the operator's home language where possible. A comprehensive manual should contain the following information:

- Instructions for the assembly, installation and commissioning of the plant
- Diagrams of the plant layout and electrical wiring (where applicable)
- Illustrated operating instructions including start-up, shut-down, backwashing and emergency actions to be taken in the case of various equipment failures.
- Maintenance instructions to include the frequency of all maintenance tasks

- Trouble shooting notes with an address or contact number for technical advice.
- Methods for chemical preparation with cautionary notices in respect of hazardous chemicals.
- Suggested values for operating parameters like the chemical dose, flowrate and terminal head loss
- Sample calculations where applicable.
- A list of suppliers of chemicals and spares.

3.4.2 Maintenance requirements

Pumps : Various types of locally produced and imported centrifugal pumps were used on the package plants. The smaller (up to 2 kW) centrifugal pumps typically are equipped with mechanical seals and none of these developed leaks during the evaluation period. Packed gland seals generally require frequent adjustment and annual replacement when used in raw water service. Six-monthly or annual pump inspections should incorporate the following checks:

- Check for leaks at the main seal, the suction port and the discharge port.
- Listen for cavitation while the pump is operating.
- Check the operation of the motor including smoothness of starting, vibration, cooling fan, corrosion and fan guard.
- Check integrity of electrical connections.
- Take appropriate corrective action.

Dosing pumps : Diaphragm dosing pumps require regular cleaning and an annual service to maintain their volumetric efficiency and delivery pressure. During servicing, the one-way valves and the diaphragm are usually replaced.

Pipework : UV resistant PVC pipework and fittings should preferably be painted if they are exposed to the sun.

Tanks : The growth of algae and the accumulation of sediment in tanks can be expected and is likely to be significant in raw water feed tanks. Annual maintenance will be required. Occasional shock dosing of treated water tanks with granular chlorine will aid in the secondary disinfection of reticulation systems and is recommended for systems where a chlorine residual is not provided by the treatment process. Shock dosing should also be carried out after tank cleaning.

Valves : Damage to the balls and seals by grit is likely to occur in PVC ball valves that are frequently used. The balls, "O" rings and teflon seals in these valves require checking if the valve begins to leak or if the valve action becomes stiff. Brass gate valves frequently do not seal perfectly once the gate has suffered erosion or corrosion due to grit in the water.

Level sensors : Various types of level sensors are available for monitoring water levels in tanks. These sensors need to be regularly checked for corrosion and dirt build-up that can affect their operation. Six monthly checks are recommended for level controlling devices fitted to treated water storage systems while more frequent checks will be required for such devices operating in raw waters.

UV lamps : As discussed in **Section 2.5.3**, the output intensity of UV lamps declines steadily with elapsed operating time and is further decreased by the number of ignition cycles. Since the UV systems fitted to the package plants in this study were not equipped with UV intensity sensors, their elapsed operating time was recorded and used as the criterion for lamp changing. This system is not ideal and should be used only in conjunction with disciplined record keeping and instrumentation that monitors the current passing through the lamp.

Sludge and mineral deposits can also build up on the wet side of the quartz tubes and these require checking. An initial cleaning interval of three months is recommended after which this period can be extended or decreased as necessary.

Pressure sand filters : The pressure sand filters used in many of the package plants were of the type typically used for domestic swimming pools. The collection manifold at the bottom of these filters which also serves as the backwash water distribution manifold often does not supply the outer perimeter of the filter bed with a sufficient flow of backwash water. On all the evaluated plants that used these filters, the outer edge of the sand bed became clogged during the evaluations. This problem usually results in shorter filter runs (due to reduced bed capacity) rather than increased filtration pressure. Removal and washing of the sand is difficult due to limited access but will be necessary if filter runs start becoming shorter for no apparent reason.

Pressure Guages : The brass Bourdon tube pressure gauges used for indication of pressure in filter vessels and pipes on package plants can become corroded within two years, especially when exposed to acidic waters and waters containing chlorine. The mechanisms are also easily fouled by dust and dirt when exposed to the weather. The gauges should be checked every six months against the readings obtained during commissioning. Difference in pressure readings with time may be due to gauge damage, filter clogging or other problems. Guages should always be tapped lightly to overcome static friction before readings are taken.

3.4.3 Availability of spares and consumables

The availability of items common to many package plants such as simple pumps, chemicals, pipe fittings and dosing pumps is described in the paragraphs that follow :

Pressure sand filters : Glassfibre and polypropylene filter vessels, multiport valves and filter internals are locally manufactured by several companies and are widely available in urban and rural areas of South Africa through industrial, swimming pool and agricultural suppliers.

Small (<2 kW) centrifugal pumps : A number of locally produced and imported makes are available through swimming pool, industrial and agricultural suppliers. Electric motors are also widely available through the same suppliers as well as armature winders in the main centres. Spares such as bearings and seals are usually only available through industrial suppliers.

Dosing pumps : Several makes of dosing pump are locally available but the agents are usually located in the main centres. Spare parts are not always available over the counter and should be ordered in advance if possible. Service kits containing all parts required for overhauling the pump heads are available for most of the dosing pumps sold in South Africa

Chemicals : Chlorine gas, calcium hypochlorite and sodium hypochlorite are all locally manufactured. Calcium hypochlorite, commonly used for swimming pool disinfection is widely available in retail outlets in urban and rural areas. Sodium hypochlorite is also available as household bleach in retail outlets but is more cost effective if purchased at higher concentrations through chemical wholesale agencies located in the main centres.

Pipe and pipe fittings : PVC, polypropylene, HDPE, LDPE, steel, SS, galvanised and copper pipes are all manufactured in South Africa. Many of the corresponding fittings are also locally manufactured and imported fittings are also available. PVC pipe and fittings are most commonly used on the package plants evaluated and are widely available through industrial suppliers in the main cities and agricultural suppliers in the rural areas.

Tanks and filter vessels : GRP tanks and filter vessels are manufactured and widely available in South Africa. Several GRP tank manufacturers offer stock sizes up to 20 m^3 and will undertake manufacture of larger tanks to specification. GRP tanks are also easily repaired on site although the repair of GRP pressure vessels (such as pressure filters) is not recommended. Rotomoulded polyethylene (PE) tanks up to 20 m^3 and filter vessels are also manufactured in South Africa. PE tanks are widely available through industrial and agricultural suppliers and they are resistant to weathering.

3.5 Effluent handling

In any process used for the production of potable water from a raw water source, a concentrate containing the matter removed from that water will be produced in some form. Any additional substances used as part of the treatment process may also be present in the concentrate. These concentrates will require disposal in a responsible manner to prevent pollution of the environment including the original water source.

No sludge treatment processes are incorporated in any of the ten package plants that were evaluated and procedures for the treatment or handling of sludges were not given in any of the operating manuals. It is recommended that effluents produced by treatment of raw waters in package plants be handled according to the guidelines presented in **Section 3.5.2**.

3.5.1 Effluent standards and legislation

The Department of Water Affairs and Forestry (DWA&F) sets standards for the quality of effluents that are discharged to rivers or streams from point sources (DWA, 1986). The current policy towards effluent standards is to assess the receiving water's capacity to assimilate the non hazardous contaminants contained in an effluent stream as well as the quality objectives relevant to subsequent use of that water (DWA&F, 1991). Site specific effluent standards are then imposed which describe the quality and quantity of effluent that may be discharged so that the Receiving Water Quality Objectives (RWQO) will be met. RWQO studies can be performed by consultants or other organisations with the assistance of DWA&F. Until a site specific effluent standard has been issued, the existing General and Special Standards for effluent quality are applicable.

The current General and Special Standards permit no more than 25 and 10 mg/ℓ of suspended solids respectively in effluents discharged to bodies of water (DWA, 1986). In most cases, even with effluents from package plants that do not use chemicals, these suspended solids concentrations will be exceeded and the discharge of these effluents without further treatment will be illegal.

3.5.2 Types of effluents and options for treating them

The characteristics of the effluents vary according to the type of process:

Sedimentation tanks or clarifiers : If chemical coagulants are used, a sludge of up to 3 % solids by mass may be produced. These sludges often do not dry out readily, particularly when flocculation aids like bentonite have been used. Supernatant water recovered from settling of dilute sludges may be recycled. Shallow ponds or sludge drying beds will be sufficient for solar evaporation of the decanted sludges from small package plants. These sludges may not be suitable for distribution on agricultural land. Where no coagulants are used, the sediment will typically consist of fine mud and silt which can be periodically removed, dried and distributed on land.

Sand filters, upflow filters, dual media filters : Where chemical coagulants have been used, the composition of the effluent will be similar although more dilute than the clarifier sludges and it may contain some of the filtration media. When this effluent is allowed to settle, most of the backwash water may be recovered and recycled. The remaining sludge and media can be periodically removed from the recovery system, dried and distributed on land.

Cartridge filter systems : Cartridges used for the filtration of raw waters are generally not washable. The suspended matter is trapped in the pleats of the cartridges and these will require disposal. Negligible quantities of effluent are produced during cartridge replacement.

Microfiltration and ultrafiltration systems : The effluents resulting from normal filtration will simply be concentrates of the rejected matter and should contain no additional substances. These effluents may contain high concentrations of colloidal matter and micro-organisms. The effluent produced by the CFMF process also falls into this category if no precoat material is used.

If sufficiently dilute, the effluent may be returned to the source (downstream of the intake) or used to supplement irrigation water. The effluents resulting from chemical cleaning of ceramic UF membranes will contain detergents or strong acid and base mixtures and should not be discharged to the environment without appropriate treatment.

Slow sand filters : Negligible effluent will result from *schmutzdecke* removal although the treated water is usually discarded until the scraped filter has restabilised. The sand accumulated from filter scraping may be rinsed and eventually used when the filter is resanded.

Precoat filtration systems : The filter washing effluent will contain both the filtered matter and the precoat media (DE, kaolin, limestone). Although precoat media such as DE may be inert, discharge of this effluent to the source water will significantly increase the suspended solids content and will probably be illegal in terms of the effluent standards. Since precoat media tends to settle readily, treatment of the effluent in a sedimentation tank will allow separation of the precoat material which can be dried and disposed of. The remaining effluent may be treated as for UF effluents.

3.6 Effects of plant capacity on capital and operating costs

Plant capacity has a significant effect on the normalised capital and operating costs of package plants (see **Figures 3.1** and 3.2). In addition, the demand for treated water in rural areas will generally increase as more individual connections are made to the reticulation system (see **Section 3.1**). For these reasons, it makes sense to plan for future capacity augmentation when choosing a package plant. Significant savings may be possible by purchasing a larger plant and operating below full capacity initially than by acquiring a smaller unit initially and supplementing it with additional modules as the need arises. The effects of plant capacity on capital and operating costs are discussed in more detail in the following sections.

3.6.1 Capital cost

The capital costs of the various plants as presented in **Section 5** include only the cost of the prefabricated unit and where stated, the commissioning costs. Value added tax (VAT) and expenses such as start-up chemicals, operator training, transport of the plant to the site and assembly are not included as these may vary from site to site.

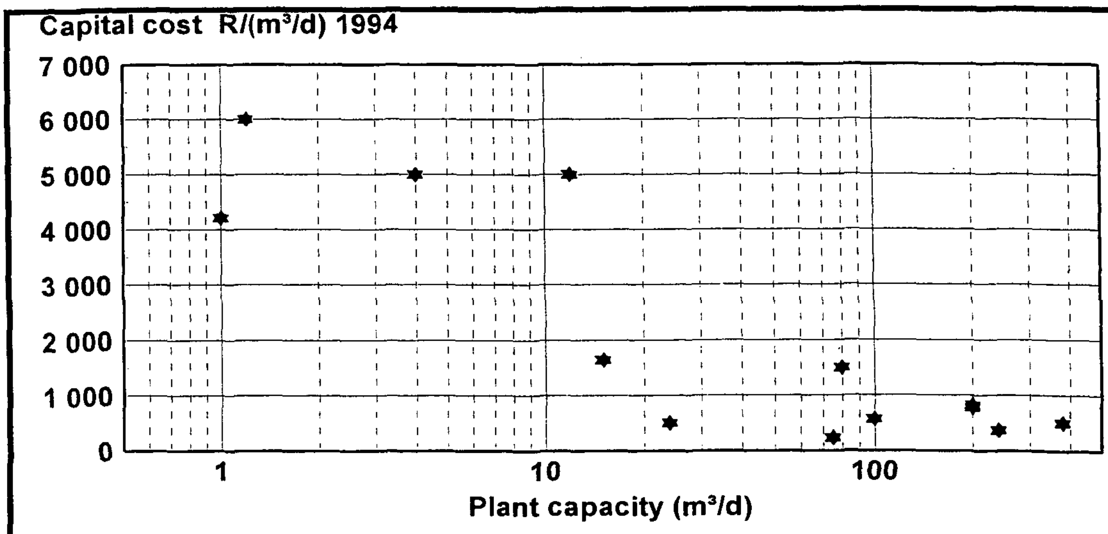


Figure 3.1 : Effect of capacity on normalised capital cost

The normalised capital cost of package plants (capital cost per unit of available capacity) is generally considerably higher for small units than for large units (see **Figure 3.1**). The more sophisticated plants also tend to be more expensive but may offer reduced operating costs and better water quality. **Figure 3.1** was compiled from the capital costs of the package plants that were evaluated as well as costs for similar plants from the same suppliers that are larger in capacity than the evaluated units.

3.6.2 Operating cost

The operating cost is comprised of cost components for chemical and consumable expenses, energy costs, wages and equipment maintenance costs. The cost of depreciation, interest and loan repayments is not included.

The operating cost of a plant may be significantly affected by the following factors:

- Increases in **raw water turbidity** can affect chemical consumption, filter run times, filter media requirements, water recovery and throughput.
- **Plant downtime** due to equipment failure or the inability of the plant to operate unattended will significantly increase the specific cost of labour and maintenance (fixed operating costs).
- The operating cost can be very sensitive to the **plant capacity** because the operating workload and energy requirements tend to be disproportionately higher for the smaller units.

Typically, the capital cost per unit of production capacity in a given manufacturer's range will be lower for the larger plants. In most cases the operating workload does not increase in direct proportion to the plant capacity so the specific labour cost can be significantly lower for large capacity package plants. **Figure 3.2** demonstrates this effect with operating costs taken from the evaluated plants. Where sufficient information was available the operating costs were also adjusted appropriately for similar plants of larger capacities.

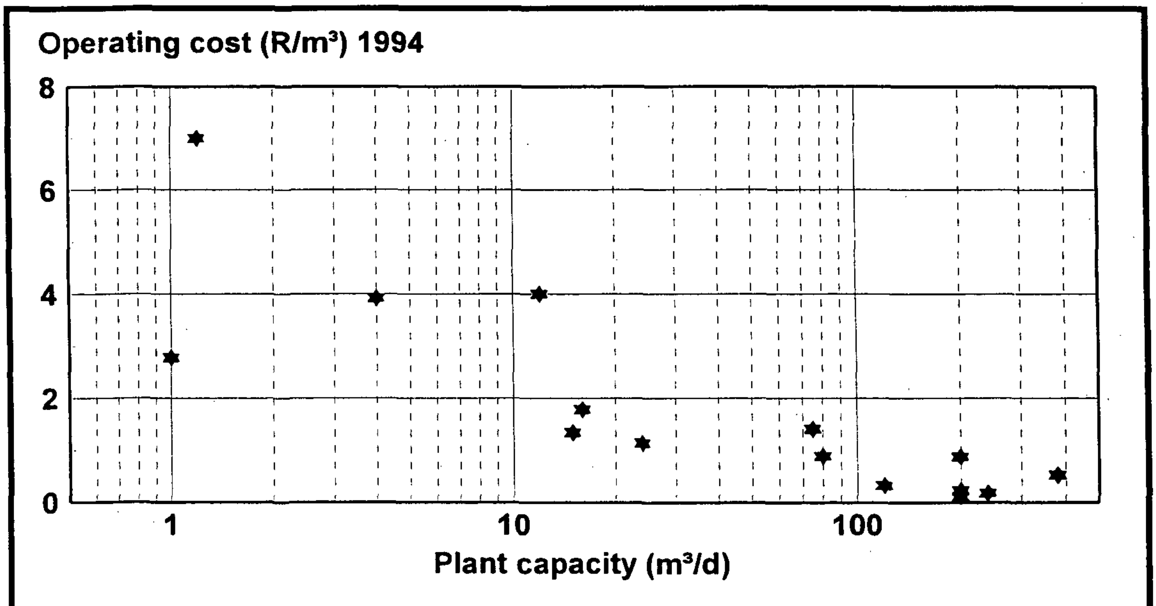


Figure 3.2 : Effect of capacity on operating cost for various package plants

Specific energy consumption is often lower for larger plants because the larger pumps and pipe diameters are often more energy efficient. However, where high operating pressures are required, such as in microfiltration units, it may not be possible to significantly reduce the energy requirements and the operating costs of these processes are likely to become less competitive as plant capacity increases.

4 Future Research and Technology Transfer

The plants evaluated during this project represent a small proportion of the package plants and related equipment that is available in South Africa, let alone internationally. New products are also frequently introduced. It is therefore not possible to comprehensively evaluate all of the package plants that are available without a considerable investment in time and money. Where plants make use of conventional unit operations, this project and the literature provide information on design and operating parameters to which the plants should conform. Technology transfer actions are required so that consultants and water organisations are exposed to the available plants and methods of evaluating their suitability for particular applications.

In the interests of technology transfer, two presentations were made during the course of this project. A paper entitled "Disinfection Methods for Package Water Treatment Plants" was presented to the IWSA International Specialized Conference on Disinfection of Potable Water held in May 1994 at the Kruger National Park in South Africa and a lecture entitled "Package Plants for Small-scale Water Supplies" was presented at a meeting of the Kwa Zulu-Natal Branch of the Water Institute of South Africa in March 1995. Both presentations generated enquiries from water authorities and consultants involved in rural water supply projects but the response to the latter presentation was far greater, possibly because it was more accessible to the relevant audience.

Where novel processes are used, there is a need for impartial scientific evaluation of the novel technology so that its limitations, integrity and reliability can be assessed. Guidelines or standards for the successful integration of such processes should be proposed and their advantages and limitations should be highlighted. As an example, UV light has been used for disinfection of water since 1909; although both the EPA and the US Public Health Service have published guidelines for the design and specification of UV disinfection processes (White, 1993) no legislated standards are known to exist.

Apart from refinements to the methodology used in this study, it is recommended that future research on package plants and technology transfer actions should emphasise factors that did not form a major part of this study. These factors include:

- Compilation of a **Register of package plants** installed in Southern Africa. This will aid in the gathering and distribution of information on small water treatment systems.
- **Presentations** at conferences and **publishing** of information in local water treatment journals.
- An **on-site survey** of installed plants to assess operational success. The Drinking Water Research Laboratory of the US EPA has conducted similar surveys in the USA and has developed a detailed protocol for surveying plants and assessing the information gathered in this way.
- **Continued evaluations** of package plants that utilise non conventional and novel technologies. These evaluations can be performed according to the method developed for this project.

- Evaluation of small scale **disinfection systems** such as:
  - i) On-site hypochlorite, chlorine and mixed oxidant gas generation by electrolysis.
  - ii) UV systems
  - iii) Electrolytic ozone generation
  - iv) Silver impregnated ceramics (Katadyn filters and through flow disinfection systems)
- Package plant systems for the **treatment of ground waters** where more emphasis is placed on stabilisation of the water and the removal of dissolved mineral contaminants that pose health risks or cause aesthetic problems.

UMGENI WATER

PROCESS EVALUATION FACILITY
SCIENTIFIC SERVICES DIVISION

and

UNIVERSITY OF NATAL

POLLUTION RESEARCH GROUP
DEPARTMENT OF CHEMICAL ENGINEERING

Report to the

WATER RESEARCH COMMISSION

on

PACKAGE WATER TREATMENT PLANT SELECTION

PART 2

LIMITED COMPARATIVE PERFORMANCE STUDY

by

WJ VOORTMAN AND CD REDDY

5 Summary of Package Plant Evaluations

Ten package water treatment plants comprising a range of different turbidity removal and disinfection technologies were evaluated during the experimental phase of the project. The plants were mostly donated for evaluation purposes by their respective manufacturers or marketing organisations. **Table 5.1** contains a list of the plants that were evaluated and the names, telephone numbers and addresses of the donor companies.

Table 5.1 : Manuafucturers and Plant Capacities

Package plant	Details of plant manufacturer	Available plant capacities
AEC: Ceramic Microfiltration Plant	**Atomic Energy Corporation** Mr F.W.C. Coetzer ☎ (012) 316 5949, Fax (012) 316 5925	0,06 to 21 m^3/h **Prototype capacity:** 0,08 m^3/h. **Dimensions :** 1 m x 0,5 m x 1,5 m
Aquasprite : Dual Media Filtration	**Aquatek** Mr. R. Starke ☎ (012) 466 261, Fax (012) 464 298 ,	1 to 12,5 m^3/h **Model tested:** D1/L8/50, 1 m^3/h **Dimensions :** 1 m x 1 m x1,5 m
Diatomaceous Earth filtration plant	A filtration plant was based on a donated filter vessel. ☎ (031) 261 7201, Fax (031) 261 7202	8 to 160 m^3/h. **Model tested:** 12 m^3/h **Dimensions :** 1,5 m x 1 m x 1,5 m
Exxflow: Crossflow Microfiltration	**Explochem Water Treatment Pty (Ltd)** Mr K. Treffry-Goatley ☎ (031) 701 4817, Fax (031) 701 8885	Built to specification. **Prototype capacity:** 8 m^3/h **Dimensions :** 12 m x 6 m x 2,5 m
CSIR Package Plant	**Division of Water Technology, CSIR** Mr D. Whyte ☎ (012) 841 2273, Fax (012) 841 4785	5, 10 and 20 m^3/h units. **Model tested:** 10 m^3/h **Dimensions :** 6 m x 2,5 m x 2,5 m
Filtrex : Direct Upflow Filter	**Explochem Water Treatment Pty (Ltd)** Mr K. Treffry-Goatley ☎ (031)701 4817, Fax (031)701 8885	Built to specification. **Prototype capacity:** 0,5 m^3/h **Dimensions :** 2 m x 2 m x 4 m
Eliminator: Solar powered UV disinfection	**Johnson's** Mr B. Johnson, C. Johnson ☎ (031)327 994, Fax (031) 372 434	0,3 and 0,6 m^3/h. **Model tested:** 0,6 m^3/h **Dimensions :**1,2 m x 0,7 m x 0,6 m
Watermaker: Batch settling and filtration	**Select Water & Engineering Services** Mr P. Mossner ☎ (011) 792 2590, Fax (011) 792 3105	2,7 to 6,6 m^3/h **Model tested:** 2,7 m^3/h **Dimensions :** 3 m x 4,5 m x 2 m
Diamond Rain Water Purification Unit	**Vector Environmental Technologies** Mr D.D. Dunk, ☎ (091) 702 331 5524, Fax (091) 702 331 5527 (USA)	0,46 to 3,45 m^3/h. **Model tested:** DRWP2, 0,46 m^3/h **Dimensions :** 2,1 m x 1 m x 1,2 m
Slow Sand Filter	In-house design by project staff ☎ (031) 261 7201, Fax (031) 261 7202	Built to specification. **Prototype capacity:** 0,1 m^3/h **Dimensions :** 2,5 m x 2,5 m x 4 m

5.1 Process descriptions

Diagrams and brief descriptions of the processes (similar to those in **Section 2**) are repeated here in **Table 5.2** for convenience. Full descriptions of these package plants are given in the introduction sections of **Sections 6** to **15**.

Table 5.2 : Package Plant Diagrams

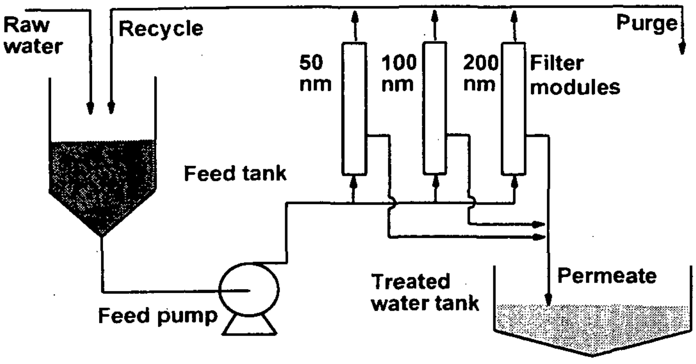
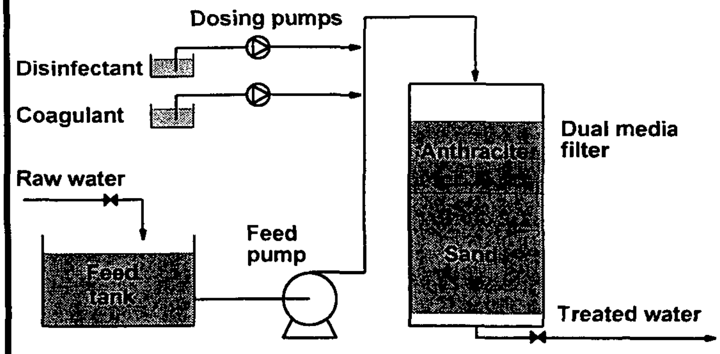
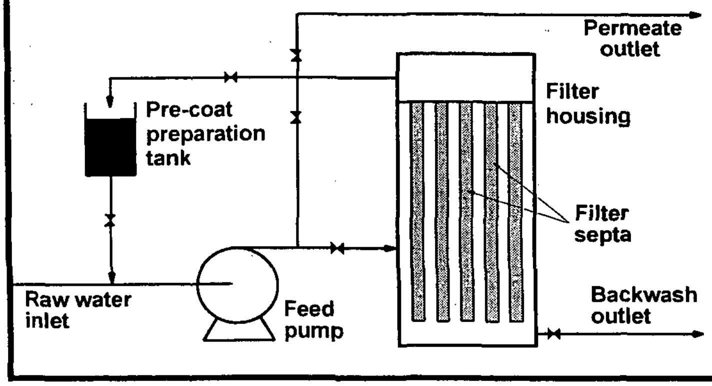
	**Atomic Energy Corporation : Ceramic Microfiltration development prototype** Water is pumped from the feed tank to the membrane modules at a pressure of 500 kPa. The clear permeate is collected and flows to a permeate storage tank. The retentate stream is recycled to the feed tank and the water lost from the system as permeate is made up by inflow of raw water. Periodic purging is required to reduce the concentration of rejected matter in the feed tank.
	**Aquasprite ; Dual media direct pressure filtration unit** Raw water, pumped from a feed tank is dosed with a coagulant and a sodium hypochlorite solution. The dosed water is filtered directly in a dual media pressure sand filter. The processes of flocculation and roughing filtration are combined in the upper anthracite layer and filtration of the remaining fines occurs in the finer sand layer. Treated water is pumped to storage.
	**Diatomaceous earth filter** Fabric covered septa are precoated with diatomaceous earth prior to each filter cycle. Suspended matter in the raw water is filtered out by the precoat, forming a cake through which subsequent filtration takes place. The filter cycle is terminated when the pressure reaches 150 kPa. The filter is washed by reversing the flow to eject the filter cake and used media.

Table 5.2 : continued

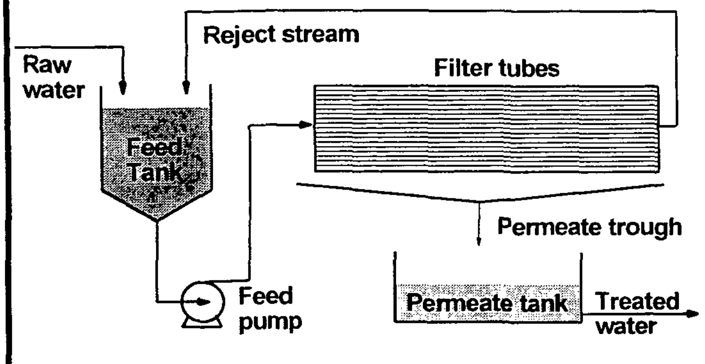
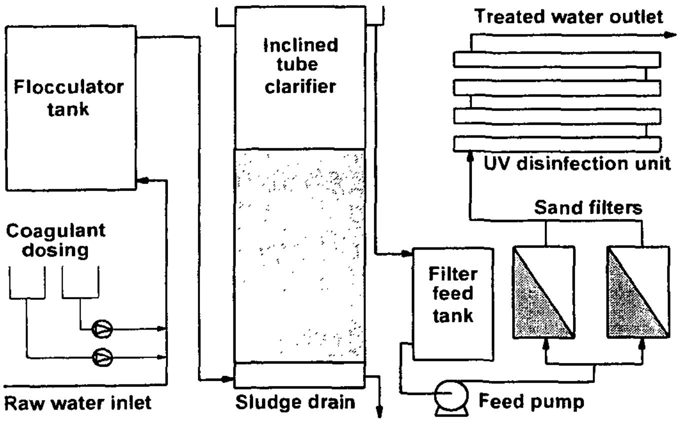
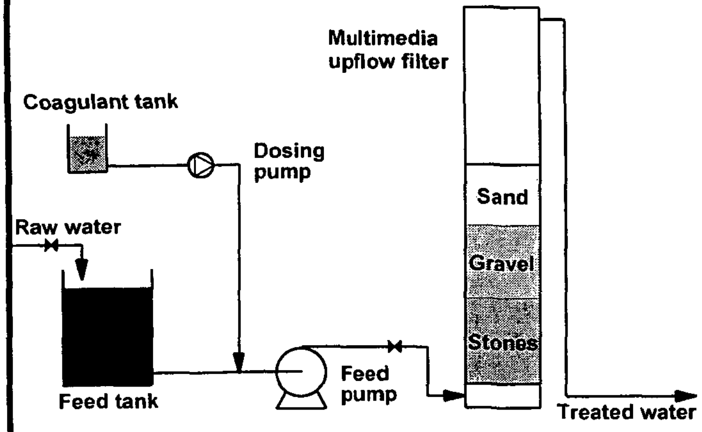
	**Explochem : Exxflow Cross-flow microfiltration plant** Feed water is pumped into a system of hollow fabric tubes precoated with limestone. Filtration occurs through a cake of suspended matter that builds up on the precoat. By maintaining a high cross-flow velocity, headloss development is retarded and long filter cycles are possible. The reject stream is recycled and the water lost as permeate is made up with raw water.
	**CSIR package plant : conventional process** Raw water is dosed with a coagulant prior to flash-mixing and flocculation. Sedimentation occurs in a rectangular upflow clarifier fitted with inclined tubes. The clarifier overflow drains into a filter feed tank from which it is pumped to a pair of pressure sand filters and disinfected by exposure to UV light. Two extra chemical dosing systems provide versatility, permitting any two of pre-chlorination, floc aid, powdered activated carbon, lime or post chlorination chemicals to be dosed.
	**Explochem : Filtrex Direct Upflow Filter** Raw water is dosed with a coagulant and pumped to the multimedia upflow filter. Flocculation and roughing filtration take place in the coarse (lowest) layer. Filtration of finer particles occurs in the progressively finer layers of media above. The overflow is typically disinfected and drained to storage.

Table 5.2 continued

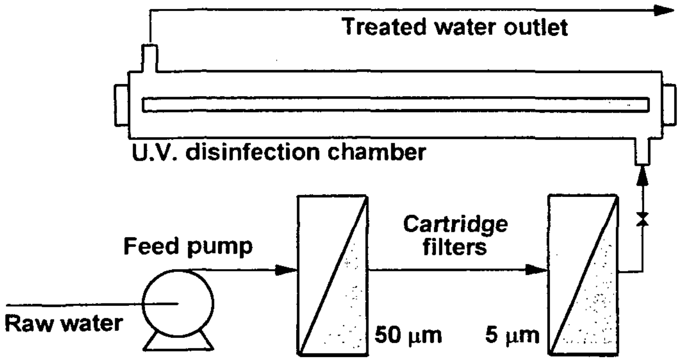
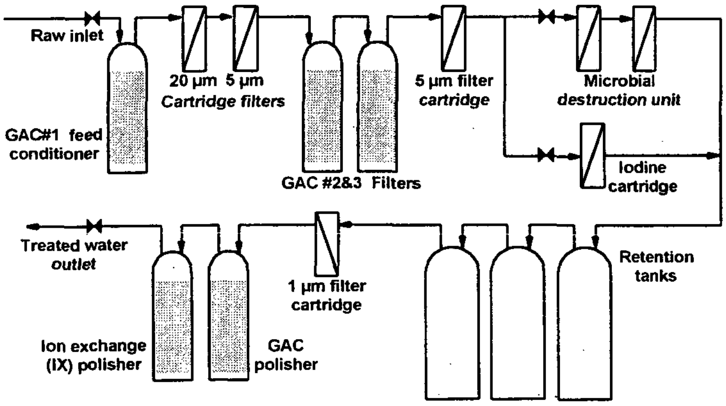
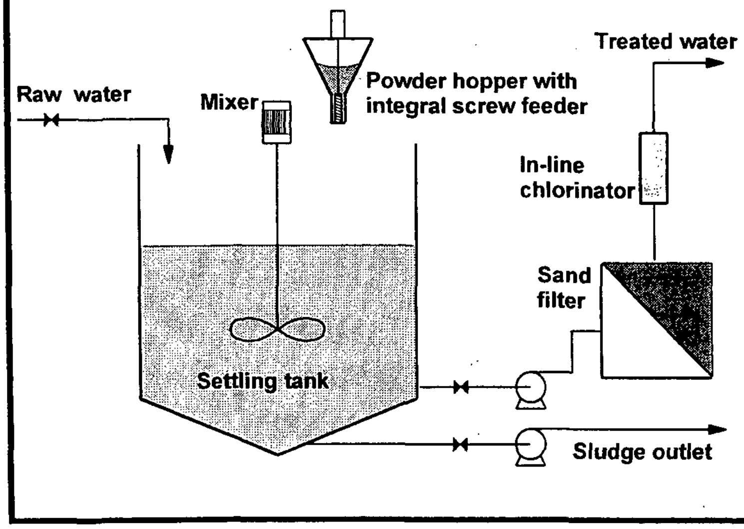
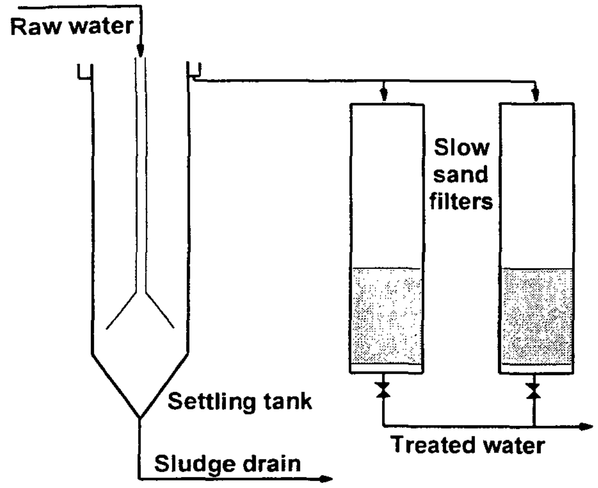
	**Johnson's Eliminator ; Solar powered UV disinfection system** Raw water is pumped through two cartridge filters with pore sizes of 50 and 5 µm respectively. The filtered water then passes through a UV disinfection chamber where it is exposed to a dose of UV light. The treated water may be used directly or pumped to storage. The unit is solar powered and a car battery is used for electrical energy storage
	**Vector Venture Corporation : Diamond Rain Water Purification Plant** (DRWP2) Raw water is passed sequentially through a series of granular activated carbon beds and cartridge filters to remove turbidity and organic contaminants. The filtered water is then dosed with iodine and passed to a system of holding tanks which provide sufficient contact time for proper disinfection. Iodine and iodide ion are then removed by sequential GAC and ion exchange treatment.
	**Watermaker Plant ; batch sedimentation and filtration** A batch of raw water is dosed with a proprietary coagulant powder and thoroughly mixed. When the mixer stops, sedimentation occurs. The supernatant water is collected and pumped through a pressure sand filter where finer particles are removed. The filtered water is dosed with calcium hypochlorite by a proprietary in-line dosing device after which it is sent to storage. Sediment is pumped out of the tank by a separate pump at the end of each cycle.

Table 5.2 continued



Slow Sand Filter

A pilot scale plant was designed and commissioned by the project staff. A conical sedimentation tower with geometry as depicted was used for clarification of raw water prior to filtration by two slow sand filters connected in parallel. No disinfection or coagulant chemicals were used. The two filters were operated at different rates to assess the effect of filtration rate on water quality and frequency of filter scraping.

5.2 Site preparation requirements

Table 5.3 summarises the additional site preparation required for each plant. In addition to the information in the table, the following points are relevant:

- All of the plants except the **Eliminator** and the **Slow Sand filter** generate significant quantities of waste sludge requiring treatment prior to discharge. In addition, the **AEC MF** plant produced acidic and alkaline effluents during the chemical cleaning procedure
- The **Eliminator** and **Diamond Rain** unit were the only plants suitable for direct supply of treated water to consumers and did not require an intermediate storage reservoir or reticulation system.

Table 5.3 : Additional infrastructure required by various package plants

Plant	Energy source	Raw water head	Type of access	Civil work		Additional storage requirements	
		(m)*		Floor	Shelter	Chemicals	Washwater
AEC MF	220 V	1	LDV	Yes	Yes	Yes	No
Aquasprite	220 V	-0,5	LDV	Yes	Yes	Yes	Yes
DE filter	220 V	0,5	LDV	Yes	Yes	Yes	No
Exxflow	380 V	3	Truck	Yes	Yes	Yes	No
CSIR	380 V	2	Truck	Yes	No	No	Yes
Filtrex	220 V	0	LDV	Yes	No	Yes	No
Eliminator	Solar	-1	Foot	No	No	No	No
Watermaker	220 V	2	Truck	Yes	Preferable	Yes	No
Diamond Rain	Gravity	10 to 40	LDV	No	No	No	No
Slow sand filter	Gravity	4	LDV	Yes	No	No	No

* The head required (relative to plant floor level) for proper operation was estimated to give an idea of additional raw water pumping or weir height requirements. Negative values indicate plants with built-in self-priming pumps.

5.3 Personnel requirements

The workload, training and skills requirements for the proper operation and maintenance of each package plant was estimated from operating experience gained during the evaluation period.

5.3.1 Operating and maintenance personnel requirements

The complexity of the operating tasks for each plant has been estimated and is graded on a scale from simple to expert with the terms explained as follows (see **Section 3.4.1**):

- **Simple** .... equivalent to or simpler than operating a domestic swimming pool filter
- **Moderate** ...... as for simple but requiring additional knowledge of dosing and dose adjustment.
- **Complex** .... equivalent to the operation of a small conventional water treatment plant
- **Expert** .... requires a qualified operator with a good understanding of the process.

Table 5.4 : Operating and maintenance workload

Plant	Operating workload	Operating complexity	Unattended operation	Maintenance workload	Installation and commissioning
	hours/week		max. hours	hours/annum	days
AEC MF	9	moderate	168	6	1
Aquasprite	18	moderate	24	4	1
DE filter	14	moderate	0,5	6	2
Exxflow	14	expert	168	48	20 to 40
CSIR	16	complex	72	15	3 to 8
Filtrex	8	moderate	24	6	2 to 3
Eliminator	2	simple	n/a	6	0,04
Watermaker	14	simple	48	6	2
Diamond Rain	7	moderate	48	24	1
Slow sand filter	3	simple	72	30	7 to 14

The workload given in **Table 5.4** relates to plant operation only. In most cases, full-time operation (24 h/day) can be achieved without the need for shift operation and a single operator working for between 1 and 4 hours per day will suffice. The exception is the **diatomaceous earth** (DE) filter where the lack of a body-feed system caused rapid head loss development. Since the plant was manually controlled with no automatic shut-down facility, continual monitoring by the operator was required. This method of operation is not feasible in the long term.

5.3.2 Plant operating manuals

Plant operating manuals were not supplied for the **Slow Sand Filter**, **Filtrex** and **Exxflow** units. All of these plants were pilot scale or prototype units. The manuals for the **Diamond Rain** and **CSIR** plants were comprehensive, including instructions for installation, commissioning, operation, maintenance and trouble shooting. In addition, both of these manuals were well illustrated and cross referenced. The manuals for the remaining five plants were rudimentary, generally providing only basic operating and maintenance notes.

All of the manuals were written in English and there was no indication from any of the suppliers that manuals are available in any of the indigenous South African languages, including Afrikaans.

5.4 Control systems

The control philosophy, procedures and hardware are discussed in detail in the plant evaluation reports (**Sections 6** to **15**). Brief summaries are presented here in **Table 5.5**.

Table 5.5 : Control Philosophies

Plant	Automation	Comments on control philosophy and its effectiveness
AEC MF	Manual	Declining-rate constant-pressure filtration is used and is compatible with this process. A flowrate based feed pump trip will be useful.
Aquasprite	Partially automated	Constant-rate dosing is used but is not compatible with declining rate filtration. Pulse controlled dosing is recommended. A head loss based trip will help to reduce the workload and prevent overloading the filter bed.
DE filter	Manual	Raw water filtration without body feed is not feasible. Head loss development is rapid at normal filtration rates and constant supervision is required. A head loss based trip is essential to prevent filter bag damage.
Exxflow	Automated	Declining-rate constant-pressure filtration is used and is compatible with this process. The fully automated PLC based control system is versatile but complex and expensive. It was not reliable and many control hardware failures occurred.
CSIR	Partially automated	The UV and post-chlorination control systems were extensively modified during the evaluation to improve performance and reduce contamination. When power failures occur a raw water shut-off and automatic start-up is required.
Filtrex	Manual	Constant-rate variable-head operation is the most feasible. A reliable automatic trip or wash cycle based on filter head loss is easily fitted.
Eliminator	Manual	The lamp alarm, flow restrictor and appropriately sized pump is the cheapest feasible UV dose control system and works adequately. The push-button control allows frequent lamp ignition cycles and will shorten lamp life.
Watermaker	Automated	Fine adjustment of the chemical and chlorine doses is not possible but this automated batch control system is reliable and effective
Diamond Rain	Manual	The low technology control method is compatible with this plant. Pressure readings should be made at comparable flowrates. Frequent monitoring, control and cleaning actions are required.
Slow sand filter	Manual	Constant-rate constant-head control by outlet valve regulation is effective but requires regular adjustment. Raw water flowrate control (constant-rate variable-head) is also feasible and allows longer periods of unsupervised operation.

5.4.1 Additional equipment for optimising and monitoring plant performance

Most of the package plants require additional analytical or volumetric equipment to enable the operator to properly monitor the treated water quality and to prepare chemical solutions. These requirements are summarised in **Table 5.6**.

Table 5.6 : Additional equipment required for effective control of package plants

Plant	Analytical Equipment			Volumetric Equipment		
	Turbidity	Residual	Jar tests	Dilution	Dosing rate	Flowrate
AEC MF	Yes	No	No	Yes	No	No
Aquasprite	Yes	Yes (DPD)	Yes	Yes	Yes	Yes
DE filter *	Yes	Yes (DPD)	No	Yes	Yes	Yes
Exxflow	Yes	No	No	No	No	No
CSIR	Yes	Yes (DPD)	Yes	Yes	Yes	No
Filtrex *	Yes	Yes (DPD)	Yes	Yes	Yes	No
Eliminator	Yes	No	No	No	No	Yes
Watermaker	Yes	Yes (DPD)	No	No	No	Yes
Diamond Rain	Yes	Supplied	No	No	No	No
Slow sand filter	Yes	No	No	No	No	No

* These units had **no disinfection equipment** but it is assumed that field applications would have pre or post-chlorination equipment.

5.5 Water Treatment Performance

The quality of the treated water produced by the plants was recorded during their operation at the PEF. Analyses of the microbiological quality and micropollutant content were conducted at Umgeni Water's SABS accredited laboratory in Pietermaritzburg. Jar tests to determine chemical doses and monitoring of pH, turbidity, suspended solids and conductivity were conducted at the PEF.

5.5.1 Disinfection

The disinfection performance is summarised in **Table 5.9**. It should be noted that the relatively poor disinfection of faecal micro-organisms and coliforms by the **Watermaker** plant was probably due to inadequate chlorine contact time since the sampling point was located immediately downstream of the chlorination device. In practice, the treated water from this plant will flow to a storage reservoir where adequate contact time should occur.

The disinfection performance of the **DE** filter was not investigated because no disinfection system was supplied with the unit and weave separation in the filter bags resulted in contamination of the treated water .

5.5.2 Turbidity and Aesthetics

The turbidity removal achieved during the package plant evaluations is summarised in **Table 5.9** and the corresponding plant operating parameters are shown in **Table 5.7**. Excellent turbidity removal (beyond that required for potable water) was typically achieved with the **AEC MF** plant and the **Exxflow CFMF** plant. In addition, the **Aquasprite** and **Filtrex** filter typically produced treated water with turbidities well below 1 NTU during the evaluation period.

The turbidity removal performance of the **DE filter** was poor because of problems with the filter bags (see **Section 8**). Turbidity removal was also poor with the **Eliminator** unit; the cartridge filtration system typically removed only 20 % of the influent turbidity. In spite of this, excellent disinfection results were consistently obtained.

Table 5.7 : Treatment system operating parameters

Plant	Flowrate used m^3/h	Filtration rate m/h	Operating pressure kPa	Water recovery %	Energy consumption kWh/m^3
AEC MF *	0,06 to 0,08	0,3	500	96 to 98	14,4
Aquasprite	0,5 to 2,5	2,5 to 15	0 to 80	95 to 98	0,23
DE filter	2,0 to 3,0	1 to 1,5	0 to 150	not evaluated	0,5
Exxflow *	7,0 to 10,0	0,1	400	93	2,45
CSIR	5,0 to 9,0	10 to 14	90 to 150	98 to 99	0,2
Filtrex *	0,5	7	70 to 80	97	2,2
Eliminator	0,6	n/a	<100	99,9	0,19
Watermaker	2,7 to 3,0	1,2	90 to 145	85	0,24
Diamond Rain	0,1 to 0,46	0,2 to 1,0	100 to 400	98	gravity flow
Slow sand filter *	0,01 to 0,03	0,1 to 0,3	20	96	gravity flow

* **Pilot-scale or prototype units.** Production package plants using these technologies will generally have much higher capacities and be more energy efficient.

5.5.3 Micropollutant removal

Three plants exhibited undesirable breakthrough of chemicals used in their respective treatment processes:

- Occasional iodide ion breakthrough occurred with the **Diamond Rain** plant when the resin in the ion exchange polisher unit (final stage in process) became saturated with respect to iodide. This will be detected if the operator monitors the iodide level on a daily basis. The supplied kit has the capability to detect both iodine and iodide ion in solution.
- If rinsing of the **AEC MF** unit is not thoroughly carried out after the acid/alkali wash procedure, nitrate breakthrough at concentrations potentially in excess of the guideline values will result. This effect was observed during the experimental work.

- Total aluminium concentrations in excess of 0,7 mg/ℓ were consistently detected in the treated water from the **Watermaker** plant. Investigation showed that the concentration of dissolved aluminium was below the detection limit. Therefore, the aluminium in the treated water is most probably due to micro colloidal aluminium hydroxide which passes through the filter.

5.5.4 Consumption of chemicals and other consumable items

The consumption of chemicals and other consumable items such as UV lamps and filter cartridges is summarised in **Table 5.8**. The slow sand filter was the only plant that consumed no chemicals for the purpose of water treatment or washing.

5.5.4.1 Chemical economy

Coagulants: The **Filtrex** plant used significantly lower doses of coagulant than any of the other plants using coagulation processes.

Chlorine: The post-chlorination processes made more efficient use of chlorine; less chlorine was used to produce treated waters with the same chlorine residuals.

Precoat media: The **CFMF** process used much less precoat media (31 g/m^3) than the **DE filter** (157 g/m^3) to produce the same volume of permeate. In addition, the limestone used by the CFMF process is less expensive than DE and the CFMF process produces a significantly better quality permeate (see **Tables 5.7** and **5.8**). Modifications to the DE process (as tested) may significantly decrease the amount of DE required for a given volume of permeate (see **Section 8**)

UV lamps: The **CSIR** plant was able to disinfect significantly more water per lamp (14 Mℓ) than the **Eliminator** unit (0,6 Mℓ). In the Eliminator, a single Philips TUV 30 W lamp was used to treat a flow of 0,6 m^3/h while in the CSIR plant, 4 Philips TUV 40 W lamps (or Willand equivalent) were used to treat flows between 10 and 14 m^3/h.

Filter cartridges: The **Diamond Rain** plant used 12 cartridges of various sizes in the production of approximately 100 m^3 of water while the **Eliminator** unit used approximately 25 similar cartridges for the same service. However, the Diamond Rain plant also used GAC filters which removed some of the suspended matter in the raw water as well as undesirable inorganic and organic pollutants and was evaluated towards the end of the test period when the raw water (from Inanda Dam) was of significantly better quality.

Table 5.8 : Consumption of Chemicals and consumables

Plant	Disinfection	Coagulation	Filter media	Other
AEC MF	None	None	None	Detergent ...... 4 g/m^3 Nitric acid ..... 7 g/m^3 as HNO_3 Caustic soda ... 7 g/m^3 as NaOH
Aquasprite	1% NaOCl ... 3,1 g/m^3 as Cl	Polyelectrolyte ... 1,6 g/m^3	None	None
DE filter	Not evaluated	None	Diatomaceous earth ..... 157 g/m^3	None
Exxflow	NaOCl .... 1,3 g/m^3 solution is used for weekly curtain wash	None	Limestone .... 31 g/m^3	None
CSIR	1% NaOCl ... Standby UV lamps ... 14 Mℓ/lamp (TUV 40W)	Polyelectrolyte ... 3,0 g/m^3	None	None
Filtrex	Not evaluated on prototype	Polyelectrolyte ... 1,2 g/m^3	None	None
Eliminator	UV lamps ... 0,6 Mℓ/lamp (TUV 30W)	None	50 µm cartridges ... 7,8 m^3/cartridge 5 µm cartridges .... 7,8 m^3/cartridge	None
Watermaker	$Ca(OCl)_2$ .... 1,25 g/m^3 as Cl	Watermaker powder .... 130 g/m^3	None	None
Diamond Rain	Iodine .... 2 g/m^3 as I from iodinating resin or direct dissolution of I_2 crystals	None	20µm cartridges ... 25 m^3/cartridge 5 µm cartridges .... 21 m^3/cartridge *1 µm cartridges .... 34 m^3/cartridge*	GAC .... < 100 g /m^3 IX Resin .... regenerated
Slow sand filter	None	None	None	None

Table 5.9 : Summary of treated water quality achieved with the units tested

Package plant	**Turbidity removal**	**Micro-organism removal**	**Comments**
AEC MF	Final NTU <0,1 for feed NTU < 200. Final NTU < 1 for feed NTU > 200 and filter cycle time was reduced.	Acceptable removal of faecal micro-organisms. Heterotrophic plate counts (HPC) typically exceeded guideline values.	Nitrate may exceed 6 mg/ℓ if rinsing is insufficient after acid wash.
Aquasprite	Final NTU <1 for feed NTU < 250.	Acceptable removal of faecal micro-organisms. HPC fell within the guideline values in 88% of samples.	THM's within acceptable limits in spite of pre-chlorination.
DE filter	Final NTU < 5 for feed NTU < 50.	Not evaluated due to poor filter performance.	Negligible removal of dissolved substances occurs.
Exxflow	Final NTU < 1 for feed NTU < 4000.	Acceptable removal of all micro-organisms in samples taken from the filter curtain. Opportunities for contamination during washing and start-up exist.	Negligible removal of dissolved substances occurs
CSIR	Final NTU < 1 for feed NTU < 20. Final NTU < 5 for 20 < feed NTU < 50.	Acceptable removal of micro-organisms occurred after modifications to the disinfection system.	Consistent with typical coagulation-sedimentation-filtration processes
FILTREX	Final NTU < 1 for feed NTU < 60. Final NTU <5 for 60 < feed NTU < 100.	No disinfection system was fitted to this prototype unit. Performance similar to the dual media filter can be expected if pre-chlorination is practised.	Consistent with coagulation-direct filtration processes. Reasonable colour, Fe and Mn removal
Eliminator	Final NTU < 5 for feed NTU < 10.	Acceptable removal of faecal micro-organisms in all samples. HPC exceeded guideline values in 89 % of samples.	Negligible removal of dissolved and colloidal matter occurs.
Watermaker	Final NTU < 2 for feed NTU < 500. Final NTU <1 with deep bed filter.	Faecal micro-organisms exceeded guideline values in 50 % of samples and HPC in 14 % due to inadequate chlorine contact time prior to sampling.	Total aluminium (0,7 to 1,0 mg/ℓ) consistently exceeded guideline values.
Diamond Rain	Feed NTU < 10 during evaluation. Final NTU < 1 on average.	Guideline values for indicator organisms were not exceeded. Most HPC values were above the guideline values.	Iodide concentration can exceed guideline values when IX resin is saturated. Daily monitoring required.
Slow sand filter	Final NTU < 1 for feed NTU < 10. Final NTU < 5 for 10 < feed NTU < 30.	Both indicator organisms and HPC were below the guideline values for an insignificant risk when the feed water turbidity was below 15 NTU.	No comment.

5.5.5 Sludges and effluents

Two of the plants, the **Slow Sand filter** and the **Eliminator** produced negligible quantities of effluent. The other plants all produced effluents containing various combinations of suspended solids, water treatment chemicals, filter media and cleaning chemicals. The nature and approximate quantity of these effluents is presented in **Table 5.10**.

The volume of effluents produced by the various plants is generally less than 3 % of the volume of water treated and this compares favourably with large-scale conventional plants. The exception is the **Watermaker** plant in which the sedimentation tank geometry and level controller settings result in approximately 0,5 m^3 of water being drained as sludge in each cycle. This water is mostly clear supernatant water from the settling process that cannot be removed by the filter intake manifold without entraining sludge (see **Section 13**).

Three of the plants (**DE filter, Diamond Rain** and **Filtrex**) are designed to use raw untreated water for washing purposes and the **Watermaker** uses supernatant water from the sedimentation stage for filter backwashing. The other four plants that use water for washing require intermediate storage of a volume of treated water for backwashing.

Table 5.10 : Effluents produced by the package units

Plant	Effluent volume % of water flow	Effluent or waste characteristics
AEC MF .... Detergent wash .... acid/alkali wash* .... Purge	0,2 0,2 3,1	Solution of SS and detergent 1 to 2 % $NaNO_3$ with SS and $1 < pH < 13$ Concentrated SS with turbidity > 200 NTU
Aquasprite ... Backwash	1,0	Dilute solution of flocculated SS.
DE filter ..... Backwash	1,3	SS and DE filter media (~1 % solids)
Exxflow ..... Wash cycle .... Purge	Total of 7	SS and limestone precoat media Concentrated SS, Turbidity ~ 200 NTU
CSIR .... Sludge drain .... Backwash	0,02 0,8	Dilute solution of flocculated SS Dilute solution of flocculated SS
Filtrex .... Co-current wash	1,7	Solution of flocculated SS
Eliminator	negligible	Used filter cartridges
Watermaker . Sludge drain .... Backwash	<18,0 0,2	Dilute solution of flocculated SS Dilute solution of flocculated SS
Diamond .... GAC backwash Rain	1,1	Dilute solution of SS (50-200 NTU) Used filter cartridges, IX media, GAC media
Slow sand filter	negligible	Dirty filter sand to be washed and recycled

5.6 Robustness and Reliability

5.6.1 Materials of construction

The construction materials used in the various plants are summarised in **Table 5.11**. In general, the choice of materials in all plants was satisfactory. Surface corrosion was observed on the steel walls of the **CSIR** clarifier after about a year but no other significant corrosion or stress related events were observed.

Table 5.11 : Summary of materials of construction

Plant component	Material used	Exceptions
Filter vessels	GRP (pressurised) PVC (non pressurised)	AEC MF, CSIR .... Stainless steel DE filter .... Steel
Tanks and chambers	GRP	AEC MF and CSIR ... Polyethylene CSIR clarifier .... Steel
Pipework	PVC Class 4 to Class 16	AEC MF .... Stainless steel or HDPE Eliminator .... Copper Diamond Rain .... PVC hose
Frames and supports	Steel (AEC... stainless, Watermaker...galvanised)	Eliminator .... GRP Diamond Rain .... Aluminium
Pumps	Cast iron or glass reinforced nylon	DE filter .... Stainless steel

5.6.2 Component failures

Very few instances of failure occurred during the evaluations with the exception of the **Exxflow CFMF** prototype where a number of gasket and other failures occurred. Many of the failures experienced with the Exxflow unit can be attributed to it being a development prototype for an emerging technology. Isolated minor failures also occurred with level control relays on the **Aquasprite** unit and the 12 V pump on the **Eliminator** plant. These failures did not recur for the remainder of the evaluation period.

5.6.3 Reliability of processes and the consequences of component failures

The desirability of simple automated trips related to various alarm conditions was stressed in **Section 3.2.1**. In practice, very few of these measures were used on the package plants that were evaluated. This affected their reliability and significantly increased the degree of human supervision that was required in order to maintain treated water quality. The most reliable plant in this regard is the **AEC MF** unit where contaminated water can only enter the the reticulation system in the unlikely event of a module seal or ceramic monolith failure.

None of the plants in which coagulant or disinfectant chemicals were used had alarms or cut-outs activated by low levels in their respective chemical storage vessels. In several cases, the dosing pumps used on these plants featured built-in alarm facilities that were not connected.

The two plants that used UV lamps for disinfection both monitored lamp operation by measuring the electric current fed to the lamps. On the **Eliminator,** an alarm was triggered if no lamp current was detected when the pump was running. On the **CSIR** plant (after modification) the filtered water was diverted to waste by a solenoid valve when the UV lamp current failed on any of the four lamps.

In the **Diamond Rain** plant, regular monitoring of the water quality is required in order to detect low iodine levels or saturation of the ion exchange resin leading to contamination of the treated water with the iodide ion.

5.6.4 Potential for expansion of capacity

The only plant in which significant potential for increasing the treatment capacity exists is the **Exxflow CFMF** plant. This prototype unit was originally designed for four modules containing eight curtains which would have given a treatment capacity of 16 m^3/h. During the evaluations, only two of the four modules were installed. The purchase and installation of the additional two modules would cost about 10% of the original capital expenditure and represents a relatively inexpensive method of doubling the plant capacity.

In most of the other package plants evaluated, increases in capacity of up to 20 % can be achieved by optimisation and eliminating bottlenecks but greater increases generally require the purchase of additional treatment modules.

5.7 Maintenance and Servicing

The availability of spares and consumable items is discussed in **Section 3.4.3** and the specific requirements of the evaluated plants are summarised in **Table 5.12**. The maintenance and servicing requirements of various items of equipment fitted to the package plants is discussed in detail in **Section 3.4.2** but comments related to specific plants are given here.

Pumps : The pumps fitted to the **Exxflow CFMF** prototype used packed gland seals which required frequent adjustment and annual replacement. The other plants generally used mechanical seals and none of these failed or required maintenance during the two year evaluation period.

Dosing pumps : Although annual servicing of diaphragm dosing pumps is recommended, none of the dosing pumps used variously on the **Aquasprite, CSIR** and **Filtrex** plants required any spare parts during the evaluation period. Occasional cleaning was required.

Pressure sand filters : Filter clogging occurred with the **Aquasprite, CSIR** and **Watermaker** pressure filters. In all cases this was due to a combination of high filtration rates, low backwash rates and inadequate facilities for measuring or limiting filter headloss. These problems may stem from the fact that the pressure filters used in these plants were primarily designed for swimming pool filtration. In potable water treatment applications these filters encounter greater solids loads and coagulants, highlighting the need for careful sizing and improved control.

Table 5. 12 : Spares and consumables with limited availability

Plant	Description of item	Availability	Frequency
AEC MF	Ceramic monoliths Pump Acids/alkalis	Atomic Energy Corporation Industrial suppliers in main centres Chemical suppliers in main centres	>5 years 2 to 5 years Quarterly
Aquasprite	No special requirements	-	-
DE filter	Filter spares	Available from manufacturer only	Annually
Exxflow	Filter curtains Pumps Instrumentation Control hardware	Gelvenor Textiles, Explochem Industrial suppliers in main centres Industrial suppliers in main centres Industrial suppliers in main centres	2 to 4 years 6 months 6 months 6 months
CSIR	UV system & lamps	UV Systems cc. Pretoria	6 months
Filtrex	No special requirements	-	-
Eliminator	Pump UV system & lamps	Yacht and Caravan suppliers Applied UV cc., agents of SA Phillips	every year 6 months
Watermaker	Watermaker powder Klorman capsules Dosing equipment	Agents of Control Chemicals Pty. Ltd. Agents of Control Chemicals Pty. Ltd. Agents of Control Chemicals Pty. Ltd.	2 to 4 months 2 to 4 months >5 years
Diamond Rain	Iodine cartridges MDU cartridges IX resin GAC Filter cartridges	Local Vector agents in main cities Local Vector agents in main cities Local Vector agents in main cities Local Vector agents in main cities Industrial suppliers	3 to 6 months 1 to 3 months 1 to 3 months 3 to 6 months 1 to 3 months
SSF	No special requirements	-	-

5.8 Capital and operating costs

5.8.1 Capital cost

The capital cost of the various plants is given in **Table 5.13**. The cost of site preparation, transportation and additional equipment such as raw water feed pumps, electrical connections and storage tanks is not included. The capital costs as given in **Table 5.13 do not include Value Added Tax (VAT)** and are based on quotations received in 1994.

5.8.2 Operating cost

Operating costs were estimated for each of the package plants based on operating experience and data gathered at the PEF. The operating cost is comprised of cost components for chemical and consumable expenses, energy costs, wages and equipment maintenance costs. The cost of depreciation, interest and loan repayments has not been included. The specific costs (cost per unit volume produced) of these components and the estimated total operating cost for each plant are summarised in **Table 5.14**.

Table 5.13 : Capital cost of package plants

Plant	Capital cost of package plant R	Capital cost per unit of capacity R/(m^3/d)
AEC MF .... 4 m^3/d (small plant)	20 000	5 000
.... 80 m^3/d (large plant)	120 000	1 500
Aquasprite .... 24 m^3/d	12 000	500
DE filter .... 54 m^3/d	9 200	170
Exxflow .... 192 m^3/d (as evaluated)	150 000	781
.... 384 m^3/d (design capacity)	165 000	430
CSIR .... 240 m^3/d	88 560	369
Filtrex .... 15 m^3/d (small plant)	19 750	1 645
.... 200 m^3/d (large plant)	165 000	825
Eliminator .... 14 m^3/d	7 150	5 948
Watermaker .... 65 m^3/d	15 000	231
Diamond Rain ..... 11,5 m^3/d	57 900	5 026
Slow sand filter .... Concrete with roof	-	4 215
.... Membrane lined earth berm	-	568

Table 5. 14 : Breakdown of estimated package plant operating costs

Plant	Labour	Energy	Chemicals & consumables	Maintenance & repair	Operating cost
	R/m^3	R/m^3	R/m^3	R/m^3	R/m^3
AEC MF ... 4 m^3/d (1P)	2,25	1,58	0,33	0,76	4,92
.... 16 m^3/d (1P4)	0,56	0,75	0,09	0,38	1,78
.... 80 m^3/d (19P)	0,10	0,50	0,09	0,20	0,89
Aquasprite .. 24 m^3/d	0,95	0,06	0,04	0,08	1,13
DE filter .... 54 m^3/d	0,58	0,07	0,67	0,04	1,36
Exxflow .... 192 m^3/d	0,04	0,66	0,02	0,15	0,87
CSIR .... 120 m^3/d	0,15	0,06	0,07	0,05	0,33
.... 240 m^3/d	0,07	0,04	0,05	0,03	0,18
Filtrex ...... 15 m^3/d (pilot)	0,50	0,60	0,04	0,20	1,34
.... 200 m^3/d	0,04	0,02	0,04	0,13	0,23
Eliminator .. 14 m^3/d	0,83	0,68	5,49	0,68	6,98
Watermaker 65 m^3/d	0,25	0,06	1,05	0,04	1,41
Diamond ... 11,5 m^3/d (gravity)	0,70	-	2,81	0,50	4,01
Rain .... 11,5 m^3/d (pump)	0,70	0,21	2,81	0,50	4,22
Slow sand .. 0,1 m^3/h (pilot)	2,78	-	0	0	2,78
filter .... 200 m^3/h	0,11		0	0	0,11

The operating cost components have been calculated according to the following basis:

- **Chemical costs** are calculated from the actual chemical consumption recorded during the evaluations. Chlorination costs have been estimated and included for the plants that were not fitted with disinfection or micro-organism removal systems (**Filtrex, Exxflow, DE filter**). Local (Durban) chemical prices were used. Due to availability and handling costs, prices may differ in other parts of South Africa.

- **Labour costs** were estimated according to a wage of R7,00/h for a trained operator.
- **Energy consumption** was estimated from the sum of the maximum rated power for all power consuming devices fitted to the plants. Compensation was made for electrical devices that do not operate continuously during plant operation. The City of Durban's 1994 "Business and General" tariff rate (R 0,2643 /kWh) was used for cost estimation. Cheaper tariffs are available but these have restricted operating hours. Cheaper tariffs may also be available in other parts of South Africa.
- **Maintenance and repair costs** were estimated as 5% of capital cost per annum (Peters and Timmerhaus, 1981). Where more accurate estimates of the maintenance costs was possible, these were used instead and incorporate the cost of spare parts and a labour rate of R 75,00/h for the artisan. In rural applications, additional costs will be incurred due to the artisan's travelling time.

6 ATOMIC ENERGY CORPORATION (AEC)

Ceramic Microfiltration Package Plant

6.1 Introduction to the AEC unit

The Atomic Energy Corporation is based at Pelindaba near Pretoria. The contact person is Mr F W C Coetzer. The telephone number is 012 - 316 6077 and the fax number is 012 - 316 6277. A range of package water treatment plants based on ceramic microfiltration (MF) modules is available (see **Table 6.1**). The capacity of these plants is given as a range rather than a fixed flowrate because the actual production capacity may vary depending on the site and the raw water quality.

Table 6.1: AEC package plant range

Model	Capacity (m^3/day)	Configuration	Size of unit h x w x l (m)
1P	1,5 - 7	1 module containing 1 membrane	1,5 x 0,5 x 1,0
7P	10 - 50	1 module containing 7 membranes	1,5 x 1,0 x 1,0
19P	30 - 130	1 module containing 19 membranes	1,5 x 1,0 x 1,0
1P4	6 - 30	4 modules, each containing 1 membrane	1,5 x 1,0 x 1,0
7P4	40 - 200	4 modules, each containing 7 membranes	3,0 x 1,0 x 1,0
19P4	120 - 500	4 modules, each containing 19 membranes	3,0 x 1,0 x 1,5

A pilot plant used for the development of this range of packaged water treatment plants was evaluated at Umgeni Water's Process Evaluation Facility (PEF) in September 1992. The ceramic membranes used in the pilot plant were similar to those used in the commercially available units.

6.1.1 Plant Design Philosophy

Ceramic microfiltration membranes are robust, inert and compact in size. The pore size of the ceramic membranes is sufficiently small (<<1 μm) for the removal of colloidal suspended solids and micro-organisms from water without the addition of chemical coagulant or disinfectant. This simplifies the operating requirements and renders this technology suitable for the production of potable water on a small to medium scale in remote areas.

Additional filter modules can be installed when an increase in demand arises. The maintenance requirements are low and involve weekly membrane cleaning. The operating workload is low as a result of the chemical free operation. Although the AEC pilot plant was manually operated, plants can be automated to suit the needs of the client.

The operating pressure is higher than conventional pressure sand filtration and only a portion of the pressurised feed water emerges from the process as permeate. Consequently, the specific energy consumption can be high (4 to 16 kWh/m^3 for a 1P model and 1 to 6 kWh/m^3 for the 1P4 model which has 4 times the capacity of the 1P).

6.1.2 General Description of the AEC pilot plant

The Membralox ceramic microfiltration membrane consists of a hexagonal, prism shaped, porous ceramic monolith containing a number of longitudinal channels into which the feed water is pumped during filtration. The monoliths are housed in a stainless steel pressure vessel to form a filter module. Three different modules containing either a single monolith or arrangements of 7 or 19 monoliths are used in the various AEC package plants.

Ceramic microfiltration is a continuous process. Water is pumped longitudinally through the monoliths and the permeate flows out radially from the side walls. The rejected matter that does not permeate through the ceramic membrane flows from the end of the monolith and may be recycled or discarded. Seals are fitted at both ends of the monolith to prevent contact between the permeate and the feed or retentate streams.

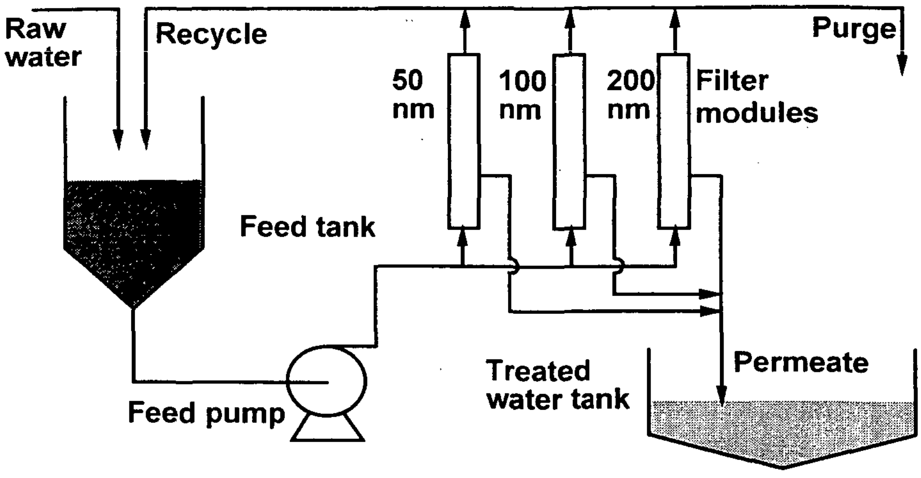


Figure 6.1 : Ceramic microfilter process flow diagram

6.1.3 Process Sophistication

Table 6.2 contains a summary of the components that comprised the pilot plant and it can be seen that a large number of valves and instruments were fitted. The commercially available package plant processes are considerably simpler to control and operate.

The AEC package plant system consists essentially of a pump, the ceramic module and a pressure regulating system. Recycling of retentate is optional. Petrol/diesel or electrically driven pumps may be used. Multistage centrifugal pumps are typically used but helical rotor pumps may also be suitable.

Table 6.2: Summary of components fitted to the AEC pilot plant

Component	Quantity	Comments
Valves	21	1 x pressure regulating valve to adjust filter pressure 4 x solenoid control valves connected to time switch 16 x ball valves for line choice and equipment isolation
Piping		40 mm PVC piping
Pump	1	1,5 kW multistage centrifugal pump
Filters	3	50 nm, 100 nm and 200 nm ceramic microfiltration membranes.
Tanks	2	1 x 200 ℓ plastic tank for clean water 1 x 200 ℓ plastic tank (with stirrer) for raw water
Indicators	7	1 x 0 to 50 ℓ/min flow indicator (filtrate flow) 1 x 0 to 150 ℓ/min flow indicator (raw water) 1 x 0 to 500 kPa pressure indicator 2 x 0 to 1000 kPa pressure indicators 2 x temperature indicators

6.2 Process Control System

During the evaluation, raw water from the pilot plant feed tank was pumped to a ceramic membrane system consisting of three single modules (pore sizes of 50, 100 and 200 nm respectively) connected in parallel (see **Figure 6.1**). The three modules were individually operated. The permeate was collected and flowed to the treated water storage tank. The retentate was recycled to the feed tank which was periodically purged to prevent the accumulation of rejected matter in the tank.

6.2.1 Operation and Control Sequence

Normal Operation : The process control system is based on the principle of constant-head declining-rate filtration at a constant pressure (500 kPa, manually adjusted). Purging is required if a recycle is used and may consist of periodic discharge of the concentrate at high flowrate or continuous discharge at low flowrates. The optimum purge rate is dependent on the raw water turbidity. A recycle was used on the pilot plant and it was purged three times daily by draining the feed tank.

Membrane Cleaning : Flowrate is used as the criterion for determining when cleaning is necessary. The flowrate of the permeate is monitored by the operator and when the filtration rate (flux) falls below a specific value, cleaning is necessary. This limiting flux can be converted to a specified minimum flowrate for each plant so it is not necessary for the operator to calculate the flux from flowrate readings. The membranes fitted to the pilot plant were manually cleaned as follows:

- A 2 %(m/v) solution of caustic soda was circulated through the modules for 45 minutes.
- The modules were rinsed with clean water for 15 minutes.
- A 2 %(m/v) solution of nitric acid was circulated and rinsed in a similar fashion.

In addition to the chemical cleaning, an automated back-pulsing system was fitted to the rig for a portion of the test. This system periodically reversed the pressure across the MF membranes in an attempt to dislodge suspended matter in the tubes and partially restore the flux but it could not be evaluated because of mechanical problems with the prototype plunger mechanism. On the AEC package plants, modules are washed with a 1% solution of conventional household washing powder which is circulated through the modules. This simplification of the washing system has reduced the dependence of the plant on hazardous chemicals. The strong acid/alkali wash may still be used but is required less frequently.

6.2.2 Degree of Automation

The pilot plant was totally manually operated. The raw water pressure was controlled by adjusting a pressure regulating valve. The filtration rate was monitored by means of a flow indicator. Manual or PLC based automatic operation can be specified when ordering a MF package plant from the AEC.

6.2.3 Monitoring of Process Parameters

The turbidity and microbiological quality of the treated water produced by the pilot plant were monitored by analysing samples while the following operating parameters were monitored directly by instruments:

- Flowrates of the feed water and the permeate.
- The pressure of the feed stream and the permeate.

The operator of an AEC package plant is required to monitor the permeate flowrate, the feed pressure and the treated water turbidity in order to assess the operation of the plant. Microbiological monitoring should be performed periodically after commissioning of the unit.

6.2.4 Effectiveness of the Control System

The process control system enables effective control of permeate production and quality (see results in **Section 6.5**). Sudden increases in the raw water turbidity will require more frequent purging of the feed tank (where used) and this will increase the operator workload. The plant can be operated without the recycle stream if a large quantity of flowing raw water is available for treatment but this significantly decreases the water recovery of the process.

6.2.5 Uncontrolled parameters which may affect final water quality

Increases in raw water turbidity appear to have negligible effect on the treated water quality but the rate of flux decline may increase with high turbidity raw waters and more frequent purging will also be necessary. This MF system does not significantly remove dissolved species (see **Section 6.5**) from the raw water and the treated water will contain similar concentrations of dissolved species to the raw water. Additional treatment for removal of dissolved species in excess of potable water guideline values may therefore be required.

6.2.6 Susceptibility to Demand Fluctuations

The *system* is designed to operate at constant pressure. As a result, the rate of permeate production will be determined by the resistance to flow of the filter module and the feed pressure. The process can be started and stopped on demand without affecting the permeate quality. Therefore, a level control system in the treated water reservoir is recommended for control of water production when the plant's production capacity exceeds the demand for water. If the demand exceeds the capacity of the plant, more frequent washing may become necessary in order to maintain a higher average flux. **The use of higher feed pressures to increase flux is not recommended!** (**Section 6.6.3**).

6.3 Personnel Requirements

Maintenance and backup personnel from the AEC are available to provide support to the plant operator when necessary. A literate operator in possession of a standard eight certificate (or equivalent) and having a technical aptitude will be required to operate the plant. An artisan skilled in the maintenance and repair of the equipment used in the plant will be required for periodic checks and repairs to the plant. Installation and commissioning will require an AEC process technician who is familiar with the design and operation of the plant.

6.3.1 Workload Estimations

Installation and commissioning : Both the pilot plant and the commercially available package plants are skid mounted. All plants are fully assembled and tested before dispatch. The installation workload involves positioning, water and electrical connection and commissioning. If appropriate site preparation has taken place, the installation and commissioning workload should not exceed 1 day depending on the model.

Operating workload : Although the plant can operate unsupervised for up to a week depending on the process layout and water quality, this is not recommended. The operator should check permeate turbidity, permeate flowrate, feed pressure, feed turbidity and the general condition of the plant daily. If a diesel or petrol powered pump is used, daily refuelling, temperature and oil level checks should be carried out. These tasks will require approximately 1 hour daily. Weekly cleaning of the modules will require an additional 2 hours weekly. The operating workload will therefore be approximately 9 hours weekly for the smaller plants in the range. This estimate is based on operating experience with the pilot plant and the raw water quality at the PEF during the evaluation. The operating workload will be relatively insensitive to the capacity of the plant where only one module is used.

Maintenance and repair : Multistage centrifugal pumps are used for the AEC package plants. A technician or fitter will be required for pump maintenance on a six monthly basis. Additional maintenance tasks that can be performed at the same time include the repair of leaks and checking the pressure seals in the filter modules. The artisan should also measure the filter flux and possibly carry out an alkali/acid wash if necessary to restore the flux when it is low. These tasks should not require more than 3 hours every six months (excluding travelling time).

6.3.2 Specific Training Requirements

The operator needs to be trained in the following activities related to plant operation:

- Maintaining an accurate logbook in which operating parameters and incidents are recorded.
- Preparation of solutions for membrane cleaning.
- Safety measures during handling of chemicals.
- Regulating the filter pressure.
- Membrane cleaning.

6.4 Infrastructure Requirements

Road access : Road access is only required during the installation of the plant. During normal operation road access will not be necessary.

Power requirements : A 380 V, 3 phase electricity supply is required. The power requirement will be between 1 and 25 kW depending on the size of the plant. If electricity is not available, a diesel or petrol powered pump will be required as well as adequate facilities for the storage of oil and fuel. Exhaust gases should be safely routed away from the plant if it is situated in an enclosed area.

Raw water provision : See Section 6.5.1

Treated water reticulation : The use of intermediate treated water storage is preferred. This will allow the plant to be more effectively utilised. A post-disinfection system may be required if long residence times occur or if there is a possibility of contamination of the reticulation system.

Sludge disposal : The concentrate that is released from the system will not contain substances not present in the raw water. In the case of a river or stream this concentrate may be returned to the source, downstream of the point of abstraction if it meets the Department of Water Affairs and Forestry standards for effluent disposal. The effluent produced during washing will contain either detergent or a dilute acid/base mixture with particulate and colloidal impurities. A tank or lagoon will be required for the effluents derived from the cleaning process, and the recommended size will vary depending on the size of plant installed.

Chemical storage : Dry, secure storage with adequate ventilation will be required for the cleaning chemicals as well as fuel and oil where used. A chemical resistant floor with suitable drainage channels is essential as corrosive chemicals (acid and alkali) are used for the cleaning process. Good ventilation is essential if the plant, chemicals and fuel are all housed in one structure. Poor ventilation may result in accelerated corrosion due to build-up of humidity and corrosive fumes. An explosion hazard exists when petrol is stored in a poorly ventilated building.

Weather protection : The plant should be enclosed by a fenced and roofed shed, providing the required ventilation, which may also incorporate the chemical storage facility.

Site establishment : The plant should be situated on a concrete slab able to support the plant.

6.5 Performance of the Treatment system

The pilot plant was operated at the PEF during the month of September 1992 and at Shongweni dam in February 1993 where the effectiveness of the system in coping with algae laden water was evaluated. Raw water turbidities at the PEF were typically between 15 and 25 NTU and at Shongweni dam between 1 and 2 NTU with high algae counts (up to 13000 cells per mℓ).

6.5.1 Raw Water Supply

Head and flowrate : A feed water pressure of approximately 5 bar is required and this is supplied by the built-in pump. The supply of raw water to the feed tank will require an additional pump if the plant is located above the raw water level. If no recycle is used the feed pump may be used to pump the raw water directly from the source to the filtration modules.

Screening : Some form of raw water screening will be required to prevent large particulates, leaves and sticks from entering the MF modules. A screen size of approximately 1 to 2 mm is recommended.

Storage : A feed tank may be required in systems where the retentate is recycled. The size of the feed tank will depend on the plant capacity. The addition of raw water as make-up to the feed water may be accomplished by using a float valve (gravity feed systems) or a level probe system if a separate raw water pump is used.

Quality of the raw water : Although the raw water turbidity was relatively low for the duration of the tests, the recycling of the reject stream to the feed tank caused an increase in the feed water turbidity to between 50 and 200 NTU (see **Section 6.5.3**).

6.5.2 Micro-organism Removal

Removal of bacteria in MF filtration systems is achieved through physical separation of the organisms from the water in the filter modules. **Table 6.3** shows the bacterial removal data that was measured for all three pore sizes in the modules fitted to the pilot plant.

100 % removal of coliforms, *E. Coli* and faecal streptococci was obtained with all three test modules. However, the heterotrophic plate counts (HPC) in the treated water were relatively high. All three modules typically produced a permeate with HPC > 10 /mℓ (@ 37 °C) and more than 100 /mℓ @ 22°C. The 200 nm module's performance was significantly poorer than the other modules in this regard. A post disinfection system may be required if these organisms cause taste and odour problems in water that is not used shortly after production. All modules achieved 100 % removal of blue-green and green algae (**Table 6.4** shows algal removal for 100 nm membrane).

Table 6.3 : Microbiological results

Date	Coliforms per 100 mℓ		*E.Coli* per 100 mℓ		F. Strep. per 100 mℓ		Plate count per mℓ @ 37°C		Plate count per mℓ @ 22°C	
	Feed	Final	Feed	Final	Feed	Final	Feed	Final	Feed	Final
50 nm module										
14/9/92	500	*	100	*	<100	*	148	*	228	*
15/9/92	580	0	240	0	10	0	>2000	81	24	97
16/9/92	430	0	70	0	2	0	>2000	258	>2000	>1000
17/9/92	890	0	830	0	56	0	>2000	81	>2000	500
18/9/92	3000	0	1100	0	112	0	>2000	0	>2000	48
21/9/92	260	0	110	0	20	0	>2000	240	>2000	1
100 nm module										
8/9/92	280	0	70	0	0	0	1000	0	1000	101
9/9/92	180	0	40	0	0	0	400	0	*	102
10/9/92	400	0	70	0	2	0	1000	1000	536	216
11/9/92	2200	0	800	0	30	0	1000	200	1000	2000
14/9/92	1600	0	1100	0	*	0	50	>1000	280	*
200 nm module										
1/9/92	4000	0	100	0	<1000	*	200	630	>2000	980
3/9/92	600	0	230	0	60	0	>1000	148	>2000	808
4/9/92	450	0	450	0	30	0	2954	250	>1000	60
7/9/92	280	0	160	0	<10	0	>1000	50	300	>1000

* no result due to lost or damaged samples

Table 6.4 : Algae removal for 100 nm module

Date	Total algae counts (cells per mℓ)		Blue-green (cells per mℓ)		Green (cells per mℓ)	
	Feed	Final	Feed	Final	Feed	Final
2/2/93	9968	0	7775	0	2193	0
9/2/93	10036	0	7728	0	2308	0
11/2/93	9437	0	6795	0	2642	0
12/2/93	11088	0	8760	0	2328	0

6.5.3 Turbidity and Suspended Solids Removal

The pilot plant was evaluated in recirculation mode. Although the raw water turbidity was normally below 20 NTU the accumulation of rejected material in the feed tank resulted in feed water turbidities of up to 200 NTU. During normal operation, the feed water tank was purged three times daily to remove accumulated solid matter. When water with a turbidity between 50 and 200 NTU was fed to the plant, a permeate with turbidity below 0,1 NTU was consistently obtained with all three modules.

This turbidity level is well within the Department of Health's 1994 draft guidelines for drinking water. **Figures 6.2a** to **6.2c** show the turbidity removal and flux decline for each module during a typical filter run.

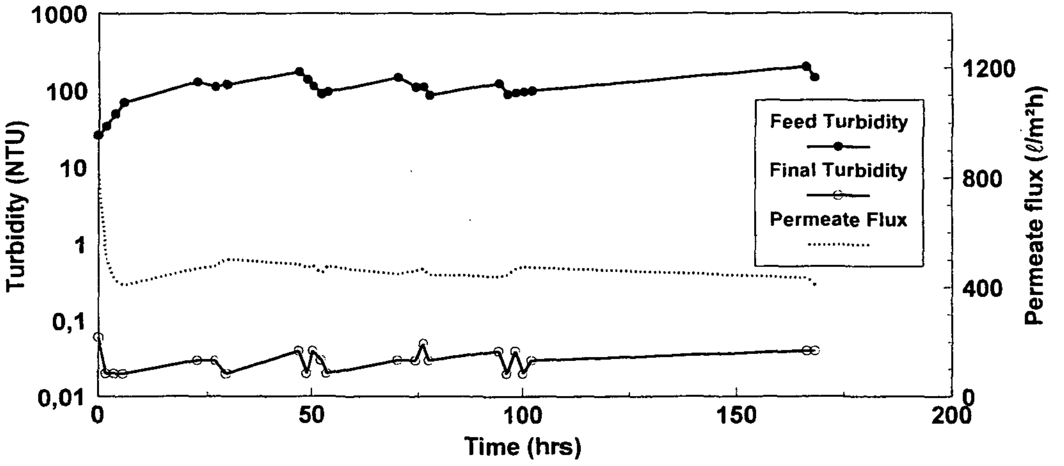


Figure 6.2a : Turbidity removal and flux variation for the 50 nm module

The starting flux was typically 1200 ℓ/m^{2}h and it declined within hours to between 350 ℓ/m^{2}h and 500 ℓ/m^{2}h. Therafter it declined gradually for approximately 1 week and the filter runs were usually terminated when the flux dropped below 300 ℓ/m^{2}h (**Note:** a flux of 1000 ℓ/m^{2}h is equivalent to a filtration rate of 1 m/h).

Since the plant was not tested on feed waters with turbidities greater than 200 NTU, the turbidity removal obtained with such waters could not be determined although significant turbidity breakthrough is not expected to occur with these MF modules. When treating high turbidity raw waters the membrane flux may decline more rapidly resulting in shorter filter run times. Under such circumstances purging will be required more frequently and additional cleaning cycles may be required. Ideally a module should maintain as high a flux as possible during filtration.

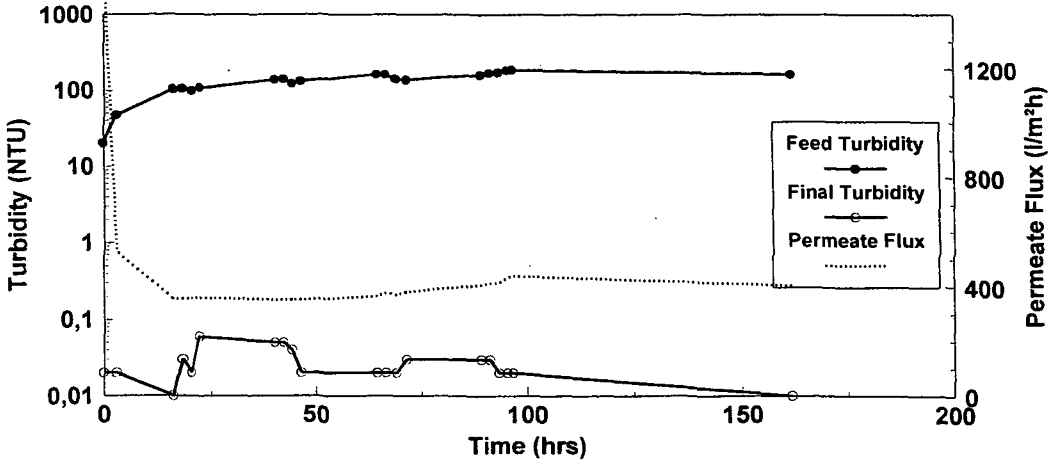


Figure 6.2b : Turbidity removal and flux variations for the 100 nm module

Both the 100 nm and 200 nm modules stabilised at a flux between 300 and 400 ℓ/m²h (equivalent to a filtration rate between 0,3 and 0,4 m/h). The 50 nm module stabilised at a flux between 400 and 500 ℓ/m²h, and appeared to perform better than the other modules because it produced consistently higher fluxes together with better turbidity and micro-organism removal.

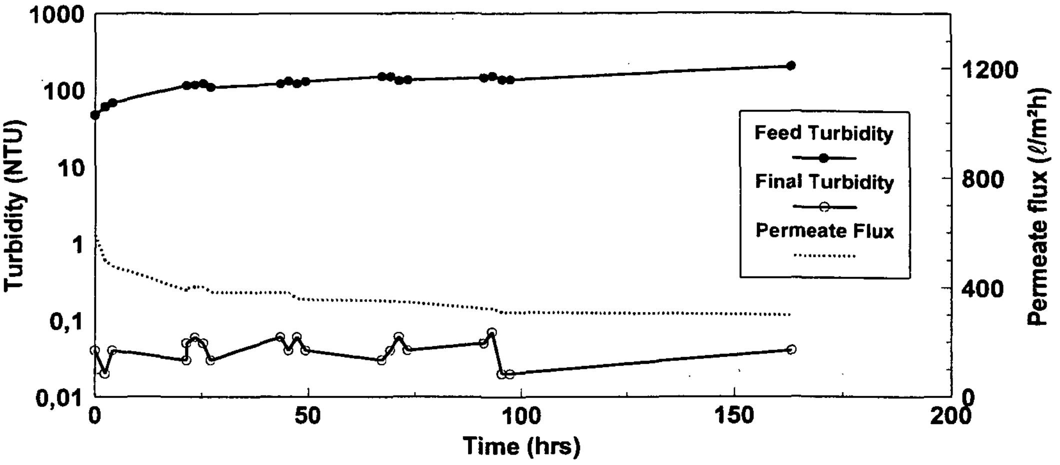


Fig 6.2c : Turbidity removal and flux variation for the 200 nm module

Definite conclusions as to the optimum pore size for this application require extended testing which was not possible in the brief period during which the plant was evaluated. The water recovery achieved by the modules when operated as described is summarised in **Table 6.5**. If the plant is used to treat raw waters with high turbidity more frequent purging will be required and the water recovery will decrease.

Table 6.5 : Water recovery

Module pore size (nm)	Water recovery (%)
50	97
100	96
200	96

An experiment was carried out in which a coagulant was dosed into the feed water and this significantly reduced the flux. The permeate flux decreased rapidly and stabilised at 65 ℓ/m²h over a 24 hour period. There were no significant improvements in water quality that would warrant operation of the unit at this significantly reduced flux. However pre-clarification of the raw water may considerably extend the overall capacity and water recovery of a MF unit when treating raw waters with high turbidity.

6.5.4 Chemical Requirements

No water treatment chemicals are required during normal operation with this MF filter. Although acid/alkali washing was used on the test rig, the use of a 1 % solution of domestic washing powder for normal cleaning of the commercial units will considerably reduce the hazard, expense and difficulty associated with the use of corrosive acids and alkalis. It is recommended that acid/alkali washing should preferably be performed by trained technicians or artisans during routine maintenance. A chlorine solution may be dosed for secondary disinfection of the treated water where required.

A 1P system delivering 4 m^3/d system will require approximately 10 ℓ/week of 2% acid and alkali solutions as well as approximately 100g/week of washing powder for cleaning. If the unit operates full-time this amounts to chemical consumption of approximately:

Domestic washing powder	4 g/m^3	@ R 10 /kg	= R 0,04 $/m^3$
Nitric acid (as 33 % m/m)	21 g/m^3	@ R 7 /kg	= R 0,15 $/m^3$
Caustic soda (as 50 % m/m)	14 g/m^3	@ R 10 /kg	= R 0,14 $/m^3$

The volume of cleaning chemicals required is directly related to the volume of the plant (including the volume of pipework and membrane modules). It is essential that the operator is properly trained in the handling and preparation of these solutions. Eye protection and chemical resistant gloves are required during handling of concentrated chemicals and appropriate safety instructions should be included in the manual.

6.6 Plant Life and Reliability

The AEC claims that the typical service life of the ceramic filter modules will exceed 5 years.

6.6.1 Materials of Construction

The test rig was constructed mostly from stainless steel and high density polyethylene piping. Corrosion, resulting from the use of the 2 % acid and alkali cleaning solutions, is unlikely although concentrated caustic is likely to attack the rubber sealing rings used in some of the valves and the filter module. The package plants may be constructed from HDPE (1P and 1P4 models only) or stainless steel (including tanks) depending on the customer's requirements.

Table 6.6 : Materials used

Component	Material	Comment
Filter unit	Stainless steel, ceramic	The pressure vessel that holds the ceramic module is stainless steel. The module itself is ceramic.
Piping	PVC	Corrosion resistant and robust
Pump	Galvanised steel	Corrosion resistant and robust
Tank	Polyethylene	Corrosion resistant
Pressure indicators	Stainless steel	Robust and corrosion resistant
Flow indicators	Plastic	These were inaccurate and unsatisfactory.

6.6.2 Reliability

Plant and equipment : The filter modules seals and pipe fittings are designed to withstand a much higher pressure than the delivery pressure of the pump. Although a manually operated plant could be left unsupervised for up to a week, this is not recommended because no automatic shutdown facility or alarms are provided. This MF filtration technology is suited to "stop-start" operation and in the field it would ideally be coupled to a level-controlled treated water reservoir.

6.6.3 Potential for Expansion of Plant Capacity

The use of increased operating pressure to increase the capacity of these filter modules is not recommended as it may lead to clogging of the modules. Water production can be maximised by ensuring that the plant operates continuously and that the permeate flux is monitored. If the duration of filter runs is shortened, higher average fluxes will be obtained but the water recovery may be reduced. If treatment capacity greater than that obtained with optimisation is required, additional filter modules may be added to the plant (a pump upgrade may also be necessary) or a modular extension to the plant may be purchased. The workload and operating skill required will not increase significantly with moderate increases in plant capacity that are achieved in this way but the volume of cleaning efffluent that is produced will increase moderately.

6.7 Servicing, Maintenance and Repair

Maintenance and technical support are available from the AEC. Spare parts for most of the plant components are available through industrial suppliers in South Africa although replacement parts for the imported filter modules are only available from the AEC. A maintenance manual provided with the plant, instructs the operator on minor maintenance and servicing tasks.

The manufacturer's claims that maintenance costs are very low could not be validated in the short period for which the pilot plant was evaluated by Umgeni Water. However, due to the simplicity and robust nature of the package plants, these claims may be justified. The feed pump is the only component that will require regular servicing.

The seals that prevent raw and treated water from contact with each other should also be checked as part of the maintenance procedure. The seals are designed to withstand a pressure 10 times greater than the working pressure of the process. However, should a seal become damaged and develop a leak, feed or reject water **will** contaminate the permeate since the feed water pressure is considerably higher than the permeate pressure.

6.8 Transportation, Installation and Commissioning

6.8.1 Transportation

The plants are fully assembled and skid mounted. The skid mounting also enables easy relocation after installation. They can be transported in a light delivery vehicle or a 3 ton truck depending on the capacity of the plant. Leaks may develop as a result of vibration during transport but these can be repaired during commissioning.

6.8.2 Installation

A concrete slab, which will give the plant a level foundation is required (see **Section 6.4**). Provision is made, for the use of lifting tackle to position the plant. The plant is then connected to an electric or internal combustion motor and appropriate connections are made to the raw water source, the treated water storage system and an effluent drain. A level control system, if used, must be installed in the treated water storage system as well.

6.8.3 Commissioning

Commissioning of the smaller plants should only take 1 or 2 hours (excluding operator training). The plant will be commissioned by AEC personnel and operator training can be provided on site. An simple instruction manual is also provided to assist the operator in his duties. At present, the manual is available in English but the AEC will undertake to translate it into any required language.

6.9 Cost

The short period for which the plant was evaluated did not allow a proper evaluation of the operating costs of the unit. The operating costs have been estimated according to the energy requirements quoted by the AEC and the operating and maintenance requirements identified during the evaluation.

6.9.1 Capital Cost

The capital cost ranges from approximately R5 000/m^3/day for the small systems to R 1 500 /m^3/day for the large systems. **Table 6.1** indicates the plant capacities that are available.

6.9.2 Operating Cost

The various components of the operating cost have been estimated from operating experience gained during the evaluation. These costs are summarised in **Table 6.7**.

Table 6.7 : Summary of operating costs

Component cost	Estimated specific cost (R/m^3)		
	1P Plant @ 4 m^3/d	1P4 Plant @ 16 m^3/d	19P4 Plant @ 80 m^3/d
Nitric acid	0,15	0,04	0,04
Caustic soda	0,14	0,04	0,04
Detergent powder	0,04	0,01	0,01
Electricity	1,58	0,75	0,50
Operator's wages	2,25	0,56	0,10
Maintenance and repair	0,76	0,38	0,20
Totals	**4,92**	**1,78**	**0,89***

* **Note:** Approximate figures only

Chemical costs : Although no water treatment chemicals are used washing powder, nitric acid and caustic soda are required for the cleaning of the membranes. For a 1P plant, based on the rates of consumption (see **Section 6.5.4**) supplied by AEC, the cost of these chemicals will be R 0,04 /m^3, R 0,15 /m^3 and R 0,14 /m^3 respectively for a total chemical cost of R 0, 33 /m^3. Similar quantities of chemicals will be suitable suitable for washing a 1P4 plant resulting in a total chemical cost of approximately R 0,09 /m^3.

Cost of power : The AEC quotes an operating cost of approximately R 0,75 /m^3, if the plant is electrically driven. The smallest plant (Model 1P) is powered by a 1 kW motor and should produce between 1,5 and 7 m^3/day. For a 1P plant producing 4 m^3/day, the power cost will be R1,58 /m^3 while the equivalent cost for a 1P4 unit will be approximately R 0,75 /m^3. These energy costs are based on Durban Electricity's 1994 'Business and General' tariff of R0,2643 /kWh. Electricity costs vary within South Africa and unrestricted supply tariffs up to 50% lower than this are available according to the AEC. The larger plants using more than 1 monolith in parallel are more efficient and average electrical energy costs of less than R 0,50 /m^3 are attainable at the lowest electricity tariffs.

Where petrol or diesel powered pumps are used the energy costs may be considerably higher than the figures for electrically operated plants.

Labour cost : The cost of operating labour is based on a rate of R 7,00 /h. The operating workload has been estimated as 9 hours weekly and is largely insensitive to the capacity of the plant. The specific operating cost for the Model 1P plant producing an average of 4 m^3/d is therefore approximately R 2,25 /m^3. A similar operating workload on the Model 1P4 plant producing 16 m^3/d will cost approximately R 0,56 /m^3. On larger plants the fixed cost of labour can decrease to less than R 0,10 /m^3.

Maintenance costs : The estimated annual maintenance workload is 6 hours and the annual cost of maintenance including spare parts and labour has been estimated as 5 % of the capital cost per annum. This means that annual maintenance costs will vary from R1000,00 for the 1P plant to R 2000,00 for the 1P4 plant. The specific cost of maintenance is therefore estimated as R 0,76 /m^3 for the 1P plant and R 0,38 /m^3 for the 19P plant when operating continuously with an average 10 % downtime. On the larger plants the maintenance cost can be as low as R 0,20 /m^3.

If a petrol or diesel motor is used instead of electricity the maintenance requirements will be considerably increased because regular servicing of the motor will be required. These estimated maintenance costs also exclude the cost of replacing the ceramic monoliths every 5 years.

7 AQUATEK

Aquasprite Dual Media Pressure Filter

7.1 Introduction to the Aquasprite Filter

The Aquasprite plant is manufactured by Aquatek, a supplier of filtration equipment based in Pretoria. Enquiries should be directed to Mr R. Starke (tel. 012-466261, fax. 012-464298).

The Aquasprite D1/L8/50 was evaluated. This unit has a nominal capacity of 1 m^3/h. A range of similar Aquasprite units with nominal capacities of 2,5 m^3/h, 5 m^3/h and 12,5 m^3/h are available. Aquatek is able to modify these units to meet specific customer requirements when necessary. A range of clarifiers is also available for pretreatment of raw waters with high turbidity.

7.1.1 Plant Design Philosophy

The Aquasprite range of dual media filters are modular units incorporating a pump, chemical dosing equipment, a control system and a filter. They were developed to provide compact, low maintenance, easily operated water purification systems for use where no potable water is available. Conventional dual-media filtration technology is used. The plants are partially automated to reduce the workload and simple, robust components are used to minimise maintenance requirements. A coagulant and a disinfectant are dosed into the water being treated and electrical energy is required for pumping, dosing and the level control system.

7.1.2 General Description of the Aquasprite Plant

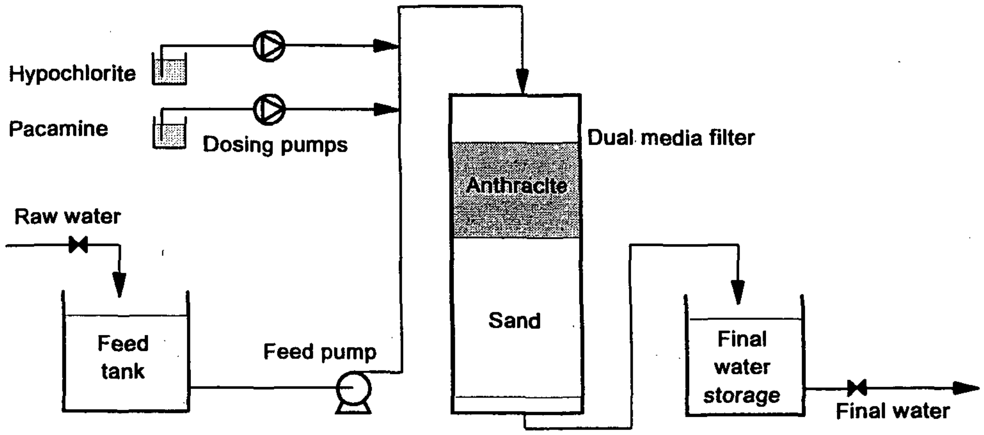


Figure 7.1: Dual-media pressure filter process flow diagram

Coagulant and disinfectant solutions are dosed into the raw water, which is pumped into a dual media pressure filter containing anthracite and fine sand (see **Figure 7.1**). The filtered water enters the treated water reservoir. The process operates continuously during a filter run and the unit operations involved are chemical dosing, pumping, flocculation and filtration. The process is normally activated on demand by level probes fitted to the treated water storage vessel but during the evaluation at the PEF, the treated water was discharged to the drain to prevent interruption of the filter runs.

7.1.3 Process Sophistication

Table 7.1 contains a summary of the components used in the Aquasprite plant. The chemical dosing is not proportional and requires frequent manual adjustment if constant doses are to be maintained during a filter run. The use of flow proportional dosing will significantly enhance the sophistication of the plant and enhance the reliability for potable water production. Monthly calibration of the dosing pumps is required to ensure adequate dosing of chemicals.

Table 7.1 : Aquasprite component list

Component	Quantity	Comments
Valves	10	4 x PVC ball valves 1 x PVC non-return valve on filter outlet 3 x 3-way valves 1 x multiport valve on top of filter
Pumps	1	0,6 kW Speck pump
Dosing pumps	2	2 x M201 Alldos dosing pumps at 10 W each.
Filters	1	GRP dual media pressure filter (0,5m diameter, 1,4m height) Anthracite (upper media) 0,8 to 1,6 mm (manufacturer's specification) Silica sand (lower media) 0,5 to 0,7 mm (manufacturer's specification)
Tanks	4	1 x 25 ℓ Pacamine tank 1 x 25 ℓ Chlorine tank 1 x 500 ℓ raw water tank 1 x 500 ℓ clean water tank

During backwashing, manipulation of the three-way valves and the multiport valve is required. The maximum working pressure across the filter is 80 kPa and regular monitoring is necessary to ensure satisfactory plant operation and treated water quality.

All components used in the construction of the plant are available within South Africa from industrial suppliers. All components with which the water comes into contact are manufactured from PVC, GRP or other plastics and contamination of the treated water with corrosion products is not likely.

7.2 Process Control System

The filter operates in the constant head declining rate mode when triggered by the level probes in the treated water reservoir. No facility for control of the filtration rate is provided. A low level probe in the raw water tank trips the pump if the raw water supply is depleted, thereby preventing pump damage. The control system uses conventional electrical contacting equipment and makes no use of sophisticated electronic circuitry. Filter runs are manually terminated for backwashing at the operator's discretion. The operating manual recommends a terminal head loss of 25 kPa.

7.2.1 Operation and Control Sequence

For the evaluation at the PEF, the Aquasprite was fed with raw water from a break pressure tank. The water surface in this tank was approximately level with the pump suction. Normal start-up and operation proceeds as follows:

- The raw water level in the feed tank must cover the high level probe.
- The raw water feed pump is primed and all valves except the multiport valve are set to the "filter" position. The multiport valve is set to the 'waste' position.
- The main switch, pump switch and control circuit isolators are switched on. Raw water will be pumped through the system and out to waste.
- The dosing pumps are primed with water before the suction lines are immersed into the chemical solutions. The dosing pump settings should be predetermined by the operator.
- The multiport valve is turned to the "filter" position as soon as a chlorine residual of 0,5 ppm Cl is detected in the treated water (using a suitable test kit).

After start-up the filter can be left to operate on demand from the treated water level probe system however; flowrate, turbidity, chlorine residual and raw water pressure should be monitored during the filtration cycle. As the filter becomes loaded with solids, the flowrate through the plant will decrease. The chemical dose therefore requires regular adjustment to prevent overdosing of chemicals. This continues until the pressure drop across the filter bed increases to such an extent that a backwash is required. Backwashing proceeds as follows:

- The plant is switched off and all valves are set to the "backwash position".
- The pump is restarted and backwashing continues until the backwash effluent appears clear.
- the pump is stopped, the multiport valve is moved to the "rinse" position and the pump restarted. The filter is rinsed until the effluent again appears clear.
- All valves are returned to the "filtration position, the dosing pumps are restarted and normal filtration resumes.

7.2.2 Degree of Automation

During normal operation, the feed and dosing pumps will be automatically activated or stopped on demand from the treated water level control system. All other aspects of plant operation are manually performed. These manual tasks include:

- Preparation and replenishment of chemical solutions.
- Backwashing
- Adjustment of chemical dosing
- Water quality monitoring

The flocculant and disinfectant solution are dosed into the pump discharge line and the degree of mixing of these chemicals prior to filtration cannot be controlled. The length of pipe between the pump and filter, the volume of the freeboard and the raw water flowrate similarly determine the duration of mixing. The filtration rate may be controlled manually by installing a valve on the outlet line. If this is not done, the flowrate decreases as the bed pressure drop increases.

7.2.3 Monitoring of Process Parameters

During operation of the plant, parameters such as treated water quality, flowrate, pressure drop and chemical dose were monitored by the operator. A summary of how these parameters were monitored during evaluation at the PEF is given in **Table 7.2**.

Table 7.2 : Monitoring of process operating parameters

Parameter	Measurement and Control
Turbidity	Measured manually with a laboratory Hach turbidity meter. Manual adjustments were made to the coagulant dosing pump to control turbidity.
Pressure	Pressure drop across the bed was calculated by the difference between the measured pressure and the pressure at the start of the filter run.
Flowrate	Calculated from the time required to fill a 10 litre bucket. Flowrate was controlled by a ball valve located at the filter outlet.
Chlorine residual	Measured manually by the DPD method with a Lovibond comparator. Manual adjustments were made to the hypochlorite dosing pump to maintain the residual between 0,5 and 1,0 mg/ℓ as Cl.

The pressure gauge fitted to the filter is difficult to read because the undamped needle fluctuated rapidly. It is recommended that this gauge is replaced by a glycerine damped pressure gauge. A reliable pressure indicator is important since the pressure drop across the bed reflects the solids loading in the filter. Since flowrate is also an important indicator of filter bed resistance it is recommended that a flowmeter is installed as well. There is no pressure controlled alarm or trip switch connected to the filter. It is recommended that a pressure switch is fitted to the plant. This switch can be adjusted to trip the plant automatically when the terminal head loss across the filter bed is attained. This will prevent accidental overloading and consequent clogging of the filter bed. The switch will also reduce the monitoring workload and allow unsupervised operation of the filter, thereby increasing the plant's effective capacity.

7.2.4 Effectiveness of the Control System

Normal Operation : The control system effectively produces treated water so that a continuous supply of clean water can be maintained . However the quality of the treated water has to be controlled manually which requires operator time and skill. Due to the lack of a pressure switch on the filter, filtration may continue after solids breakthrough in the filter has occurred and contamination of the treated water may occur. Diligent monitoring of treated water quality and filter bed pressure drop is required to prevent this. In addition, the lack of flow control or, alternatively, flow proportional chemical dosing means that the operator is required to regularly check the flowrate during filtration and adjust the chemical doses accordingly.

The present instruction manual requires more detail. The correct filter bed pressure drop needs to be specified in order to determine the length of the filtration cycle irrespective of the raw water quality. The plant cannot be run according to fixed filtration cycle times since raw water quality may undergo seasonal changes.

Filter backwashing : Initially the filter was operated to a 25 kPa terminal head loss, according to Aquatek's recommendations. This resulted in a high solids loading, a backwash time (downtime) of between 20 and 40 minutes and a 67 % reduction in flowrate over the duration of the filter run. After the initial period, the plant was operated such that the measured pressure drop across the filter was between 5 and 17 kPa and the filter run time was typically between 6 and 12 hours. The backwash cycle time was between 10 and 15 minutes and was terminated when the effluent appeared clear. In order to reduce the solids loading and downtime as well as increasing the average flowrate, a terminal head loss of 15 kPa is recommended.

An indication of the efficiency of backwashing can be seen in **Figure 7.2** where the filter feed water pressure after backwashing consistently returned to its original value (28 kPa). The backwash rate was 24 m/h which is lower than the 40 to 50 m/h suggested by Degrémont's *Water Treatment Handbook* for an effective sand size of 0,55 mm. The filter pump was unable to deliver a backwash rate in excess of 24 m/h. In addition there was an average anthracite loss of 35 g per backwash at a backwash rate of 24 m/h. There is a possibility of larger anthracite losses at backwash rates in the range of 40 to 50 m/h.

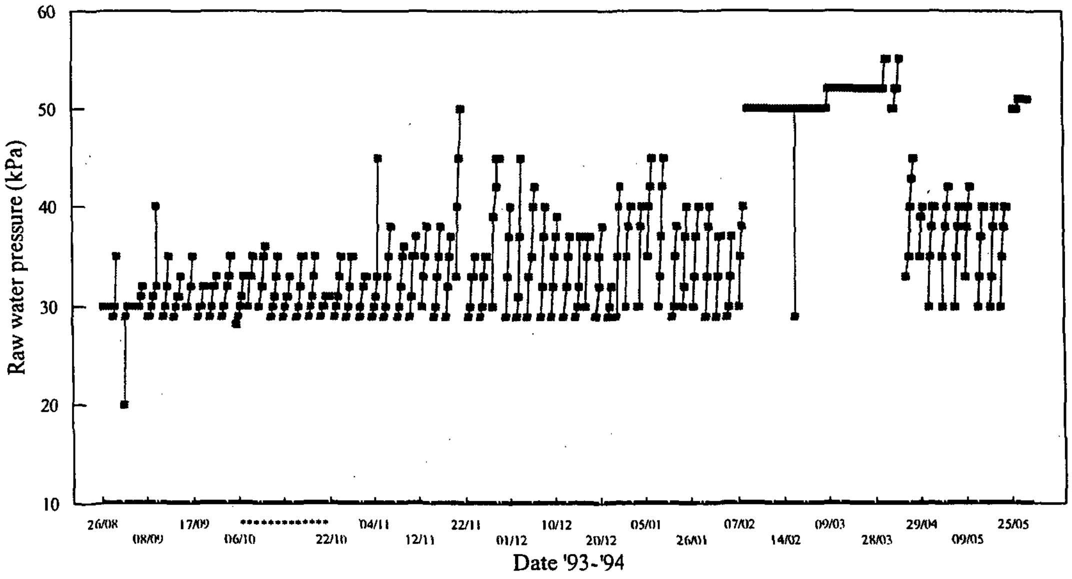


Figure 7.2: Filter feedwater pressure fluctuations

7.2.5 Uncontrolled Parameters which may affect Final Water Quality

Rapid fluctuations in raw water turbidity may affect the final water quality during a filter run. The chemical dosing is not controlled proportional to the raw water flowrate, and although the flowrate drops with time, overdose of chemicals can be just as detrimental to the operation of the process as underdosing. Jar tests may be used to aid the operator in making appropriate dosing adjustments to compensate for such fluctuations. The optimum pH for both the coagulant and the disinfectant is between pH 7 and 8. There is no facility for pH correction on the Aquasprite.

7.2.6 Susceptibility to Demand Fluctuations

The Aquasprite is able to operate on demand from the level probe system and interruption of filter runs does not measurably affect treated water quality. Provided that the average demand for treated water does not exceed the capacity of the plant, it will be able to satisfy the demand. The capacity is not the maximum flowrate after backwashing, but an average production rate.

Recommended filtration rates for dual media pressure filters are between 9 and 12 m/h (Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities - US EPA). The nominal flowrate of the Aquasprite is 1 m^3/h but these rates indicate that the Aquasprite can be operated at flowrates up to 2,3 m^3/h. The backwashing time of 10 to 15 minutes every 6 to 12 hours represents downtime of between 1,4 and 4 % of a normal filter run.

7.3 Personnel Requirements

A technician and electrician will be temporarily required for installation and commissioning of the plant. A literate operator with technical aptitude will be required for operation and an artisan such as a plumber or electrician will be required for routine maintenance work. The tasks, workload and level of competency required for each of these categories has been estimated in the following sections.

7.3.1 Workload Estimations

Installation and commissioning : The tasks are described in **Section 7.8** and the plant can be installed and commissioned in 1 day if appropriate site preparation has been completed beforehand (see **Section 7.4**). Operator training can be incorporated in the commissioning period. An electrician will be required to make the electrical connections and a technician should be present to supervise operator training, the correct assembly of the plant and the commissioning process.

Routine operation : The routine operating workload is approximately 2 to 3 hours daily and includes adjustment of dosing pumps, cleaning, backwashing, chemical replenishment and water quality monitoring. The workload and operating skill requirements can be reduced if either automatic flow control or proportional dosing equipment is installed on the unit.

Maintenance and repair : The routine maintenance workload may be limited to six monthly checks on the operation of the control system, valves, dosing pumps, filter pump and the plant in general. With the exception of travelling time and where repairs are required, the workload involved in routine maintenance should not exceed 2 hours every six months.

7.3.2 Specific training requirements

Previous training in the principle of operation of the plant and watercare practices in general will be an advantage. The **operator** will require training in :

- The basic principle of operation of the pumps, dosing pumps, filter and level control system.
- Chemical solution preparation including dilution and dosing calculations
- Water quality monitoring
- Backwashing and cleaning of the plant
- Simple trouble shooting
- Maintaining an accurate logbook of operating history.
- Sampling and water quality monitoring.

A simple but detailed instruction manual will be required for reference. All instructions concerning operator tasks should be accompanied by clear illustrations to overcome any literacy problems.

The maintenance artisan should preferably be an electrician with pipework experience or a plumber with electrical experience. In addition to practical experience the artisan will require training in :

- The principles of plant operation.
- Trouble shooting related to the Aquasprite plant.
- Problems associated with dosing pumps.

7.4 Infrastructure requirements

Road access : Vehicular access to the site of the plant will be required.

Power requirements : A 220 V, 16 A domestic power socket will be required. A 1 kW generator may be used if there is no domestic supply.

Raw water provision : The use of a raw water feed tank supplied by a separate pump is recommended where possible (see **Section 7.5.1**).

Treated water reticulation : A tank with a holding capacity of at least one day's water production and an additional 1 m^3 for backwashing purposes is necessary.

Sludge disposal : 500 to 1000 ℓ of effluent is produced per backwash. A drain is required to return the sludge to the raw water source (downstream of the intake) or to direct it to a drying pond. Recycling of the backwash effluent may be feasible in arid areas but will require an additional settling tank. It may be possible to use the effluent for crop irrigation although the presence of chlorine and residual coagulant in the effluent may be detrimental to crops.

Chemical storage facilities : The decomposition of sodium hypochlorite solution is accelerated by light, heat and impurities. Thus a storage facility that is cool, dark and dry is required and the hypochlorite containers must be properly sealed during storage. It is recommended that no more than 1 month's supply of hypochlorite solution is kept in stock and that stocks are rotated (first in, first out).

Weather protection : Shelter from the elements will prolong plant life and improve safety.

Site establishment : A level slab, not less than 1 m^2, should be laid as a foundation for the filter. A raw water reservoir may be considered if the raw water source is any distance away from the plant.

7.5 Performance of the Treatment system

The Aquasprite was installed at the Process Evaluation Facility and operated intermittently during working hours from January 1993 to July 1994. It is estimated that a total of approximately 1,26 Mℓ of treated water was produced during this period. The maximum flowrate (with a clean filter) was 3 m^3/h (average 2,75 m^3/h) while the filtration rate varied between 2,5 and 15 m/h. The electrical power was provided from a conventional domestic power point (220 V, 16 A), and the process consumed approximately 0,23 kWh/m^3 (total power consumed by pumps was 0,62 kW) .

7.5.1 Raw Water Supply

Head and flowrate : For gravity feed a raw water head of 8 m is required. The present pump has a suction head of 1,5m of water therefore the intake cannot be more than 1,5m below the level of the plant. A foot valve will be required to aid in the priming of the pump.

Screening : The pump casing incorporates a basket strainer that will remove coarse particles, sticks and leaves from the raw water.

Quality of the raw water : The raw water turbidity range during the period of evaluation varied between 1 and 500 NTU.

7.5.2 Micro-organism Removal

A free available chlorine concentration of 0,5 mg/ℓ for a contact time of 30 minutes at a pH less than 8 is sufficient to remove pathogenic bacteria and the poliomyelitis viruses (Degrémont *Water Treatment Handbook*, 6 ed., 1991). The shorter the contact period, the greater the dose of free available chlorine that is required to ensure proper disinfection. A 1 % (m/v) solution of sodium hypochlorite was used for disinfection during the evaluation. The chlorine dose was adjusted during plant operation to give a free available chlorine residual of 0,5 to 1,0 mg/ℓ as Cl. The residence time of disinfectant dosed water in the Aquasprite filter was 15 minutes at 1 m^3/h and 7,5 minutes at 2 m^3/h. Passage of the treated water through a reticulation system will provide additional contact time.

The Dept. of Health's (DoH) 1994 draft guidelines for chlorine residual are 0,2 to 5 mg/ℓ as Cl. All treated water samples conformed to the DoH guidelines for microbiological quality and chlorine residual. The results of microbiological tests showed 100 % removal of Coliforms, *E.Coli* and faecal streptococci (see **Table 7.3**) in all samples. However, small quantities of standard plate count organisms occurred in 18 percent of clean water samples. The DoH guideline for standard plate count organisms incubated at 22°C is 100 /mℓ and this was not exceeded in any of the samples. Trihalomethanes (THMs) were formed as a disinfectant by-product. However the THMs in the treated water ranged from 5 to 15 µg/ℓ which is well within the DoH guideline of 100 µg/ℓ.

Table 7.3 : Disinfection Results

(The percentage disinfection and the residual count are shown for each determinand)											
Date	**Coliforms**		***E. Coli***		**Faecal Strep.**		**Plate counts @ 22°C**		**Plate counts @ 37°C**		**Chlorine residual**
	%	/100mℓ	%	/100mℓ	%	/100mℓ	%	/mℓ	%	/mℓ	mg/ℓ as Cl
27/08/93	100	0	100	0	100	0	100	0	100	0	0,4
31/08/93	100	0	100	0	100	0	100	0	100	0	0,5
17/09/93	100	0	100	0	100	0	99,3	2	100	0	0,7
22/09/93	100	0	100	0	100	0	98,4	12	100	0	0,6
29/10/93	100	0	100	0	100	0	99,3	1	100	0	0,7
03/11/93	100	0	100	0	100	0	98,2	4	100	0	0,9
11/11/93	100	0	100	0	100	0	99,7	1	100	0	0,7
20/11/93	100	0	100	0	100	0	99,4	19	99,2	1	0,5
01/12/93	100	0	100	0	100	0	98,2	16	100	0	0,5
15/12/93	100	0	100	0	100	0	100	0	100	0	0,7
05/01/94	100	0	100	0	100	0	100	0	99,2	3	0,5
07/02/94	100	0	100	0	100	0	100	0	99,8	1	0,5
03/03/94	100	0	100	0	100	0	100	0	63,8	212	1,2
26/04/94	100	0	100	0	100	0	99,9	1	100	0	0,5
24/05/94	100	0	100	0	100	0	99,1	2	99,6	1	0,6
27/06/94	100	0	100	0	100	0	92,9	25	77,2	228	0,9
14/07/94	100	0	100	0	100	0	97,2	3	99,6	3	0,7

It was difficult to maintain a constant chlorine residual in the treated water. Since the raw water flowrate varied with the filter bed resistance, regular (manual) adjustment of the chlorine dose was required in order to maintain a constant chlorine residual. The "% stroke" scale on the dosing pump was inaccurate due to some free play in the mechanism and a particular scale setting did not always yield the same dosing flow. Nevertheless, the chlorine residual can be reasonably well controlled with operator diligence. **The use of a proportional dosing pump is recommended as it will significantly reduce the operator's workload and permit better control of water quality.**

There are no alarms that indicate over or under dosing of chlorine. However, routine monitoring of the chlorine residual (using the DPD test) provides a reliable safeguard. No significant taste and odour problems were detected when the coagulant and chlorine dose were carefully regulated by the operator.

7.5.3 Turbidity and Suspended Solids Removal

During the operation of the plant at the Process Evaluation facility the raw and final water turbidities were measured. The Aquasprite seldom produced treated water with a final water turbidity above 1 NTU (Department of Health guideline) from raw waters with turbidity between 0 and 250 NTU. However, in one run where the plant was operated **without coagulant**, the final water turbidity consistently exceeded 1 NTU. It can be seen in **Figure 7.3** that for raw water turbidities below 60 NTU the treated water turbidity was generally well below 1 NTU and did not exceed 10 NTU. For raw water turbidities from 60 to 200 NTU the treated water turbidity frequently exceeded 1 NTU and occasionally exceeded 10 NTU. Severe turbidity breakthrough occurred when the raw water turbidity exceeded 250 NTU.

As raw water turbidities increase filter run times are reduced and more frequent backwashing is required. This reduces the time available for filtration and therefore reduces the overall capacity of the unit. The effect becomes significant when raw water turbidities exceed 100 NTU. During the evaluation a water recovery between 95 and 98 % was obtained.

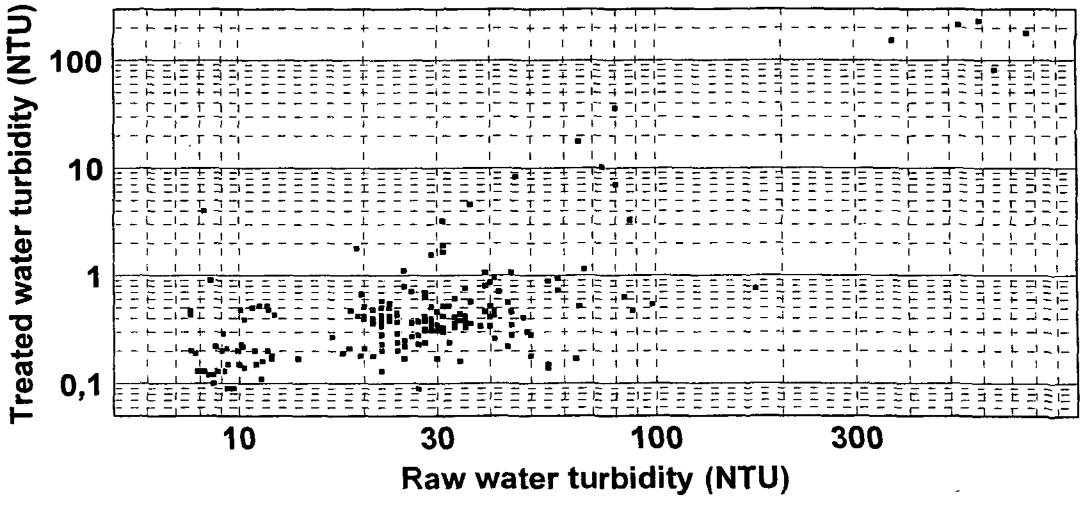


Figure 7.3: Turbidity removal

7.5.4 Chemical Requirements

A sodium hypochlorite dose of approximately 3 mg/ℓ (as Cl) was required to obtain a chlorine residual between 0,5 and 1,0 mg/ℓ in the treated water. A 28 kg (25 ℓ) drum of 13,5 % sodium hypochlorite solution should therefore be sufficient for disinfecting approximately 1,2 Mℓ of filtered water (approximately one month's full-time production). 25 ℓ clear plastic drums were used for the dosing solutions. When these tanks were exposed to direct sunlight, rapid decomposition of the hypochlorite solutions occurred and by the second or third day apparent chlorine doses in excess of 20 mg/ℓ were required to maintain a residual of 0,5 mg/ℓ. **This illustrates the importance of storing the bulk solution and the diluted dosing solutions in a cool, dark, dry place even during use.**

A coagulant called Pacamine (supplied by Aquatek) was initially used. Several other coagulants were also used during the evaluations and no significant differences in dose or treated water quality were observed. The coagulants used included Floccotan K10P, Zetachem Z464N and Pacamine (supplied by Aquatek). These polymeric coagulants have the advantage of being pH independent and eliminate the need for the operator to control pH (see below). Consumption of blended polymeric coagulants was 1,56 mg/ℓ on average. The use of alum and ferric chloride was not investigated and is not recommended because the effectiveness of these coagulants is pH dependent and the need for pH control will complicate plant operation. Since the shelf life of most polymer coagulants is longer than that of sodium hypochlorite, these may be purchased in 5 ℓ quantities which should be sufficient for 2 to 3 months of full-time operation.

Both the disinfectant and coagulants were too concentrated to be dosed as supplied and dilution was necessary. The hypochlorite solution was diluted from the bulk concentration to 1 %(m/v) and the coagulant from the pure form to 0,5 %(m/v) for dosing. Once diluted, the disinfectant should be used within three days and the coagulant solutions within two weeks. Sodium hypochlorite bulk solution is corrosive and should not come into direct contact with the skin. This solution should be stored in an opaque container (preferably black) since exposure to light reduces its shelf life.

7.6 Plant Life and Reliability

The Aquasprite performed reliably during two years of operation at the Process Evaluation Facility.

7.6.1 Materials of Construction

The plant is constructed almost exclusively from corrosion resistant materials. The water being treated is not exposed to any metallic surfaces other than the stainless steel used for the level probes and parts of the pump shaft and seal.

The pump volute casing, pipework, filter vessel and filter components are constructed from glass reinforced plastics (GRP) and PVC as summarised in **Table 7.4**. These materials have reasonable resistance to weathering but the life of these components will be prolonged if they are sheltered from the sun. Class 6 PVC fittings and pipe are used and while these are suitable for the working pressure of the unit they will not withstand the stresses of repeated relocation as well as Class 16 PVC fittings.

Table 7.4: Summary of the materials of construction

Component	Materials	Comments
Filter module	GRP vessel, PVC components	Robust, weather resistant, suitable chemical and thermal tolerance for this application.
Piping	PVC	Painting will prolong service life of exposed pipes.
Pump casing	GRP, aluminium	Suction and discharge ports reinforced with aluminium rings that do not make contact with the process fluid.
Tanks	GRP	Light weight, easily repaired.

7.6.2 Reliability

Plant and Equipment : The length of time for which the plant could be operated without supervision was 4 hours without compromising final water quality. During the two years of operation a level relay failed but was easily replaced with a new relay. Circumstances under which untreated and undisinfected water can enter the potable water reticulation system could be avoided by covering the tanks and fitting alarm equipped foot valves to the chemical suction tubes in the dosing tanks. These alarm switches can also be configured to trip the filter pump and halt water production if either of the chemical solutions run out.

Dosing System : Two Alldos dosing pumps with a maximum capacity of 1,4 ℓ/h each are provided for chemical dosing. The stroke rate is fixed at 60 strokes/min and the stroke length is manually adjustable. The chemical doses are varied by means of stroke length adjustments. The pumps are not proportional and the dosing flowrate remains constant once it has been set. Depending on the raw water turbidity the plant will only operate at maximum capacity for short periods. The chemical tanks have a capacity of 25 ℓ which is sufficient for three 8 hour runs or four 6 hour runs (a total of 24 hours). Monthly calibration of the dosing pumps at a given stroke setting is recommended as this will indicate any deterioration in the dosing pump's performance and may also be used to check the doses being administered. A graduated measuring cylinder and a stopwatch are required for calibration of the dosing pumps.

The dosing points are positioned on the pump discharge line leading to the filter inlet. The turbulence in the pipe, multiport valve and elbows is used for mixing. The dosing points were not positioned at the pump inlet because the suction at the pump inlet results in chemicals being sucked through the dosing pump at a relatively high flowrate, even when spring-loaded dosing valves are fitted.

If either dosing tank runs dry during filtration the treated water quality will deteriorate and may not be fit for potable use. Since no low level alarms are fitted to the chemical tanks the plant will not trip when this happens and the treated water in storage will become contaminated.

7.6.3 Potential for expansion of capacity

The present pump is too small to operate the plant at its maximum capacity for long periods. The flowrate declines to less than 0,5 m^3/h as the solids loading in the filter bed increases during a run. A larger pump together with a throttling valve can be fitted to maintain the flowrate. If automatic flow control is not used a manually adjusted valve will be required to keep the filtration rate between 9 and 12 m/h.

An increase in filter area (additional filters) can also be used to increase capacity. If either the pump or the filters are uprated, the system should still operate within the filter rate guidelines and backwashing rates of the original design.

Expansion of plant capacity may necessitate increases in the capacity of the raw water supply system, the electrical system and the storage facilities.

Table 7.5 : Expansion potential of the plant components

Unit	Expansion Capability
Pump	Pump capacity may be increased if a corresponding increase in filtration area is used.
Piping	The existing 50 mm piping is suitable for flowrates up to 6 m^3/h. Larger piping can be installed where this flowrate will be exceeded but the pump and multiport valve have 50 mm solvent weld sockets. Therefore adapters will be required.
Tanks	Larger storage capacity will provide greater buffer capacity for demand fluctuations and improved backwash capability.
Filter	Several similar Aquasprite filter modules may be connected in parallel if appropriate pumping capacity is fitted. It may be possible to supply multiple filters from one large pump but the installation of two smaller pumps will mean that standby capacity is available in case of pump failure.

7.7 Servicing, Maintenance and Repair

The operator should be responsible for general cleaning duties including the tidiness of the plant and its surroundings, cleaning of the basket strainer, the level probes and the effluent system. Mechanical maintenance and repair will occasionally be required for the pump, dosing pumps, all valves and electrical switchgear as discussed below.

Raw water pump : An annual check on the condition of the pump motor and the main shaft seal is necessary. The seal can be replaced *in situ* but repairs to the pump motor will usually require dismantling of the pump and removal to a properly equipped workshop.

Dosing pumps : The one-way valves and the pump diaphragm should be checked and cleaned every six months. Intake foot valves should be fitted to prevent the intake of solid particles which may damage the one-way valves in the pump head. Annual replacement of one-way valves and the pump diaphragm may be expected although this has not been necessary on the plant that was evaluated.

Valves and fittings : The rubber 'O' ring seals, teflon spacers and PVC balls used in the various valves can become worn, especially when the raw water is gritty. These items should be checked and replaced if necessary on an annual basis.

Electrical switchgear : The electrical relays used for the level probe system and pump motor should be checked annually. Although a level probe relay failed during the evaluation this should be considered an unusual occurrence. The level probes become fouled with time and should be kept clean to enhance their operation.

7.8 Transportation, installation and commissioning

7.8.1 Transportation

The unit can easily be transported by a half-ton truck or minibus but tanks larger than 1 m^3 may require larger vehicles. The pipework has suitably positioned unions making the plant easy to dismantle and fit into a vehicle without mechanical lifting equipment. The plant does not require permanent fixtures on-site. The plant components are reasonably portable and the plant can be rapidly dismantled and reassembled. The filter vessel is not equipped for the use of lifting tackle and it is recommended that the media is removed prior to any attempts at moving the filter.

7.8.2 Installation

The unit is match marked for easy assembly of pipework. Electrical connections include the main supply, filter pump and the level probe connections. The level to which sand and anthracite must be filled is marked on the filter vessel.

The plant should be mounted onto a level slab equipped with connections for the raw water, treated water, effluent and electrical system. The length of time from delivery to full scale operation of the plant can be as little as two days if appropriate site preparation (see **Section 7.4**) has been completed.

7.8.3 Commissioning

Commissioning involves filling up the raw water tank, setting valve positions, connecting the power, switching on the pump and control circuit isolators and commissioning the dosing pumps. The time required for commissioning is 5 hours. This time was required mainly to experiment with the chemical dose needed to produce a treated water of acceptable quality. The dosing pumps were primed and calibrated while the plant was in operation. The commissioning period may be used for operator training.

7.9 Cost

7.9.1 Capital cost

The capital cost was R 12 000 (June 1993). However this cost does not include tanks or storage facilities. The cost of a 1000 ℓ tank in 1993 was approximately R 1 300.

7.9.2 Operating costs

The operating cost is made up of labour, maintenance, electricity and chemical components. These have been estimated and are summarised in **Table 7.6**. Where applicable the operating costs have been calculated from assumed operation of the unit for 8 hours daily with a mean treated water flowrate of 2,75 m^3/h.

Table 7.6 : Summary of operating costs

Component	Specific operating cost (R /m^3)
Chlorine	0,03
Coagulants	0,01
Electricity	0,07
Labour	0,95
Maintenance	0,08
Total	**1,14**

Chemical cost : The average cost of blended polymeric coagulants in 1994 was R 4,00 /kg and a 28 kg drum of 13,5 %(m/m) sodium hypochlorite cost approximately R 41,00. For a coagulant dose of 1,5 mg/ℓ and chlorine dose of 3,1 mg/l, the average chemical costs will be R 0,01 /m^3 and R 0,033 /m^3 respectively.

Cost of power : The business tariff for electricity is R 0,2643 /kWh. The plant's specific power consumption has been estimated at 0,23 kWh/m^3. The specific power cost for the plant as installed at the PEF is approximately R 0,061 /m^3. This estimate does not include the cost of power required for provision of raw water from a remote source or the additional power cost of a reticulation system.

Labour cost : Due to the low degree of automation, the operator is required to monitor plant operation frequently. Depending on the raw water quality, 8 to 12 hours per day of filter operation can be achieved with about three hours of operator supervision at R 7,00 /h. Assuming that the plant operates an average of 8 hours per day with an average flowrate of 2,75 m^3/h, then the cost of operator remuneration will be approximately R 0,95 /m^3. This is a worst case estimate. When the raw water turbidity is less than 20 NTU, filter runs may be considerably extended and operation overnight may become feasible. Full-time operation in this manner may cut the specific cost of operator remuneration (assuming an average flowrate of 2 m3/h over the 24 hour period). However, the labour cost for this relatively low capacity unit will remain the most significant portion of the overall operating cost.

The workload involved in operating the larger Aquasprite units will be similar and the specific cost of operator wages will therefore be lower. The addition of a pressure drop activated trip switch and level sensors on the chemical tanks may further reduce the operating cost.

Maintenance and servicing cost : The cost of maintenance, repairs and servicing by trained artisans was estimated from an assumed charge rate of R 75,00 /h. The maintenance and repair workload during the period of the evaluation was approximately 4 hours per annum. The cost of spare parts over the same period amounted to approximately R300,00 per annum. The specific cost of maintenance was therefore approximately R 0,075 /m^3.

8 Diatomaceous Earth Filter

8.1 Introduction to the Diatomaceous earth filter unit

A diatomaceous earth (DE) filter was evaluated to assess its effectiveness for use in package water treatment plants. The filter that was evaluated was primarily designed for swimming pool filtration.

8.1.1 Plant Design Philosophy

The use of diatomaceous earth filtration for potable water production began in the early 1940's. The highly porous nature of the silica particles in diatomaceous earth endow the packed material with high permeability and small average pore size.

The filter that was evaluated is a modular filtration unit incorporating its own pump, filter vessel and precoat preparation tank. In all but the smallest of installations, multiple filter units would be installed so as to ensure the continuity of supply during backwashing, servicing or failure of individual modules. Typical applications of the larger units include filtration systems for large swimming pools, resort complexes and industrial applications. Other than DE media, no other chemicals are required and operation of the filter units is extremely simple.

8.1.2 General Description of the Plant

The filter unit consists of a cylindrical precoat pressure filter in which filtration is achieved by a layer of diatomaceous earth (precoat) deposited onto filter cloth supported by plastic septa (see **Figure 8.1**). The filter unit is provided with a precoat preparation tank and features a high filtration capacity for its size (see **Table 8.1**)

Table 8.1 : Manufacturer's specifications

Parameter	Specification
Filtration area	2,0 m^2
Dimensions	Height: 1,07 m Diameter: 0,55 m
Nominal capacity	12 -15 m^3/h (swimming pool duty)
Recommended terminal head loss	15 m (equivalent to 150 kPa pressure-drop)
Recommended max. operating pressure	200 kPa
Precoat density	1 - 2 kg/m^2
Recommended DE grade	Celite 545/ Celite Supercel Hiflo
Recommended service interval	2 years

Complete installations including header tank, feed pump and treated water storage, can be designed and supplied by the manufacturer but the unit used for this evaluation was supplied without peripheral equipment and was not fitted with a disinfection system. The unit is designed to operate continuously until backwashing is required. After backwashing, precoating with new diatomaceous earth is required before filtration can continue.

Operation of the plant is simple; backwashing involves the manipulation of 3 valves and is accomplished in minutes while precoating involves manipulation of an additional two valves and can be completed in 15 minutes. During filtration, the operator is required only to monitor the flowrate, pressure and permeate quality.

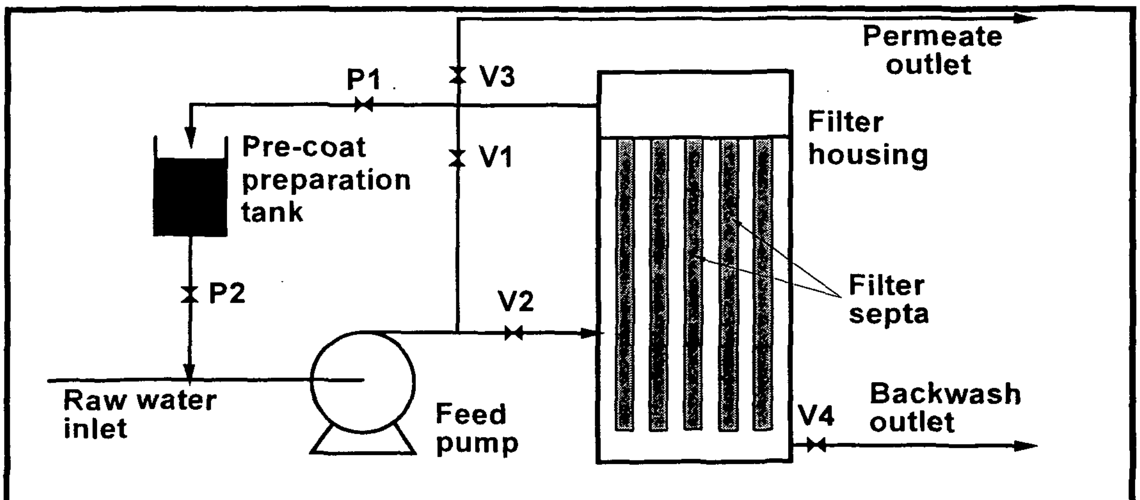


Figure 8.1 : Diatomaceous earth filter process flow diagram

8.1.3 Process Sophistication

It was decided to investigate DE filtration as a potential package plant technology because the filters are generally compact (approximately half the size of a pressure sand filter of equivalent capacity), easy to operate and have low maintenance requirements.

The filter unit was connected to a raw water pump as shown in **Figure 8.1**. No disinfection system was used and the micro-organism removal capability of the filtration system alone was not assessed. No body feed system was used and the filter was operated as a precoat filter without body feed addition. Raw water was used for backwashing. A summary of the process components is given in **Table 8.2** with details in the paragraphs that follow.

Table 8.2 : List of Process Components

Component	Quantity	Comments
Tanks	1	2,0 m^3 GRP feed tank. No treated water storage capacity installed.
Pumps	1	1,5 kW, 220 V, single phase Lowara centrifugal pump
DE Filter	1	12 m^3/h filter module with integral precoat preparation tank
Valves	7	4 x 50 mm PVC ball valves for backwash and filtration control 2 x ¾" brass stopcocks on precoat system 1 x 50 mm brass gate valve for backwash outlet

Valves ; Valves are used to control precoating, backwashing and normal operation. The valve numbers refer to the valves depicted in **Figure 8.1**.

- For the precoat system, domestic brass stopcocks are used. The first (P1) is used to fill the precoat tank from the permeate manifold and the second (P2) to control the flow of precoat slurry from this tank to the pump suction line.
- 50 mm PVC ball valves have been used for filtration and backwash flow direction control. During backwashing, the permeate flow must be cut off (V3) and the flow reversed (V1 opened and V2 closed). However, the use of a ball valve (V2) on the pump delivery line does not permit easy adjustment of the feed flow and a 50 mm gate valve would be better suited for this duty. During backwash, the filter cake and backwash effluent flow out of a 50 mm brass gate valve (V4) that is fitted to the bottom of the filter module. This valve is normally closed during filtration.
- For isolation of the feed tank from the rest of the system, a 50 mm PVC ball valve (not shown in Figure 8.1) is fitted to the suction line.

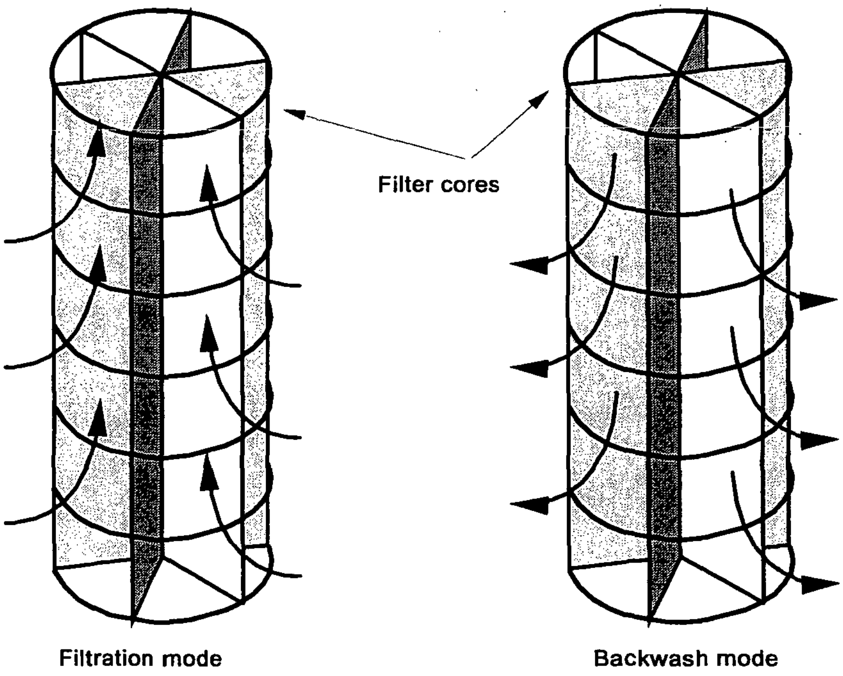


Figure 8.2 : Permeate flow in filter cores during filtration and backwash

Filter Unit ; The filter unit consists of a cylindrical steel filter housing in which filter septa are suspended from a manifold plate. The septa are held in place by a pressure plate and sealed with rubber "O" rings. The septa are arranged in a triangular pattern to maximise spacing between elements and avoid bridging. Each septum has six longitudinal ribs extending radially from the axis with horizontal circular bracing bands (see **Figure 8.2**). They are covered by monofilament polyethylene bags, although polypropylene bags can also be used.

Tanks ; A 2 m^3 GRP header tank was used for buffer storage between the raw water supply and the feed pump. The tank was fitted with a float valve to regulate raw water flow into the tank.

Feed Pump ; A 1,5 kW Lowara centrifugal pump with stainless steel volute casing was used to supply the filter with raw water. The pump uses a conventional 220 V, 16 A domestic power source.

8.2 Process Control System

The filter was operated at a given start-up flowrate during the evaluation. The subsequent development of filter headloss and the accompanying flowrate decline was monitored as the run progressed. A terminal headloss of 150 kPa was generally used as the criterion for initiating a backwash cycle. The flowrate was monitored by an inductive flowmeter and adjusted by means of a valve (V2) on the pump discharge line. Other control philosophies that may be used for DE filters include constant head (declining rate) filtration and fixed run-time filtration.

8.2.1 Operation and Control Sequence

The unit is operated by switching the feed pump on or off. Backwashing is a manual task initiated by the operator. The plant has four operating modes; filtration, quiescent, backwash and precoat.

Filtration mode : In filtration mode , valves V1, V2 and V3 (see **Figure 8.1**) are set in the "filtration" position as denoted by the stickers on the valves. All other valves are closed. During filtration, cake growth occurs on the outside of the filter bags until the pressure reaches a point at which the operator decides to backwash the filter. No pressure alarms are fitted.

Quiescent mode : In quiescent mode all valves are set as for the filtration mode but the pump does not run. This may occur as a result of pump failure or when the unit is switched off.

In this mode, the filter cake and precoat may fall from the filter bags to settle on the bottom of the filter vessel. When the pump is restarted, the turbulence caused by the incoming flow mixes up the settled solids and deposits them on the filter bags. Because some mixing will have taken place between the precoat DE and the filtered material, the cake characteristics may differ from those of the original precoat. While the cake is being re-established, the filtrate quality will be poor and should be *discarded. In order to achieve the best filtrate quality, filter runs should be uninterrupted if possible.*

Backwash Mode : Once the filter inlet pressure reaches a predetermined value, the backwashing sequence is initiated. The manual operations of backwashing include switching off the feed pump, draining the filter unit and adjusting the filter valves to reverse the direction of flow. During backwashing, the pressure drop is reversed and the bags are 'inflated' away from the septa. This movement of the bag in addition to the reversed flow dislodges the cake from the bags. It is then flushed out of the tank through the backwash outlet. In order to remove all the cake it may be necessary to backwash the filter several times.

Precoat Mode : Precoating must take place at the start of a filter run (that is, after backwashing). In order to conserve water, the precoat tank should be filled with permeate during the previous run, immediately prior to backwashing. Precoating proceeds as follows:

- A predetermined quantity of DE is poured into the precoat tank and mixed into a slurry.
- The pump is started and valve P2 simultaneously opened. The slurry is drawn into the pump suction line and pumped into the filter unit where the DE will be deposited onto the filter bags. Valve P2 must be closed before any air is drawn into the system.

8.2.2 Degree of Automation

The process was entirely manually operated at all times during this evaluation. The potential for automation of this process is limited to pressure switches or pressure alarms (not fitted to the unit as tested). Automation of the backwashing and precoating process would prove difficult and costly on the unit that was evaluated but totally automated DE filtration units have been described in the literature.

8.2.3 Monitoring of Process Parameters

The operator monitors the pressure drop across the filter unit and initiates backwashing at his discretion. In addition, the operator must monitor the permeate quality in order to determine if any filter bags have been damaged. Turbidity monitoring can be simply performed by using comparator slides. Detailed water quality monitoring should be regularly undertaken by technical support staff.

8.2.4 Effectiveness of the Control System

The 'control system' relies on operator vigilance. If used for potable water production it is recommended that a pressure cut-off switch and alarm is fitted to the filter inlet line. This will trip the pump when the pressure exceeds a certain level (say 150 kPa). The pump should not be capable of generating a filter pressure drop greater than 200 kPa. This will reduce the possibility of filter bag damage. A pressure cut-out switch on the pump discharge line will also effectively trip the pump if the operator attempts to manipulate the flow reversal valves while the pump is running.

8.2.5 Uncontrolled parameters which may affect Final Water Quality

No coagulation step is used in this process and this has the following consequences:

- Raw waters with a high proportion of colloidal suspended solids may not be effectively filtered as the colloidal matter will either pass through the filter or clog it (depending on the grade of DE in use). Removal of turbidity from such waters may be ineffective. Clogging of filters by colloidal matter is characterised by rapid, almost exponential headloss development and filter run times can be significantly shortened.
- Raw waters with high suspended solids loads may cause rapid loading of the filter, resulting in shortened operating cycles. This will result in increased DE consumption and reduced water recovery as more water will be used for backwashing.

The grade of DE being used is important. Different grades have different porosities and cake resistances. Celite 545 was recommended by the suppliers for potable water treatment but some raw waters may be more efficiently filtered by other grades. The practice of chemically coating the DE with alum or polymer coagulants during precoat preparation has been described in the literature and typically enhances turbidity removal but reduces run times.

8.2.6 Susceptibility to Demand Fluctuations

The filter should operate continuously during a run. When a filter run is prematurely halted, as would happen if the filter were controlled by the level in a tank, the cake falls from the bags to the bottom of the filter (quiescent mode). Restarting the filter will necessitate cake redeposition and poor permeate quality will occur until the cake has been re-established.

The permeate flowrate should impart a drag force to the precoat/cake layer that will be sufficient to hold the cake in place on the filter bags. This drag force results in the pressure drop across the cake. If the flowrate (and hence drag force) decreases too much or if an uneven distribution of flow occurs in the filter at low flowrates the cake layer may fall from the filter cloth in places. This is more likely to happen at the beginning of a filter run, prior to the deposition of a more resistant cake layer on the precoat. If large demand variations occur and automation becomes essential then the control system should be based on flowrate control. In such applications control of the filter feed flowrate has several advantages:

- The feed flow can be matched to the demand and the reservoir need only have sufficient capacity to meet the demand while backwashing is in progress. A smaller reservoir can therefore be used.
- Average permeate quality will be improved because the filter will operate continuously.
- If the filter unit has capacity in excess of the average demand, throttling will cause the filter to operate at lower pressures thereby reducing bag stress. Energy savings may also be achieved by using pump motor speed control although this is unlikely to be economically feasible for small units.

8.3 Personnel Requirements

8.3.1 Workload Estimation

The operating workload estimate is based on the project staff's experiences during the operation of the plant at the PEF.

Installation and commissioning : The installation of the unit involved connection of the unit to the backwash drain, raw water supply, treated water system and electricity supply. The workload involved will be site specific but installation at the PEF took two days. A fitter and assistant will be required for installation of the filter, tank and pump. An electrician will be required for the electrical connection.

Routine operation : The operator is responsible for routine operation, backwashing, precoating and simple water quality monitoring. Based on operating experience, the rapid headloss development that occurs without body feed (see **Section 8.5.3**) means that the plant cannot be operated without frequent supervision. A plant which operates for 8 hours daily at a flux of 3,6 m^3/h, will require operator supervision for only 2 hours per day. When an installation consists of several DE filter units in parallel, the workload will increase in proportion to the number of units.

Maintenance and Repair : A 2 year service interval was recommended for the DE filter when used for swimming pool filtration. However, in potable water treatment applications where a higher turbidity raw water is treated, more frequent maintenance of pumps in particular will be required due to the more abrasive nature of raw surface waters. It is recommended that a six monthly service interval be used for plants of this type in potable water service. Pumps may require dismantling and repair at a central workshop. Filter bag replacement requires dismantling of the filter unit but is easily performed *in situ*. The maintenance and repair workload is therefore estimated at approximately 6 hours per annum excluding travelling time.

A trained operator will be required for routine operation of this plant. Although a unit consisting of one or two units will not require full-time supervision the filters and disinfectant systems (where used) should be monitored on a daily basis and corrective action taken if necessary. Typical filter runs last up to 8 hours and since there is no automated shut down, the operator must be present at the start and end of each filter run. In addition, the operator will be required for other tasks such as cleaning, ordering of chemicals and water quality monitoring. The operator should be capable of simple trouble shooting such as diagnosing filter bag failures and filter clogging.

More highly skilled technical personnel will be required less frequently. A technical support team from a central organisation (local government or water authority) might have responsibility for a number of package plants in a district. Such a support team will be required for monthly and bi-annual maintenance tasks such as water quality monitoring and machinery maintenance respectively.

8.3.2 Specific Training Requirements

The backwashing and precoating procedures have been described (**Section 8.2**). Operators will require training in these procedures and in simple trouble shooting.

The technical support team will require training in the operation of the plant, performance monitoring, sampling, plant maintenance and repairs. Typically these tasks will include fitting of pump seals, brushes and bearings as well as occasional replacement of filter bags and valve components. A qualified fitter will be suitable but will require additional training in other technical support tasks such as sampling techniques and simple analytical techniques.

8.4 Infrastructure Requirements

Road access : Vehicular access to the site of the installation should be provided. Such access will ease the job of the technical support crew, especially with regard to removal of the pump or filter housing for repairs that cannot be effected on-site.

Power requirements : Each unit uses a centrifugal pump of up to 1,5 kW. The power requirements of additional equipment such as disinfectant dosing pumps and level controllers are negligible. Pumps of this type are widely available in either 380 V, 3-phase or 220 V, single phase form. If the unit is to be installed and operated out of doors, weatherproof cabling and switchgear will be required. In mountainous regions, if raw water can be supplied with a head of about 15 m, a pump may not be necessary.

Raw water provision : See **Section 8.5.1**

Treated water reticulation : This unit typically produces more water than would be consumed by a single supply point (such as a standpipe). To be effective the unit should be connected to a treated water storage reservoir of at least 50 m^3 from which a reticulation system can be supplied.

Sludge disposal : The quantity of DE in the backwash effluent will be significant in relation to the amount of suspended solids removed by filtration Pollution of the raw water source with DE contained in the backwash effluent should be avoided. It is recommended that a sedimentation tank is included in the sludge drainage system. DE settles readily and a relatively small sedimentation tank will suffice. The tank should be designed in such a way as to enable drainage and removal of the settled DE when necessary.

Chemical storage facilities : The diatomaceous earth and disinfectant chemicals require a proper storage facility. A roofed storage facility that is cool and dry is required. Disinfectant containers should be properly sealed.

Weather protection : A roofed enclosure is required for the entire plant to protect the equipment against weathering and rust. The electrical switchgear should also be protected against rain and lightning.

Site establishment : In order to minimise the time required for proper installation, a certain degree of site preparation will be necessary to allow safe and reliable operation of the unit. The following facilities should be constructed on the site prior to installation of the filter unit:

- A reinforced concrete plinth of 1 m x 2,5 m for mounting the filter unit and pump.
- Adequate drainage for backwash effluent.
- Weatherproof storage for diatomaceous earth, disinfectant chemicals and electrical switchgear.
- A covered reservoir for storage of treated water.

During preparation of the site, these facilities should be laid out in such a way that future expansions of the plant capacity (additional filter units) can be achieved with minimum expense.

8.5 Performance of the Treatment System

The filter was operated intermittently from commissioning in March 1993 until November 1993. Subsequently, a second filter of similar type but with an effective filtration area of 3,0 m^2 was installed and operated during March 1994. A total of approximately 210 m^3 of permeate was produced (excluding backwash and precoat water) in 14 separate filter runs during these operating periods. Runs 1 to 8 were performed with the 2,0 m^2 filter and produced about 85 % of the total volume of permeate.

Two grades of DE were used; Celite 545 and Celite Supercel Hiflo. These two grades have a median particle size of 36,2 μm and 22,3 μm and median pore size of 17 μm and 7 μm respectively. No significant differences in pressure drop or turbidity removal were noted. The filter units were typically precoated with 1 kg/m^2 of precoat and the flowrate during precoating was kept at approximately 7 m^3/h (equivalent to 3,5 m^3/m^2h for the 2,0 m^2 filter).

During the initial commissioning run (Run 1) the filter was operated with an initial flowrate of 15 m^3/h and the pressure built up rapidly, exceeding 200 kPa within 15 minutes of operation. The pump was switched off and restarted in order to break up and redeposit the precoat (a technique called 'bumping'). The starting pressures of the second and third 'bumps' or stages were successively higher. During the third stage, the filter pressure exceeded 200 kPa within 1 minute from a starting pressure of 75 kPa. Operation at the flowrate recommended for swimming pool duty was therefore clearly not suitable for raw water filtration and all subsequent runs were performed with flowrates less than 3,0 m^3/h.

8.5.1 Raw Water Supply

Head / Flowrate : The recommended maximum operating pressure of the unit is 200 kPa. If the raw water source is located below the level of the filter unit, then the additional head and friction losses should be taken into account when selecting a pump for the installation.

Screening : Screening of coarse material will be necessary to avoid damage to the pump and filter bags. The use of a strainer with a 2 mm mesh on the raw water intake is recommended.

Storage / Reservoir Capacity : Raw water buffer storage is unnecessary if the source is able to supply the peak raw water demand (up to 15 m^3/h during backwashing).

Quality of Raw Water : The raw water turbidity varied between 8 and 700 NTU during the evaluation.

8.5.2 Micro-organism Removal

The unit was not fitted with a disinfection system. Relatively poor turbidity removal occurred and stable operation was difficult to achieve (see **Section 8.5.3**). For this reason, no evaluation of the microbiological removal with DE filtration alone was made. Appropriate dosing systems for disinfection include:

- Sodium hypochlorite solution dosed by means of a dosing pump. The pump should be self priming and control should be based on the treated water flowrate. pH control may be necessary for effective disinfection with chlorine based systems. Dilution of the stock solution and periodic calibration of the dosing pumps will be necessary. Additional operator training will be required.
- Calcium hypochlorite dosing of the treated water storage reservoir. A number of proprietary systems for dosing calcium hypochlorite are available.
- Chlorine gas may become an economical alternative in larger installations. Gaseous chlorine dosing systems require additional safety measures and training of operators.
- Ultra-violet (UV) systems are reliable, simple to operate and can be more economical than chlorination. However, UV systems do not leave a residual in the treated water, and sometimes provide inadequate disinfection especially when transmittance of the water is poor. In these situations the water is susceptible to recontamination and regrowth. UV disinfection should be avoided if factors that enhance regrowth (such as high nutrient levels, long reservoir residence times and exposure to light) are present.

8.5.3 Turbidity and Suspended Solids Removal

Raw water turbidity was less than 40 NTU in 82 % of the samples but ranged from 8 NTU to 700 NTU. **Figure 8.3** shows the corresponding raw and filtered water turbidities obtained in all filter runs performed during the evaluation. It can be seen that the 3,0 m^2 filter was generally less effective for turbidity removal than the 2,0 m^2 unit.

The relationship between raw and filtered water turbidity is shown in **Figure 8.4**. The filtered water turbidity was less than 5 NTU in only 48 % of samples and ranged from 1,01 NTU to 470 NTU. It can be seen that filtered water turbidities less than 1 NTU were not achieved and that the filtered water turbidity is relatively sensitive to raw water turbidities up to approximately 30 NTU. The Dept. of Health's 1994 draft guidelines for potable water quality recommend turbidities less than 1 NTU for potable water with 5 NTU as the maximum limit above which a significant threat to health may exist. Filtration of raw waters with turbidity greater than 50 NTU with these filters as operated during the evaluation is therefore not recommended.

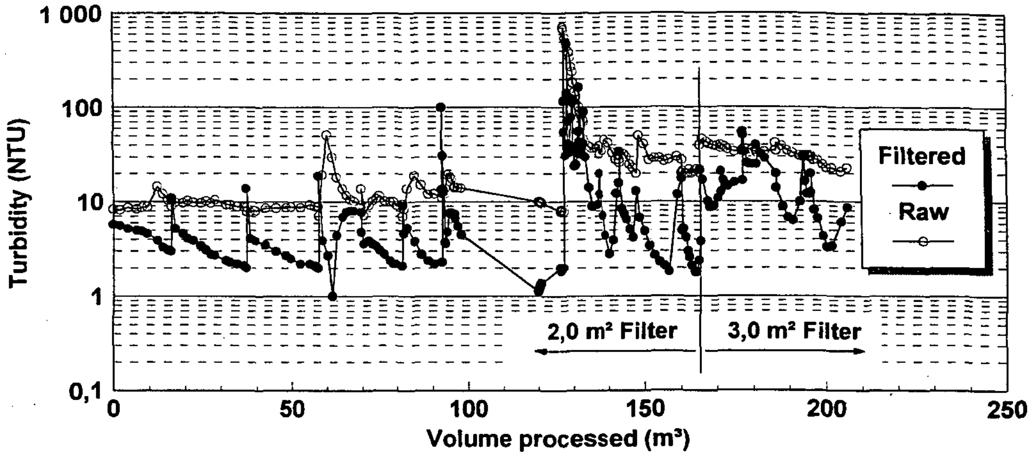


Figure 8.3 : Turbidity removal

The use of limestone (an alternative, cheaper, filter medium) was evaluated in Run 4 (see peak between 92 and 96 m^3 in **Figure 8.3**). Kulu 15 limestone with a median particle size of 15 μm was used. The permeate remained 'milky' for 15 minutes after precoating, indicating persistent loss of the precoat into the permeate possibly as a result of pinholes in the filter bags. Turbidity removal was less effective with the limestone precoat than was achieved with DE in the preceding and subsequent runs (Runs 3 and 5 respectively). Limestone precoating media as small as 2 μm has been used successfully in cross-flow microfiltration using woven tubes for support.

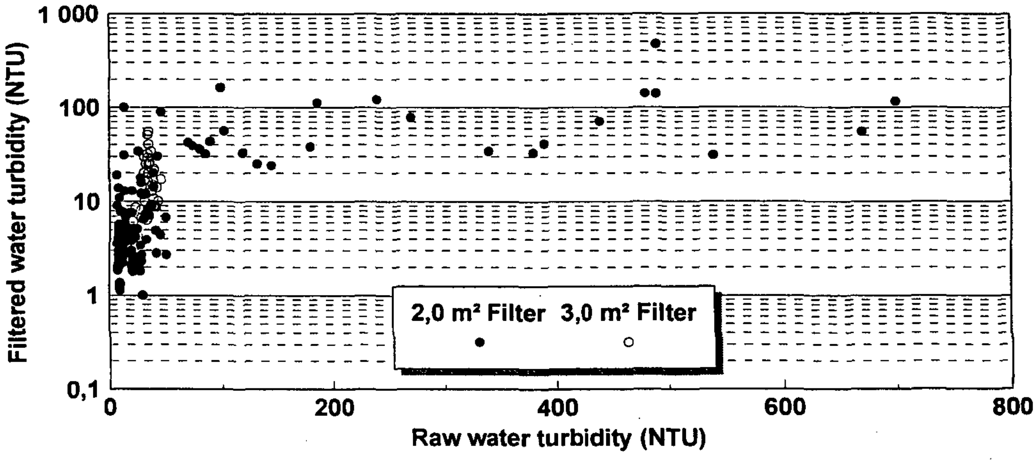


Figure 8.4 : Relationship between raw and filtered water turbidity

The effect of pressure drop on filtered water turbidity is shown in **Figure 8.5**. This shows that while high turbidity permeates can occur at any pressure, operation with pressure drops in excess of 50 kPa always yielded permeate turbidities higher than 1 NTU. The line on the graph represents the minimum permeate turbidity that was achieved for pressure drops between 50 and 200 kPa. These results indicate that a terminal headloss of 50 kPa should be used with this filter system as evaluated.

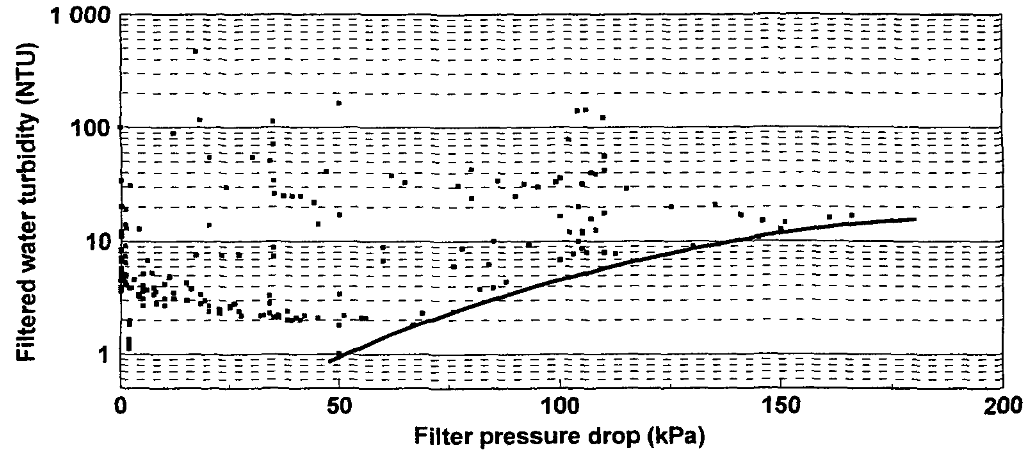


Figure 8.5 : Effect of pressure drop on turbidity removal

The variation in pressure drop and flowrate with permeate volume is shown in **Figure 8.6** for Run 2. It can be seen that the pressure drop develops exponentially, especially in stages 1 and 2. This type of headloss development is typical of:

- precoat filtration where the precoat becomes clogged by the suspended matter in the feed.
- body feed filtration where excessive body feed is added.

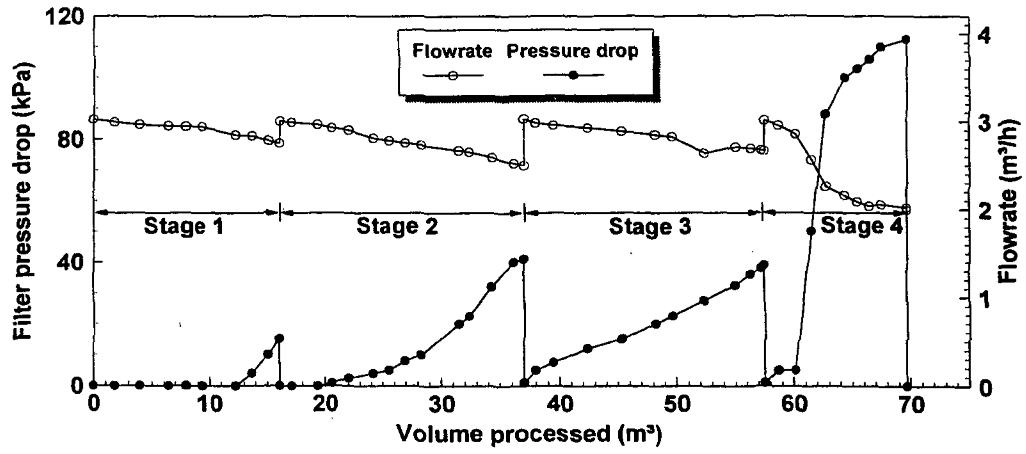


Figure 8.6 : Pressure drop and flowrate variations during Run 2

Backwashing typically required less than 0,4 m^3 of water. During the evaluation, backwashing was performed with feed (raw) water as would occur in swimming pool systems. This can lead to clogging of the filter cloth and is not recommended for raw water treatment systems.

Precoating also involved the loss of water from the process. Attempts were made at precoating in the total recycle mode where all permeate is returned to the precoat tank until acceptable clarity is achieved. This was not practical for several reasons:

- The valves on the precoat system limited the circulation rate during precoating. This caused cavitation in the pump and possibly poor precoating due to DE settling in the filter vessel.

- The 20 ℓ precoat tank was too small.. Manville (suppliers of Celite filter media) recommend that precoat tanks should be larger than the filter vessel by a factor of 1,2. This would require a precoat vessel of approximately 160 ℓ for the filter that was evaluated.

As a result, precoating had to be performed on-line while pumping raw water into the filter. The resulting permeate was of poor quality and had to be discarded until the permeate clarity improved. Much of the turbidity in the discarded permeate was due to DE that had passed through the filter and was lost from the system.

Although DE filters currently operate successfully in numerous large swimming pool and resort complexes in South Africa it has been shown that the turbidity removal achieved with this unit at the PEF was inadequate for the production of potable water. Nonetheless, DE filtration of surface waters for potable water production is successfully practised, especially in the USA, and is widely reported in the literature. Several reasons for the comparatively poor performance of the filter are suggested as follows:

- **Fabric weave separation at higher pressures :** While investigating the causes of turbidity breakthrough at higher operating pressures, separation of the cloth weave was observed at the seams where the stitches perforated the filter cloth. The resultant 'pinholes' were up to 0,5 mm in diameter; sufficiently large to prevent bridging by the DE media. New bags were fitted but there was no improvement in performance and the same weave separation effect was observed with the new bags. Turbidity breakthrough was observed in every run at pressures between 70 and 90 kPa, significantly below the recommended maximum operating pressure of 200 kPa. The use of seamless bags or a different seam construction may alleviate this problem but was not investigated.
- **Precoat filtration without body feed :** The use of body feed (continuous addition of a small dose of DE to feed water during filtration) is universally recommended in the literature for the production of potable water from surface water sources containing colloidal suspended solids. Body feeding was simulated during runs 12 and 13 by manually adding small amounts of DE to the feed tank during filtration. After commencing with manual body feeding the pressure drop decreased slightly but the permeate turbidity increased significantly during both runs. The turbidity increase was possibly a result of weave separation in the filter cloth.
- **Operating parameters :** In swimming pool applications, the feed water is of low turbidity (usually < 1 NTU) and the pool volume is recycled (turned over) every 4 to 8 hours. Even though the turbidity of water entering the filter may be very high during cleaning of the pool, this turbidity represents settled (coarse) particles rather than suspended (colloidal) solids. The coarse matter is more easily removed by the filter and its accumulation on the precoat layer results in a filter cake with less flow resistance than a cake of colloidal matter. These factors permit the effective operation of pool filters at higher rates than can be used for potable water production. **Table 8.3** provides a comparison of the filtration parameters recommended for swimming pool

filtration and parameters quoted in the literature for treatment of raw surface waters for potable water production. Operating parameters which differ markedly are shaded in the table.

Table 8.3 :

Parameter	Units	Swimming pool filtration	Potable water production*
Precoat density	kg/m^2	1 - 2	1 - 2
Pre-coating rate	m^3/m^{2}h	3,5	2,4 - 4,8
Filtration rate	m^3/m^{2}h	6 - 7,5	1,2 - 5
Terminal head loss	kPa	150	60 - 300**
DE media type	-	Celite 545, Supercel Hiflo	Similar grades
Body-feed rate	mg DE/mg SS	none	1 - 10

* American Water Works Association, *Water Quality and Treatment*, 4 ed, Mc Graw Hill, 1990 and several AWWA Journal articles on DE filtration.

** Includes filters using wire mesh support that can operate at higher differential pressures.

8.5.4 Chemical Requirements

Filtration media requirements : Based on operation of the filter unit at the PEF, 33 kg of DE were used for the production of 210 m^3 of permeate at an average media consumption of 157 g/m^3. The use of body feed at appropriate doses would allow longer filter runs at a higher average flux for any given pressure drop. An overall reduction in DE consumption can be achieved in this way.

Dosing of diatomaceous earth for precoating purposes is simple (see **Section 8.2**). If diatomaceous earth is supplied in bulk, then a measuring container will be required so that the operator can add the correct amount of powder during precoating. If a body feed system is fitted, a dosing system and stirred slurry tank will be required.

The DE media should be stored in a dry place and sufficient stocks for 1 month's operation should be kept. The DE media is inert and stable.

8.6 Plant Life and Reliability

8.6.1 Materials of construction

The mild steel filter housing and internal plates are epoxy bitumen coated for corrosion and abrasion resistance. A range of different coatings may be specified for various duties and the housings can be galvanised prior to coating. Stainless steel filter vessels are available for industrial applications and these may be more suitable for use with acidic raw waters. The exterior of the filter vessel is coated with enamel paint which will require an annual touch-up.

Brass valves are used for control of the precoating system and backwash outlet and are fitted directly to the filter vessel. All other external pipework is PVC. The filter's construction is robust and no significant corrosion problems can be expected as a result of normal usage.

8.6.2 Reliability

Plant and Equipment : The components of this process that are most likely to fail are the filter bags (see **Section 8.5.3**). High filtration pressures place unnecessary strain on the bag seams, resulting in pinholes which allow DE media and turbidity to pass through the filter and contaminate the permeate. The primary elements of control for this unit are the valves. PVC ball valves and brass stopcocks have been used and are unlikely to fail in normal use. No other equipment failures were experienced with the filter but the possible consequences of various equipment failures are summarised in **Table 8.4**.

Table 8.4 : Consequences of filter component failures

Component	Direct Consequence of failure	Effect on water quality
Feed pump	Flow to filter unit will cease. Filter cake may settle to the bottom of the filter unit.	Potable water production will cease.
Pressure gauge	Operator will be unable to measure filter pressure drop. Filter bag damage may occur	Potable water flowrate will decrease as filter pressure drop increases.
Filter bags	Unfiltered water will enter the permeate. Pressure drop may decrease and flowrate may increase.	Permeate turbidity will increase.
"O" rings	Unfiltered water will enter permeate through the pressure plate. Pressure drop may decrease and flowrate may increase.	Permeate turbidity will increase

Control System Components : Flowmeters and pressure indicators should be checked periodically to ensure reliability. Although the flowmeter is located in the treated water line it still requires periodic cleaning against the accumulation of grit. All pressure indicators should preferably be glycerine damped to reduce fluctuations in the needle.

8.6.3 Potential for expansion of Capacity

As a result of the modular design of the unit, capacity can be increased by the installation of additional complete filter units. However, marginal increases in capacity may be obtained by combinations of the following:

- Increase the capacity of the pump in order to increase the flux. This may result in increased operating pressures. It is not advisable to operate the unit way above the recommended settings. Increased operating pressures will place larger stresses on the filter bags and the pressure plate.
- Add diatomaceous earth as body feed during filtration. This will have the effect of reducing the filter cake resistance, increasing flux and extending the duration of filter runs.
- Backwash the filter at lower pressures. By backwashing more often the average pressure drop across the filter will be reduced and the average flux will be higher. It is important to establish the optimum terminal headloss because the increased average flux will be offset by the production of a greater quantity of backwash effluent. Increasing permeate production in this way will result in increased DE costs because the permeate yield per unit mass of DE used will decrease.

8.7 Servicing, Maintenance and Repair

Raw water pump : An annual check on the condition of the pump motor and the main shaft seal is necessary. The seal can be replaced *in situ* but repairs to the pump motor will require its removal and transport to a properly equipped workshop.

Dosing pumps : A dosing pump will be necessary should final water disinfection be included in the installation. Dosing valves should be periodically washed in water to prevent blockages due to the accumulation of suspended particulate matter. The pump diaphragms will require replacements over the long term. Therefore a trained maintenance technician should visit the site at least once in 6 months or whenever emergency repairs are required.

Valves and fittings : All valves should be checked annually for wear, especially those in the inlet stream which may be exposed to abrasive precoat and raw water particles. Replacement of teflon seals should be performed if they are damaged during disconnection of pipe fittings. Blockages that develop in the valves and fittings due to accumulation of precoat and raw water solids will also require removal.

Electrical switchgear : Electrical switchgear should only be checked by a trained electrical technician. At this stage only the pump contains electrical switchgear. During the course of the evaluation electrical failures of the pump did not occur.

Operator Maintenance Tasks : The operator should be responsible for:

- Weekly cleaning of the plant.
- Weekly monitoring of diatomaceous earth stocks according to specified inventory levels.

Servicing and Repair Tasks : Skilled personnel are required for maintenance of the pump and filter housing. The following checks, with corrective action, should be made on an annual basis:

- Check the operation of the feed pump and filter unit.
- Check the condition of the filter vessel, all valves, filter bags, O rings and seals; replacing or repairing components where necessary.
- Electrical system checks.
- Pipework system checks and repair of any leaks.

8.8 Transportation, Installation and Commissioning

8.8.1 Transportation

The filter is compact and an installation consisting of filter housing, pump, associated electrical cabling and pipework can be dismantled into individual components and transported in a light delivery vehicle. The individual components can be carried by hand but two people would be required to carry the filter housing. Transport of tanks may require a larger vehicle depending on the tank size.

8.8.2 Installation

Provided that the site has been prepared as described in **Section 8.4.2**, installation of the unit is simple. The use of PVC pipe with solvent welded fittings allows quick installation although 24 hours are needed for the solvent welded joints to set to full strength. Pipe unions should be included at appropriate points to facilitate dismantling and reassembly. Installation of the unit at the Process Evaluation Facility took about two days.

8.8.3 Commissioning

Commissioning of the unit installed at the PEF took about an hour. In a rural application this would take longer, especially if a reservoir level control system is used. A potable water treatment unit would also incorporate a disinfection system which would require calibration and adjustment.

Optimisation of the unit after commissioning involves analysis of raw and treated water from the site and monitoring of filter fluxes and run times. As raw water quality will vary from place to place and season to season, it is possible that different grades of DE or different DE dosing strategies will be required to optimise operation of the plant. Optimisation of the plant in this way is part of the commissioning process and should not be left to the operator.

8.9 Costs

8.9.1 Capital cost

The capital cost of this installation in 1993 was approximately R9 200,00 The component costs are summarised in **Table 8.5**.

Table 8.5 : Capital cost

Description of item	Capital cost (Rands 1993)
Filter Unit	5000,00
Centrifugal pump	2200,00
GRP Buffer tank (2,0 m^3)	1600,00
Associated pipework	400,00
Total	9200,00

* These costs do not include the capital cost of site preparation, treated water storage, the disinfection system and reticulation facilities.

8.9.2 Operating cost

The components of the operating cost include chemical, power, maintenance and labour costs. These costs have been individually estimated for the filter based on operating data obtained during the evaluation and are summarised in **Table 8.6**.

Table 8.6 : Operating costs

Component cost	Estimated specific cost (R/m^3)
DE media and chemicals	0,67
Electrical power	0,07
Labour	0,58
Maintenance and repair	0,04
Estimated Total	**1,36**

Chemical costs : The cost of DE media was approximately R 4,00 /kg in 1993 and the DE consumption rate during the evaluations was 157 g/m^3. The media cost is therefore approximately R 0,63 /m^3. The cost of sodium hypochlorite dosing for disinfection purposes is typically less than R 0,04 /m^3. The total cost of treatment chemicals should therefore not exceed R 0,67 /m^3.

The use of body feed should significantly increase the permeate yield thereby reducing the chemical operating cost.

Cost of power : At a cost of approximately R 0,2643 /kWh for electrical power, the estimated electrical cost of operating the filter during the evaluation was based on a 1,5 kW pump producing a flowrate through the filter of 2-3 m^3/h . This is an unrealistic estimate because the pump was selected for operating parameters of 12 m^3/h at 200 kPa which resulted in the pump being overspecified for this unit. Based on actual operating fluxes and pressures experienced during the evaluation, a pump of approximately 0,6 kW would have been suitable and the operating cost would have been approximately R 0,07 /m^3.

The use of body feed to increase permeate yield and reduce operating pressure would result in lower specific energy costs.

Labour cost : The cost of operating labour is based on a rate of R 7,00 /hour. If the operator works for 2 hours per day on a plant which operates for 8 hours daily at a flowrate of 3,0 m^3/h, the cost will be approximately R 0,58 /m^3.

Maintenance costs : The cost of skilled maintenance work will be limited to annual servicing and occasional filter bag replacement. The frequency of filter bag changes was not determined. The cost of a routine service will depend on the extent of the repairs but should not exceed R400,00 (excluding travelling time). This will cost R 0,045 /m^3 for a filter that operates for 8 hours daily at a flux of 1,5 m^3/m^{2}h.

9 EXPLOCHEM WATER TREATMENT (Pty) Ltd
Crossflow microfiltration unit

9.1 Introduction to the Crossflow microfiltration (CFMF) unit

The Crossflow microfiltration unit has been under development as part of a Water Research Commission project (WRC project K5/386). The University of Natal (Durban) and Umgeni Water have been involved in the design and operation of a prototype unit and Explochem Water Treatment (Pty) Ltd market the technology. The contact person is Mr K Treffry-Goatley. The telephone number is 031-764 6792 and the fax number is 031-764 6799.

The plants are of modular design and can be custom sized and built to suit the client's needs.

9.1.1 Plant Design Philosophy

The plant under evaluation was designed around filter modules consisting of two filter curtains per module. Each curtain consists of 70 parallel woven tubes 12 mm in diameter. The fully automated plant requires minimal operator control and is intended for application in rural and peri-urban areas. The filtration technology uses a precoat system and provides a reliable water treatment facility requiring low maintenance. Apart from precoating, no additional chemicals are required.

The CFMF unit is larger than the other package plants that were evaluated and would supply a larger community. The technology uses relatively large pumps and would require an adequate power supply. The energy consumption is approximately 2,5 kWh/m^3. Few mechanical connections to pumps and storage tanks would be required during installation.

9.1.2 General Description of the Plant

The plant comprises a feed water tank and a permeate tank. Water is cycled through the cross-flow microfilter back to the feed tank. The filtered permeate is collected in a trough under the filter module and pumped to the permeate tank (see **Figure 9.1**). A filter module comprises two curtains. The flow is directed longitudinally though the tubes of the curtain. The inherent pressure causing flow through the tubes creates a pressure difference across the tube material (filtration medium) resulting in a radial filtration.

The reject water passes through the curtain and is returned to the feed tank. This mode of operation is a batch / recycle type operation. A dead end filtration mode has been considered and would apply to raw water with lower turbidities. Each filter module contains two curtains which together give a filtration area of 40 m^2. A limestone precoat was used to increase the filtration flux and improve the operation of the plant.

The Exxflow plant was tested in a semi batch mode. The precoating, filtration and washing cycles are automated by a Programmable Logic Controller (PLC). The tube velocity is designed to be 2 m/s under an operating pressure of 400 kPa which creates an average permeate flux of 100 ℓ/m²h.

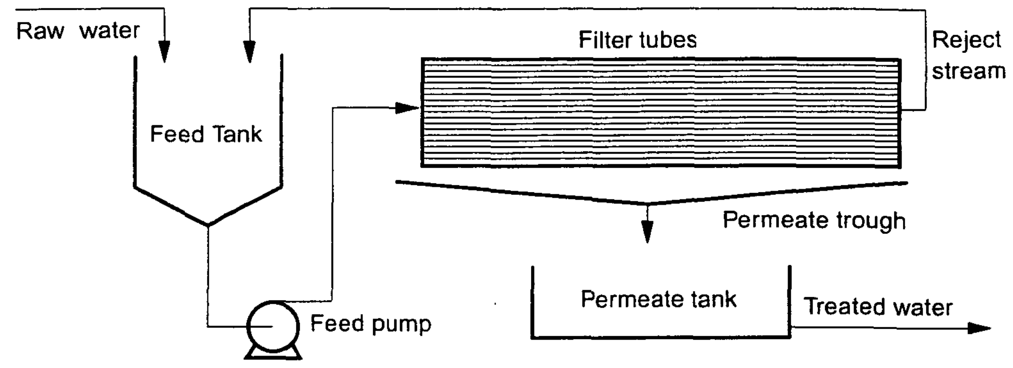


Figure 9.1 : Cross-flow microfilter process flow diagram

9.1.3 Process Sophistication

The Exxflow process is relatively sophisticated in comparison with most package plants and incorporates recent cross-flow filtration technology. The physical separation of particulate and colloidal matter in this membrane process requires no addition of chemicals, but a high degree of automation and control. In comparison to many package plants the Exxflow process is complex, but the use of PLC control is justified by the reduced operator input that is required.

Table 9.1 : Component list

Component	Quantity	Comments
Valves	>25	Ball valves for isolating lines, tanks and filter curtains Pneumatically operated control valves Electrically operated control valves
Pump	5	1 x Centrifugal feed pump - 37 kW - 380 V 1 x Centrifugal permeate recycle pump - 3 kW - 380 V 1 x Centrifugal permeate distribution pump - 4 kW - 380 V 1 x Spray mono pump - 18,5 kW - 380 V 1 x Dosing mono pump - 5,5 kW - 380 V
Filter modules	2	Each module contains 2 polyester curtains, 70 tubes of 12 mm diameter.
Tanks	2	1 x 5 cubic metre feed tank 1 x 5 cubic metre clean water tank
Dosing apparatus	1	A limestone dosing tank and dosing mono pump
Control unit	1	PLC, 32 digital inputs and 40 relay outputs

Table 9.1 gives a list of the number and type of process components. All components are locally manufactured or supplied. The high degree of automation and the large mechanical equipment required

suggest a large capital expense. On the basis of 25 ℓ per person per day a plant of this size could supply a community of over 3000 people.

There are a large number of pneumatically and electrically operated solenoid valves which control the flow through the plant. The valves and fittings are PVC welded and cannot be rapidly dismantled should the plant have to be moved. The plant would however be manufactured and assembled at a factory or workshop, and delivered whole in parts to site where final installation and commissioning would take place.

9.2 Process control system

The control system makes use of PLC to control the batch operation of the plant. In filtration processes it is common to control the process on either the filter pressure drop or filtration rate, but in this case the PLC operates on a time basis. The cycles are pre-set on timers within the PLC which controls the plant by pneumatic or electrically driven control valves.

9.2.1 Operation and Control Sequence

The process comprises four steps :

Precoating of the curtain : The raw water feed tank is filled with 5 m^3 of water. A limestone slurry is mixed in a separate vessel and added to the feed tank. At this point the filtration is started and the limestone is deposited on the inside of the curtain material. The amount of precoating required is approximately 50 g/m^2. The permeate and rejected streams are recycled to the feed tank until all the limestone has been deposited.

Filtration of Raw Water : Once the precoating is complete the permeate is directed to the final water (permeate tank). It is important that the pressure in the tubes of the curtain is not released as the precoat may dislodge and filtration will be affected. As the raw water is filtered, the level in the feed tank is maintained by a level probe which automates the opening of the raw water valve. In situations where the water supply is below the level of the plant an additional pump will be required to maintain the supply of water.

As filtration occurs through the curtain, the rejected matter builds up on the inside of the tubes. The velocity of the water through the tubes however, performs a scouring role and prevents the filtered material from building up to such an extent that the tubes become blocked. This is the principle of 'Crossflow'. The thickness of the rejected layer on the tubes also causes a reduction in the filtration rate as the resistance and permeability increase, leading to a decrease in the filter flux. The scouring effect subsequently also helps to maintain a more constant flux which increases the run cycle time and the water recovery of the plant.

Cleaning / Wash Cycle : Five cubic metres of clean water (permeate) are used to clean both filter modules. Clean water is pumped through the tubes at a pressure of 50 kPa (gauge). The filter cake and precoat is sheared off the inside walls of the tubes by the high velocity of water through the tubes, and the reject is discarded. At the same time clean water is also sprayed onto the outsides of each curtain at a high pressure of 2500 kPa (gauge). This water spray has a backwashing and pinching effect on the curtain where the cake is dislodged and washed out in the direction of the cleaning water. This cleaning cycle lasted for 5 minutes during the test phase. During this cycle the feed tank is emptied, thus purging the system of all suspended matter which was separated during the filtration cycle.

Alternative cleaning systems include the brush cleaners employed by Renovex and a "squeegee" rod system proposed by the Pollution Research Group (University of Natal). The rod system will be implemented and assessed during future developmental phases.

9.2.2 Degree of Automation

The plant is fully automated. The limestone has to be added as a powder and mixed into a slurry in the precoat tank before being added to the feed tank. Future inclusions in the design of the plant will include a dedicated precoat tank which is separated from the feed tank. This will also be controlled by the PLC and reduce the amount of operator input even further.

The pressure and flowrates through the plant are controlled generally by the sizes of the pumps. The flowrates are regulated and pre-set during commissioning after which they need to be monitored on a regular basis. The operation of the plant is based on timer settings which dictate the plant capacity.

9.2.3 Monitoring of Process Parameters

The turbidity and microbiological monitoring of process parameters is required on a regular basis. The number of samples required is determined by the number of people the plant serves, and the determinands for analysis are detailed by the Department of Health Draft Guidelines 1994, for potable water. During the evaluation and testing at the Process Evaluation Facility, **Table 9.2** shows the parameters that were monitored and how the measurements were made.

Table 9.2 : Monitoring of operating parameters

Parameter	Measurement
Raw Water Turbidity Permeate Turbidity	Hach ratio laboratory turbidity meter.
Inlet Pressure Outlet Pressure	0 - 800 kPa pressure gauges installed on the plant
Flowrate	A water meter measures a total flow. This was read regularly and permeate fluxes were calculated.
Cycle time	This is measured and controlled by PLC.

The operator would have to monitor the production of water and basic operating parameters including turbidity, pressure, daily flowrate as well as report any operational problems. A basic technical understanding would be required to assess the performance of a sophisticated plant.

9.2.4 Effectiveness of Control System

The control system is effective in that minimum operator supervision is required. The plant manages to produce high quality of potable water by controlling the length of the filtration and cleaning cycle time.

9.2.5 Uncontrolled parameters which may affect Final Water Quality

The Exxflow process is relatively insensitive to variations in operating parameters. A physical barrier is formed in the tubes by precoating, which ensures an excellent quality final water. Should the operator not add sufficient precoat or a power failure is experienced, the precoat may become dislodged resulting in a poorer separation and an increase in the final water turbidity for 5 to 10 minutes.

Some problems have been experienced with long term operation of the plant in that the curtain material developed pin holes (caused by grit in the high pressure cleaning water), resulting in ineffective filtration. This should not occur, and can be significantly minimised or eliminated by regular maintenance checks which would include a scrutiny of the condition of the curtains.

9.2.6 Susceptibility to Demand Fluctuations

The plant is operated such that the filtration cannot be stopped and restarted. Once a cycle has begun, a stoppage would initiate a cleaning cycle. Premature stoppages of this nature would drastically reduce the water recovery of the plant.

Should the demand exceed the capacity of the plant, the time cycles for operation would have to be optimised so as to maximise the water production. By decreasing the filtration cycle time, a higher average flux may be possible. In very arid regions this would not be advisable as the water recovery would drop. In such cases additional filter modules would have to be included to meet the required demand.

9.3 Personnel Requirements

The operation of the plant requires very little attention due to the sophisticated control system, but an operator with at least a standard eight certificate (or equivalent) with a technical aptitude will be required to make daily and weekly measurements. A skilled artisan (preferably electrical or mechanical technician) will be required to make periodic checks and be responsible for maintenance and breakdowns.

9.3.1 Workload Estimation

Installation and Commissioning : The plant is constructed in sections and most of the components are assembled in a workshop. Installation involves positioning of the sections of the plant, and connection of tanks and pumps. A connection to the supply of raw water (or positioning of a raw water abstraction pump), and piping to a final water reservoir will also be required. Electrical connection to a substation will also be required. **Table 9.3** shows the staff complement and the estimated time required to accomplish these tasks. The commissioning will include tasks such as water testing and repairing any water leaks, as well as setting up the PLC for operation. The size of the plant and the number of valves and fittings may result in the installation and commissioning phase taking longer than commonly expected for package plants.

Table 9.3 : Description of the workload requirements

Work	Description	Hours	
Installation Commissioning	Assembly of the plant components Connections to raw water, final water Electrical connection and PLC install. Checking for leaks Checking operation of PLC inputs and outputs Training of operators	40	Electrician Operator Supervisor Welder 5 Labourers
Routine Operation	Daily sampling Turbidity and flowrate measurement Make up of precoat slurry	2 per day	Operator
Maintenance and Repair	Pump maintenance, repair of leaks Curtain and PLC checks	4 per month	Technician

Routine Operation : The operator will have to take daily and weekly samples and measure operating parameters such as flowrate, pump operating pressure, feed and permeate turbidity. In the situation where a final water reservoir is used, a disinfection system may be required to ensure that the quality of the permeate conforms to the guidelines of the Department of Health. In such cases the operator would have to check a chlorine dosage and measure chlorine residual.

Maintenance and repair : Large centrifugal pumps and high pressure mono pumps will require regular attention. Additional maintenance tasks include the repair of leaks and checking the curtain for pinholes and blockages.

9.3.2 Specific training requirements

The operator will require training in the following aspects :

- the routine operation of sample measurement and identifying problems.
- maintaining an accurate logbook
- making up of precoat solution
- dismantling and cleaning of spray nozzles.

It is assumed that the maintenance and repair would be performed by a qualified technician. The operating manual would include details as to specific routine maintenance.

9.4 Infrastructure requirements

Road access : Road access is needed during the commissioning and installation phase although specific maintenance tasks, such as pump replacement, may also require access by road. The size of the plant would however be suitable for a larger community, where the infrastructure would be more developed, and road access would be more likely.

Power requirements : A 380 V and 3 phase power supply is required. The power requirement will be between 37 and 50 kW. Should a raw water pump be required the power requirement will have to be substantially increased.

Raw water provision : The raw water could be pumped or fed by gravity to the raw water / feed tank. The control of the flow would then be effected by starting or stopping a pump or by controlling a solenoid valve. If a separate precoat tank is installed, the raw water could be pumped from the river or dam without having to provide a feed tank. The rejected material would then be recycled back to the river or dam (see **Section 9.5.1**).

Treated water reticulation : A tank size suitable for the demand will be required. The tank would have to be accurately sized so as not to reduce the efficiency of the Exxflow process and decrease the water recovery. The Final water storage tank must be covered and some form of post disinfection may be required to ensure final water quality.

Sludge disposal : The recycle flow could be returned to the source, eliminating the need for a raw water tank. The sludge removed from the filter modules during cleaning, however, should be directed to a drying pond. This will have to be considered during the design of the plant.

Chemical storage : A secure, dry enclosure is required for the storage of the limestone. No other chemicals were used, but should final disinfection be included, storage for chlorine or hypochlorite will be required.

Weather protection : A proper enclosure will prolong the life of the plant components and will also improve safety. There is a tendency for algae to grow on the curtains and on the water collection trough, if the plant is situated in the open.

Site establishment : The Exxflow plant requires a stable compacted or reinforced concrete base for support. Sufficient area must be provided for the filter modules and storage tanks.

9.5 Performance of the Treatment system

9.5.1 Raw water supply

Head and flowrate : Raw water was supplied at the Process Evaluation Facility at a pressure of 200 kPa. A solenoid valve was used to control the inflow to the feed tank. Should the raw water source be located below the level of the plant a raw water pump will be required.

Screening : No pre-screening was used during the evaluation. Although problems were not experienced, the degree of automation and the sophistication of the equipment, requires careful attention to ensure that particulate matter does not damage any moving parts. The tubes of the curtains are also narrow and are susceptible to possible blockages. For this reason a pre-screening device should be installed at the abstraction point to prevent leaves and sticks from entering the plant.

Storage / Reservoir capacity : A 5 m^3 tank was used on the plant as a buffer capacity but a larger tank may be used if the consumer foresees interruptions in raw water supply of longer than 1 hour.

9.5.2 Micro-organism Removal

The Exxflow process has been operating at the Process Evaluation Facility since 1992 and has been monitored very closely over a long period of time. The cross-flow microfilter disinfects the water by a physical separation of the microcontaminants. The precoat and filtered solids form a dynamic membrane which reduces the effective pore size of the filter cloth. Although chlorine was used approximately once per week to disinfect the filters, the permeate collection troughs and to prevent algae and bacterial growth, the quality of the permeate was well within the guidelines recommended by the Department of Health. **Table 9.4** shows the extent of microbiological removal. In all the samples submitted for microbiological analysis, no residual chlorine was detected. The samples were taken directly from the filter curtain and may not reflect the quality of the final water from the plant. Opportunity for contamination of the water exists as the permeate falls into an open trough on the prototype unit that is also exposed to wash water during the cleaning cycle.

Table 9.4 : Microbiological removal

Date	Coliforms /100mls		E.Coli /100mls		F. Strep. /100mls		Plate count /ml 37°C		Plate count /ml 22°C	
	Feed	Final	Feed	Final	Feed	Final	Feed	Final	Feed	Final
25/11/93	460	0	440	0	16	0	240	0	2470	0
25/11/93	4980	0	4900	0	80	0	504	0	1000	0
01/11/94	30	0	30	0	16	0	2192	5	4144	7
18/11/94	1616	0	4	0	4	0	260	28	2472	378

It can be noted in **Table 9.4** that one of the samples showed higher Heterotrophic Plate Counts at 37°C and 22°C. Under such circumstances, there is a possibility that microbiological regrowth can occur.

The results indicate excellent disinfection of the feed water and highlight that cross-flow microfiltration has great potential as a complete potable water treatment process. The need for primary disinfection is eliminated although secondary disinfection of the water reticulation system may be required.

9.5.3 Turbidity and Suspended Solids Removal

During the period of evaluation (September 1993 to November 1994) raw water turbidities of between 50 and 200 NTU were successfully treated by the Exxflow process. During the filter cycle, the turbidity in the feed tank rose to between 200 and 600 NTU before cleaning was initiated. Under extreme raw water turbidity conditions, turbidities between 3000 and 4000 NTU were measured. The plant is therefore able to treat a wide range of turbidities without affecting the quality of the final water.

In attempting to optimise the plant, it was operated in semi batch mode with three different conditions of operation viz. raw water only, filter aid and precoat.

Raw water : In this mode no chemicals or powder are added to assist with the filtration. The raw water is pumped directly through the tubes, and the particulates in the water deposit on the filter cloth forming a filter cake. This is commonly ineffective and produces low filtration rates.

Filter aid : Under conditions of filter aid (also termed 'body feed') a limestone solution is added continuously during the filtration cycle. A filter aid is intended to separate close packing particles, thereby decreasing the cake resistance and increasing the permeate flux.

Precoat : In the precoat condition a limestone solution is recirculated for only 30 minutes and then discarded, after which the filtration cycle starts. Precoat layers are often not compressible and create a less resistant filter cake resulting in higher filtration fluxes.

All three of these filtration modes produced a filtered water turbidity below 1 NTU. However, the filter operation with a limestone precoat produced clean water at an higher average flux of 100 ℓ/m^2h. (see **Figure 9.2**).

With raw water only, the final water turbidity required approximately 15 minutes to drop below 1 NTU, which is as a result of a resistant cake being formed on the inside of the filter tubes. With both filter aid and precoat conditions a final water turbidity of below 1 NTU was produced almost immediately. The water recoveries for raw water, filter aid and precoat conditions were 70 %, 80 % and 93 % respectively. The precoating option performed the best but further development work is required.

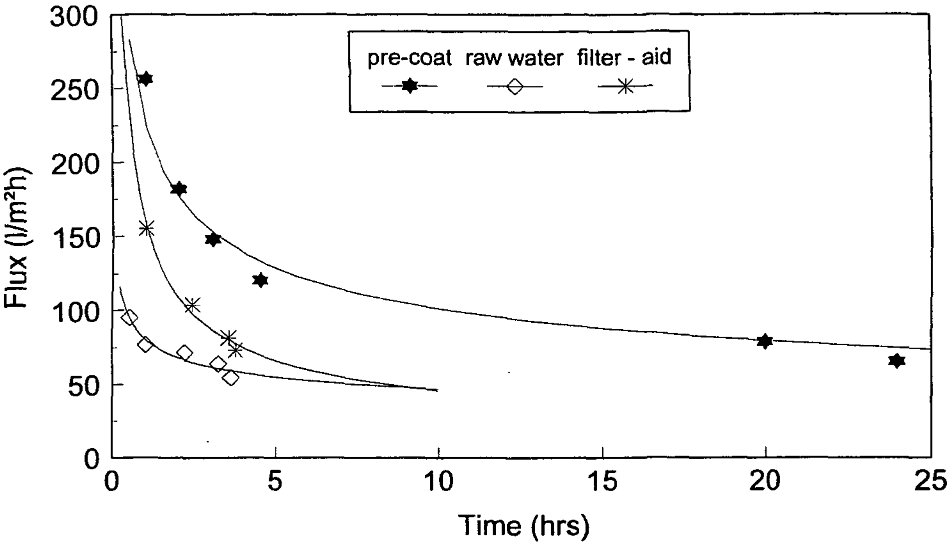


Figure 9.2 : Permeate flux for various operating conditions

Figure 9.3 shows treated water turbidities achieved during the plant evaluation. Pinholes in the curtains, caused by grit in the wash water system, resulted in slightly higher turbidities for a short period of the operation. In addition, the results shown in **Figure 9.3** include turbidities measured shortly after start-up while the filter cake was still being established in the tubes. It can be seen that the treated water turbidity is generally below 1 NTU and usually below 0,2 NTU.

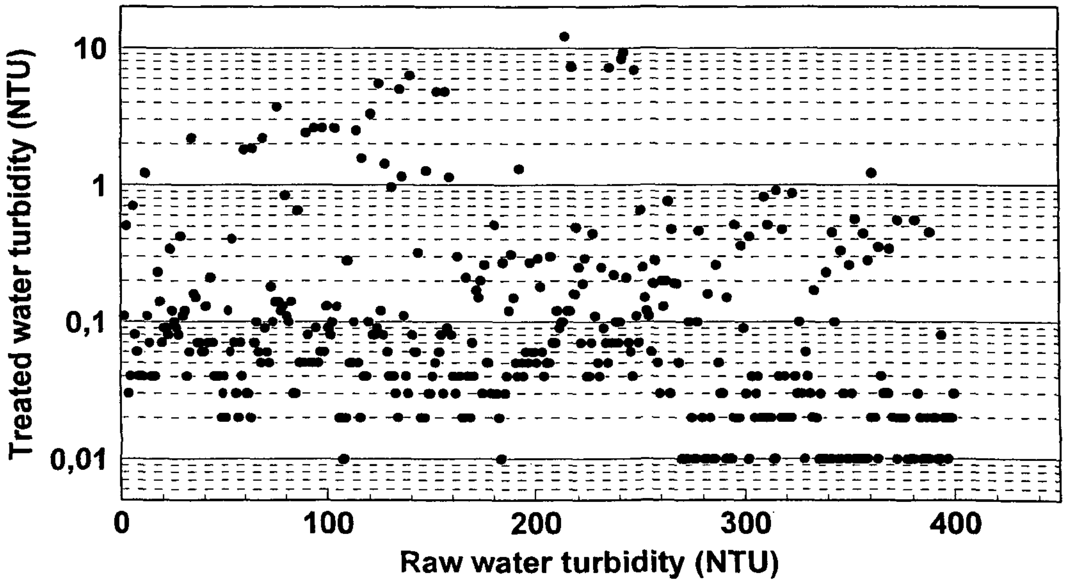


Figure 9.3 : Cross-flow microfilter turbidity removal

9.5.4 Chemical requirements

1,2 kg/m^3 of limestone solution was used for the precoat of each 24 hour run while a 1,4 mg/ℓ solution of chlorine was used for disinfection, once a week.

A one month inventory of chemicals should include 200 kg of limestone and 50 g of HTH for a 192 m^3/day plant. However, the minimum quantity of HTH sold commercially is 2 kg which will last for 1 year and 8 months. (The shelf life of HTH is approximately 3 years).

Minimal preparation of chemicals is required. 6 kg of limestone (95 % $CaCO_3$ and 4 % $MgCO_3$), Kulubrite 5, is emptied into the 5 m^3 feed tank and the contents are recirculated through the process for 30 minutes. Similarly, 10g of HTH (70 % of $Ca(OCl)_2$) is emptied into the feed tank.

9.6 Plant Life and Reliability

It should be borne in mind that, since this is a test plant, problems relating to plant life and reliability can still be improved upon after modifications.

9.6.1 Materials of construction

The mild steel components of the plants, especially those exposed to the process liquids, are prone to long-term galvanic corrosion (especially in a highly automated plant with a large power consumption). Evidence of rust can be seen in parts of the mild steel frame where the galvanised coating has deteriorated. The rusted heads of the mild steel bolts (without galvanised coating) sheared off during attempts to remove them. These were then replaced by stainless steel bolts.

Table 9.5 : Description of major materials of construction

Component	Material	Comment
Filter unit	Mild steel Polyester	Galvanised mild steel was used for the framework The filter curtains were made of polyester.
Pumps	Cast iron	Pumps are painted for corrosion resistance.
Piping	PVC	Corrosion resistant, robust and reliable
Tanks	GRP	Corrosion resistant, robust

The asbestos packing used in the feed pump was also found to be inadequate. Leaks developed in the feed pump were possibly due to the abrasion caused by the limestone slurry on the packing material.

9.6.2 Reliability

Plant and Equipment : During the test phase, the length of time for which the plant ran without supervision was 24 hours. However, depending on the capacity of an automated limestone feed system, the plant can operate without supervision in excess of 1 week.

Plant downtime during the test phase were caused by tube blockages, problems with the spray cleaning system, problems with the manifolds and miscellaneous mechanical and electrical problems. Some of the problems are listed in **Section 9.7** which addresses maintenance and servicing of the equipment. All of these problems were easily solved with the assistance of a technician and the plant operator.

Additional tanks, for provision of standby capacity, to suit the demand requirements could easily be incorporated into both the feed and reticulation system.

9.6.3 Potential for expansion of capacity

Modules in the form of curtains can easily be added to the present frame. The existing pump is large and was originally specified for 4 modules. An increase in the number of filter modules will require an increase in the quantity of limestone. The sizing of the limestone storage and dosing equipment would have to be considered and modified if necessary.

Table 9.6 : Expansion potential of the CFMF

Unit	Expansion Capability
Pump	The existing pump was specified for 4 filter modules. Only two modules were used.
Piping	If more than 4 modules are required then additional pipework is easily added.
Filter	The existing frame can take more than 4 modules
Tanks	Although existing tanks are large enough for 4 modules, additional tanks are easily added.

9.7 Servicing, Maintenance and Repair

Table 9.7 below indicates the main maintenance and repair problems that were experienced with the pilot plant over a three year period. Problems like gasket failure, tube blockages and cleaning of nozzles were attended to by the operator, sometimes with the assistance of an unskilled labourer. Frequent gasket leaks and failures on the manifold end-blocks were eventually solved on the prototype by modifying the end-block design. Occasional mechanical and electrical problems (such as pump repairs and relay switch replacements) were repaired by a trained technician. Curtain replacement was labour intensive and it required about 4 to 5 labourers.

Table 9.7 : Maintenance problems encountered with the Exxflow unit

Frequency of fault occurrence			Comments
Electrical	Mechanical	Maintenance	
1			faulty relay, replaced
	7		gasket failures and leaks, end-blocks modified to improve sealing.
		1	cleaning nozzles serviced, cartridge filters installed on spray water line.
	1		replace module due to damage caused by particulates in spray water

With the benefit of full-scale experience in maintenance and repair problems during the test phase, a proper maintenance, repair and servicing manual will be produced to assist the plant operator. Spare parts are available locally.

9.8 Transportation, Installation and Commissioning

9.8.1 Transportation

It may be difficult to transport the Exxflow plant in its entirety. The framework however can be constructed in sections which are then easily transportable, together with curtains, pumps, tanks etc. to the site for installation. A 3 ton truck should suffice for this transportation.

9.8.2 Installation

The laying of a concrete slab, piping and the actual installation of the plant itself is labour intensive. Local people can be involved in the installation phase, with the aid of supervisory personnel. The plant should be fully operational within a week from the start of installation.

9.8.3 Commissioning

After proper installation, commissioning should involve electrical checking and functioning of the control valves and PLC. Tank filling and pump priming as well as water and pressure testing of the mechanical installation will follow before the plant is operated manually, and then automatically. Sample analysis instruments for an on site laboratory may have to be calibrated. In addition, the filtration and cleaning cycle time should be determined for the raw water supply of the particular rural area.

Commissioning, without optimisation, will take approximately 3 hours. The optimisation of the cycle times may take a week. Nevertheless, potable quality water will still be produced. The operator can be trained on site during the first week of operation.

9.9 Cost

9.9.1 Capital cost

Although the plant operates at approximately 200 m^3/day (2 modules) it was actually designed for 400 m^3/day (4 modules). The capital cost of the CFMF plant with a capacity of 400 m^3/day is approximately R300 000. This translates to a general capital cost of R750 / (m^3/day) for a custom sized plant.

9.9.2 Operating cost

The chemical costs have been based on the present operating flowrate of 8 m3/h whereas the labour, power and maintenance costs are based on an operating flowrate of 16 m^3/h since the pumps and plant were designed to cater for a capacity produced by 4 modules.

The total estimated operating cost of the Exxflow plant is R 0,87/m^3. The breakdown of the cost is shown in **Table 9.8** below.

Table 9.8 : Operating costs for the Exxflow plant

Component cost	Estimated specific cost (R/m^3)
Chemicals	0,02
Electrical power	0,66
Labour	0,04
Maintenance and repair	0,15
Estimated Total	**0,87**

Chemical cost (based on 8 m3/h) : A chlorine disinfectant and a limestone precoat make up the chemical consumption of the Exxflow plant. The cost of limestone is R 0,80 /kg. Precoating once every 24 hours at 50-75 g/m2 (80m^2), results in a cost of limestone at R 0,024 /m^3.

Only 10g per week of a commercial disinfectant (70% $Ca(OCl)_2$ by mass) is used for shock chemical treatment of the curtains and troughs. With the consumption of disinfectant at 0,01 g/m3 of water produced, and the cost of commercial disinfectant at R 10 /kg, the overall cost of disinfection is R 0,0001 /m^3 . This is considered to be negligible.

Cost of power (based on 16 m3/h) : At a power consumption of 2,5 kWh/m^3 at a rate of R 0,2643 /kWh, the energy cost is R0,66/m^3.

Labour cost (based on 16 m3/h) : Based on 2 hour operator input per day at a rate of R 7 /h, the labour cost is R 0,036 /m^3.

Maintenance cost (based on 16 m3/h) : In calculating the maintenance cost an estimate of 5% of the capital cost per annum was assumed for materials. A downtime of 10 % was also assumed which is a worst case estimate. The cost of materials is therefore R 0,12 /m^3.

The amount of skilled labour required to adequately maintain such a sophisticated plant is estimated at 4 hours per month. A labour cost of R 75 /h has been assumed resulting in a cost of R 0,03 /m^3. This would result in a total maintenance cost of R 0,15 /m^3.

10 CSIR Package Water Treatment Plant

10.1 Introduction to the CSIR Package Water Treatment Plant

The Water Technology division (Watertek) of the Council for Scientific and Industrial Research (CSIR) conducts multi-disciplinary research into all facets of water treatment, storage and provision in Southern Africa. The contact person at the Division of Water Technology is:

Dennis Whyte

Telephone : (012) 841 2273
Facsimile : (012) 841 4785

Watertek
CSIR
P.O.Box 395
Pretoria

Packaged water treatment systems for potable water treatment, iron and manganese removal, defluoridation, industrial effluent and domestic effluent are available from the CSIR. A range of conventional water treatment package plants with capacities of 5 m^3/h, 10 m^3/h and 20 m^3/h are available. The 10 m^3/h plant was evaluated.

10.1.1 Plant Design Philosophy

The CSIR identified a need for an affordable, low maintenance, easily transportable water treatment package plant for small communities. This led to the development of a range of containerised water treatment package plants for both potable water production and wastewater treatment.

The CSIR package plants can be customised for particular applications by adding optional modules for the treatment of waters containing high concentrations of iron, manganese, algae, organic colour, fluoride or nitrate. The modules are typically housed in standard 6 m or 12 m shipping containers. The plants can be purchased, hired or leased from the CSIR.

The plant that was evaluated makes use of conventional water treatment technology. The operating workload has been reduced by partially automating the process. The energy consumption has been minimised by using gravity feed for the clarification system and batch operation of the filter and disinfection system. All components used in the construction of the plant are locally manufactured and are locally available in South Africa.

10.1.2 General Description of the Plant

A conventional potable water treatment system is used except that an optional UV disinfection system is also available. The process consists of the following unit operations:

- Fixed rate dosing points for pH correction and coagulant addition.
- Flash mixing and flocculation vessels.
- An inclined tube upflow clarifier.

- Pressure sand filters
- Ultraviolet disinfection system with optional post chlorination dosing point.

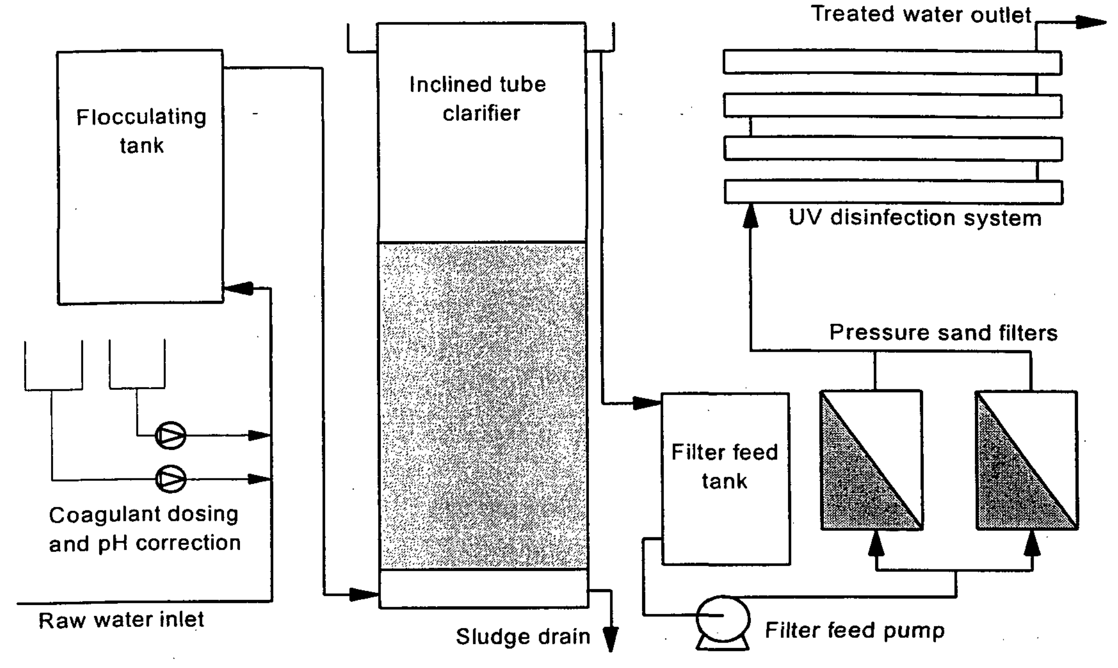


Figure 10.1 : CSIR package plant flowchart

Figure 10.1 shows the process flow diagram for the plant. The flash mixer, flocculator and clarifier operate continuously. The clarified water is discharged into a filter feed tank. The sand filter operates in batch mode, triggered by level probes in the filter feed tank. Initially, the UV disinfection system was similarly controlled but it was subsequently modified (see **Section 10.1.3**). The physical layout of the system is depicted in **Figure 10.2**. Piping details have been omitted for clarity.

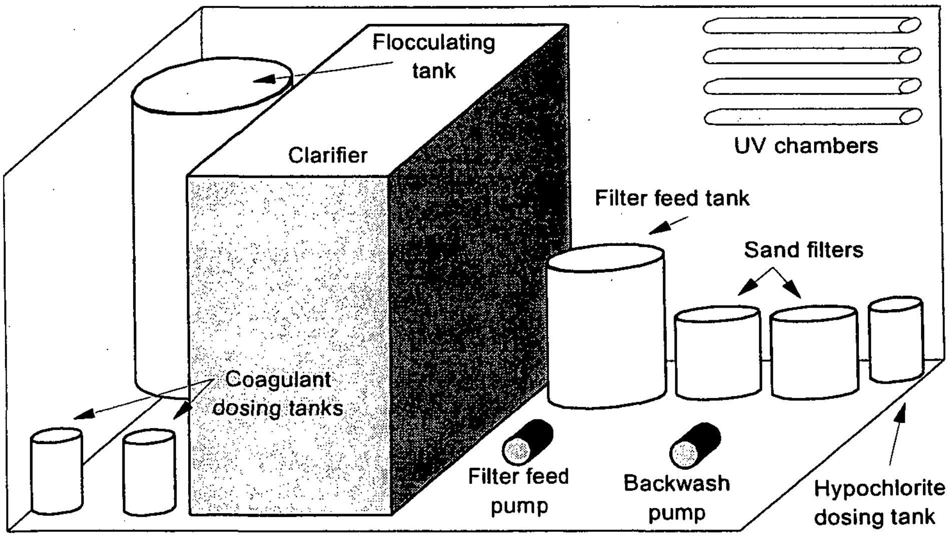


Figure 10.2 : Physical layout of plant

The plant was also fitted with a post-filtration granular activated carbon (GAC) adsorption system for the removal of organic contaminants from the treated water. However, the GAC beds were not used during this evaluation and the GAC module was bypassed.

The plant is designed to operate from a 380 V 3 phase electrical supply and operation of the plant is largely automated (see **Section 10.2.2**). The total power requirement will not exceed 2 kW (excluding raw water feed pumps where used). The maximum working pressure of the unit is approximately 150 kPa in the pressure sand filters.

10.1.3 Process Sophistication

Table 10.1 shows a summary of the components and equipment fitted to the CSIR package plant. The components comprising the GAC treatment system have been excluded.

Table 10.1 : Summary of CSIR Package Plant Components

Component	Quantity	Description
Pumps	2	Filter feed pump, centrifugal, 1,1 kW, 220 V Backwash pump, centrifugal, 0,55 kW, 380 V
Dosing pumps	3	Alldos M201 positive displacement diaphragm pumps, 0 - 5 ℓ/h
Valves	16	1 x 110 mm PVC ball valve (desludging), 2 x 50 mm PVC non-return valves, 2 x multiport valves (sand filters), 2 x 50 mm brass solenoid valves (UV isolation) , 9 x 50 mm PVC ball valves.
Rotameters	1	For measurement of raw water flowrate, PVC, 1 000 - 10 000 ℓ/h
Tanks	5	3 x 0,2 m^3 chemical feed tanks, 1 x 1m^3 flocculating tank, 1 x 0,5 m^3 filter feed tank. All of rotomoulded polyethylene
Clarifier	1	Depth, 1,95 m; Area, 1,88 m^2; upflow through inclined 50 mm tubes
Stirrer	1	Flocculator stirrer, vane impeller, 10 rpm, 0,375 kW, 380 V
UV chambers	4	Willand 75 W modules.
Filters	2	0,44 m^2 pressure sand filters, 0,35 m bed depth.
Electrical panels	3	2 x Willand UV control units with hour meters, 1 x main distribution panel containing all switchgear and circuit breakers.

The clarifier, flocculation vessel and flash mixer are all custom designed and built by the CSIR. Only the flash mixer can be removed and dismantled, whereas the flocculator and clarifier are fixed in position in the container. All other process components are locally available in South Africa and can be removed if necessary for maintenance and repairs.

Dosing points : Two manually adjustable Alldos dosing pumps with 200 ℓ chemical tanks were provided for dosing the raw water. This allows flexibility of operation because in addition to the primary coagulant, one other chemical such as a floc aid, powdered activated carbon, disinfectant or pH buffer can also be dosed. A third dosing point was provided for chlorination of the treated water, either as a back-up to the UV system or as a secondary disinfectant. The maximum dosing flow was 5 ℓ/h from each pump. The coagulant and disinfectant dosing pumps are set manually and require occasional calibration. The dosing pumps are not flowrate controlled and require manual adjustment if the raw water flowrate is altered for any reason.

Flash mixer and flocculation vessel : In the original plant design, the turbulence created by the rotameter float (downstream of the dosing points) was used for flash-mixing of the coagulant solution with the raw water. It became apparent that this was ineffective and a 10 ℓ cylindrical PVC flash mixer containing two orifice plates was installed.

The flocculation tank was originally fitted with a tangential inlet to promote swirl and gentle mixing in the tank. During the evaluation it also became apparent that the mixing energy was insufficient and a 10 rpm vane stirrer was installed to improve the flocculation.

Clarifier : The upflow clarifier was fitted with an array of 50 mm PVC pipes inclined at about 60° to the horizontal and was designed for a maximum capacity of 10 m^3/h (hydraulic loading rate of 8 m/h through the tube bundle). The base of the clarifier sloped down (at about 10°) to the sludge drainage outlet. Sludge is drained manually from the clarifier when necessary. The clarifier was constructed from mild steel plate and was permanently welded into the container.

Pressure sand filter system : Two Collins pressure sand filters (domestic swimming pool type) are used and are connected in parallel. Each filter has a bed depth of about 0,35 m and a filtration area of approximately 0,44 m^2. Filter operation is controlled by means of multiport valves and level probes in the filter feed tank (see **Section 10.2.2**).

Disinfection system : A proprietary "Willand" UV disinfection system was fitted to the plant. The system consists of four PVC chambers connected in series. The filtered water flows in the annular space between the centrally located lamp and the walls of the chamber. 75 W low pressure mercury lamps are used.

10.2 Process Control System

The process control system has been designed to minimise operator workload during normal operation of the unit. Control of the chemical dosing system is based on maintaining a fixed raw water flowrate. From the filter feed tank onwards, batch operation of the filter and UV chambers is controlled by level probes fitted to the tank. Adjustment of chemical doses, desludging and filter backwashing are performed manually. There are no control loops and no complex electronic equipment is used.

10.2.1 Operation and Control Sequence

A detailed operation and control sequence is listed in the operator's manual. A brief description follows:

- Prior to start-up, the chemical solutions are prepared and the dosing tanks filled. Jar tests may be used to determine the coagulant dose. The multiport valves should be in the filter position.

- To start the plant, the raw water inlet valve is regulated to give the desired flowrate. The flocculator impeller and UV system must also be switched on.
- The dosing pumps are switched on and adjusted to give the correct dose. Since the raw water flowrate is relatively constant, subsequent adjustments will only be required to compensate for changes in the raw water quality.
- The flocculator and clarifier fill sequentially. When sufficient clarified water overflows into the filter feed tank, filtration and UV disinfection commences automatically on a batch basis.
- Turbidity (raw clarified and filtered water), filter head loss, sludge build-up and the operation of the UV lamps should be regularly monitored.
- The sludge from the clarifier is wasted at intervals determined by operator experience.
- Backwashing is required when turbidity breakthrough occurs or when the filter headloss exceeds a certain value (see **Section 10.2.5**). Filtered water and a separate backwash pump are used for backwashing and the process involves the manipulation of at least six valves.

10.2.2 Degree of automation

Two aspects of plant operation are automated. These are:

- **The filtration system.** This must be automatically controlled because the filter flowrate is usually considerably higher than the raw water flowrate. Filtration is controlled by level probes in the filter feed tank.
- **The disinfection system.** The lamps must be monitored during operation. If any of the lamps fail, the disinfection efficiency will be compromised and the danger of contaminating the treated water storage reservoir exists, especially if the post chlorination system is not in use. In order to prevent such contamination from occurring, the original UV system was modified so that treated water would be diverted to waste if any of the UV lamps failed.

All other operating tasks are manually performed by the operator. Once all settings and adjustments have been made, the plant can operate without supervision until either the filters require backwashing or the chemicals are depleted. Although the dosing pumps can be equipped with low level alarms, these were not fitted. Chemical solutions are manually prepared and replenished. Recalibration of the dosing pumps is required whenever a solution of different composition or viscosity is used.

The operator's control of the duration and intensity of flash mixing is limited to flowrate adjustments. The intensity of mixing in the flocculator is fixed since the stirrer speed cannot be adjusted while the mixing intensity of the flash mixer is dependent on the flowrate.

The raw water flowrate is adjusted by means of a ball valve on the inlet pipe. This determines the rate at which the plant treats raw water. The plant was not equipped with any facility for automatic shut down or start-up based on demand although this could easily be incorporated. Backwashing, sludge drainage and changes in the chemical dose are all initiated at the operator's discretion.

10.2.3 Monitoring of the Process Parameters

Effective operation of the process requires monitoring of the following parameters:

- **Treated water quality** including turbidity and disinfection performance.
- Sand filter **head loss.**
- **Chemical tank levels.**
- Clarifier **sludge build-up.**
- Raw water **flowrate** and chemical dose rates

The instrumentation supplied with the plant does not permit accurate monitoring of turbidity, chlorine residual or sludge build-up. The single pressure gauge fitted initially to each sand filter was ineffective for monitoring the filter bed head loss (see **Section 10.2.5**). The filters were modified to include a second gauge on the filter outlets which allowed more accurate monitoring of the head loss.

Turbidity and chlorine residual can be effectively monitored by means of relatively inexpensive, simple comparator kits. Periodic checks by a competent laboratory are recommended. During the evaluation, extensive use was made of the jar test to determine optimum coagulant doses. Jar testing equipment and training in its use will be required for effective operation of this plant.

The degree of sludge build-up in the clarifier was difficult to assess. The slope of the clarifier base may be insufficient for proper sludge drainage. During the evaluations, the plant was desludged on a weekly basis but the sludge was always dilute and had a similar solids content to the backwash water.

10.2.4 Effectiveness of Control System

If a constant raw water flowrate is maintained and no malfunctions occur, the control system is effective. However, there are a number of uncontrolled parameters that can result in poor treated water quality or contamination of the treated water.

10.2.5 Uncontrolled Parameters which may affect Final Water Quality

Raw water dosing system : The dosing pumps are not flow controlled so any change in the raw water flowrate affects the chemical dose. In addition, low level alarm switches were not installed and this means that the operator is not alerted when the chemicals are depleted.

Flashmixer and flocculator velocity gradient : In order to obtain the design G value for coagulation, the plant must be operated at the design flowrate (10 m^3/h). Lower flowrates will cause lower G values and insufficient flash mixing may result. If the plant is typically operated at a flowrate other than the design rate, it will be beneficial to install appropriately sized orifice plates in the flash mixer. The original flocculator however, did not provide good flocculation and was modified to include a 4 blade vane turbine that rotated at 10 rpm. An increase in floc size was observed at all flowrates after this modification.

Filter bed pressure-drop monitoring : The pressure gauges fitted to the multiport valves only reflect the filter inlet pressure and give an unreliable indication of solids loading. This pressure consists of the pressure drop across the bed and in the subsequent piping. As the filter becomes loaded the bed's pressure drop increases and the pressure drop in the subsequent piping drops because of the slightly reduced flowrate. The two effects mask each other and as a result, the solids loading in the filter bed is underestimated. This effect is enhanced when the pressure drop due to downstream pipework becomes significant, as it does on this plant where the UV system and optional GAC system are installed downstream of the filter. During a normal filter cycle the filter inlet pressure typically increased by less than 10 kPa even though the flowrate decreased significantly. An additional pressure gauge was installed on the filter outlet when the UV system was modified and accurate monitoring of the filter bed head loss became possible.

UV system control : Several problems were noted with the original system (see **Section 10.5.2**). These included reduced lamp life, siphoning, lack of alarms and lack of automatic treated water diversion during lamp failure. The plant was modified so that the lamps would stay on continuously during normal operation and an automatic bypass was installed upstream of the UV system that diverted the treated water to waste when lamp failure occurred.

Post disinfection dosing apparatus : The original post disinfection system was wired to operate continuously in spite of the batch nature of the filtered water flow. This would have caused severe disinfectant dose fluctuations in the treated water and the system was never used. It was recommended to the CSIR that this system be rewired so that it would only operate in conjunction with the filter pump.

10.2.6 Susceptibility to Demand Fluctuations

The plant can be operated at any flowrate up to the maximum of 10 m^3/h. At low flowrates (below 2,5 m^3/h) the flash-mixing energy is insufficient and floc development is affected. Although the coagulation and flocculation is improved at high flowrates (above 7,5 m^3/h), considerable floc carry-over from the clarifier was observed. The plant is therefore most suited to installations where it can be operated between 2,5 and 7,5 m^3/h, supplying a reservoir from which there is a relatively constant demand.

10.3 Personnel Requirements

A part-time operator is required for about three hours per day to backwash filters, drain sludges, make up chemical solutions and occasionally to clean and replace UV lamps. Maintenance personnel are required for maintenance and repairs to pumps, dosing pumps and the electrical system.

Although the plant is able to operate for several days without operator attention, the lack of an emergency shut down system means that it should be checked on a daily basis by the operator.

Three-monthly visits by a technician are recommended, mainly to check on the treated water quality, chemical dosing systems, the UV lamps and the pumps.

10.3.1 Workload Estimation

Installation and commissioning : The CSIR estimates the time required for installation and commissioning to be between 5 and 8 days (including on-site training of the operator). During installation the raw water, backwash water, treated water and sludge drain pipes require connection. In addition a 3-phase electrical system must be connected. Provided that the site has been properly prepared and that all pipework and fittings are available, installation can be completed in six hours (see **Section 10.7.2**). A pipe fitter and an assistant will be required.

During the commissioning phase, a process technician will be required to start-up the plant and check the operation of all components. The commissioning phase may also be used for operator training. Installation and commissioning of the plant at the PEF took approximately 1 week. An experienced installation team could install and commission the plant in 1 day (excluding operator training).

Routine operation : The operating manual provides a list of daily and weekly operating tasks. The daily tasks will require about two hours of an experienced operator's time and the additional weekly tasks, another two hours each week. The total operator workload during routine operation is therefore approximately 16 hours per week.

Maintenance and repair : The maximum recommended maintenance interval is about three months. During these maintenance visits a technician will be required to:

- Calibrate and check the operation of dosing pumps and carry out repairs as required.
- Check the operation of the pumps, mixer and any electrically operated valves fitted to the plant.
- Check the solids build-up in the clarifier and the condition of the sand filters
- Check the operation of the UV disinfection system and clean the quartz sleeves.
- Retrain or advise the operator when necessary
- Take samples for monitoring of treated water quality.

These tasks will take approximately three hours. Repairs to pumps or motors may necessitate removal of the faulty component and this will require additional time. The maintenance and repair workload, excluding travelling time is therefore estimated at approximately 15 hours per annum.

10.3.2 Specific Training Requirements

Since this plant uses conventional water treatment technology the process is similar to many existing municipal plants in South Africa. Prospective operators should preferably have an N3 certificate in Water and Wastewater Treatment and at least, a Standard Eight certificate and technical aptitude. Operators will require training in:

- The basic principle of operation of each plant component.

- Storage and preparation of chemical solutions
- Jar tests
- Adjustment of chemical doses according to flowrate and jar test results
- Backwashing of filters and sludge drainage from the clarifier
- Keeping an accurate log of operating parameters and events.
- Basic maintenance and cleaning of the UV system.

The technician will require more detailed training in the maintenance and repair of all mechanical and electrical equipment on the plant including:

- Dosing pump repairs, servicing and calibration.
- UV system cleaning and lamp replacement.
- Repair, servicing and fitting of pumps.
- Trouble shooting and assessment of mixer, clarifier and filter operation.
- Sampling and analysis procedures.

An operating manual written in English is available from the suppliers. The manual explains all routine operating tasks including start-up, backwashing, sludge drainage, daily operating tasks and shut down as well as providing advice on safety, plant maintenance, trouble shooting and obtaining spare parts. Process flow and electrical circuit diagrams are provided with the operation manual.

10.4 Infrastructure Requirements

Road access : The plant is housed in a standard 6 m shipping container. These containers are normally transported by a 5 to 7 ton truck equipped with hydraulic lifting apparatus. Access to the site for such a vehicle will be necessary.

Power requirements : The plant requires a 3 phase 380V power source. The plant's power consumption during normal operation does not exceed 2 kW (excluding raw water pump). If an additional raw water pump is used, provision must be made for the extra power requirement.

Raw water provision : See **Section 10.5.1**

Treated water reticulation : Since the plant operates continuously at a constant rate, sufficient storage capacity for two days production is recommended. This will allow sufficient buffer capacity in case of a temporary reduction or increase in the demand for treated water. Treated water is also required for backwashing the filters so the storage reservoir should be suitably positioned. The reservoir should be provided with an audible high level alarm.

Sludge disposal : Sludge should not be returned to the water source unless the effluent conforms to the standards promulgated by the Department of Water Affairs and Forestry. The backwash effluent and clarifier sludges settle easily, producing a supernatant that may be recycled and a settled sludge that may be distributed on pasture or dried by solar evaporation after decanting of the supernatant.

Chemical storage facilities : A roofed storage facility that is cool, dark and dry is required. It should also be well ventilated and secure. Storage of chemicals in the container is not recommended since limited space is available and the build-up of fumes may accelerate corrosion in the plant.

Weather protection : The plant is protected against the weather since it is enclosed in a container. **Site establishment :** A level concrete slab and where necessary, security fencing, will be required. Drainage channels and facilities for treatment and disposal of effluents will be required.

10.5 Performance of the Treatment System

The plant was intermittently operated between 11 November 1993 and 30 August 1994. It is estimated that the plant was in operation for about 50 % of this time and that approximately 11 600 m^3 of treated water was produced. Intermittent stoppages were due to power failures, maintenance, carrying out modifications and temporary removal of the plant from the PEF for demonstration purposes.

Several plant modifications were recommended to the CSIR on the basis of the plant's performance during the first six months of operation. In July 1994 the mixing system (see **Section 10.2.3**) and the UV control system (**Section 10.5.2**) were modified by the CSIR .

10.5.1 Raw Water Supply

Head / Flowrate : Raw water is required at a continuous flowrate of up to 10 m^3/h and a pressure of approximately 25 kPa depending on the type of flash-mixing in use. If this flow is not available under gravity, a raw water pump with appropriate screening will be required. The existing 3 phase electrical system can accommodate a pump of up to 10 kW if necessary.

Screening : The raw water should be screened at the intake point to prevent ingress of suspended material larger than about 3 mm in size.

Storage / Reservoir Capacity : Storage of at least 1 m^3 of filtered water is required for backwashing. Since the plant's flowrate is too high for direct supply to consumers, a storage and reticulation system will be required. A 500 m^3 storage reservoir will accommodate two days production at the maximum flowrate.

Quality of Raw Water : The raw water turbidity ranged between 1 and 200 NTU during the evaluation. The best results were achieved with raw waters below 30 NTU (see Figure 10.4).

10.5.2 Micro-organism Removal

The disinfection system fitted to the plant is versatile in that any combination of pre-chlorination, post-chlorination and UV disinfection can be practised. However, control of the various options on the original plant was inadequate. This can be seen from the microbiological results that were achieved with the system prior to the modifications that were carried out in July 1994. The microbiological results are shown in **Table 10.2**. The shaded area represents the results obtained after the control system modifications had been carried out.

During the evaluations, the chlorination points were not used for the following reasons:

- The post-chlorination system is inadequately controlled (see **Section 10.2.3**)
- Both raw water dosing systems were typically used for alternative coagulants during the evaluations so pre-chlorination could not be accommodated.

The UV system was therefore used for primary disinfection. Prior to modification, the lamps were switched simultaneously with the filter pump. This was found to be undesirable for two reasons:

- The life of UV lamps is severely reduced by frequent cycles of operation. During the evaluation, the lamps were typically switched on and off every fifteen minutes (the frequency of filter cycles) and the first lamp failed after approximately 500 hours of operation. Typically, a lamp life of 7 500 h should be obtained with 8 hour operating cycles.
- It was observed that water continued to siphon through the filter system after the completion of a filter cycle. This was due to the hydraulic design and layout of the system and resulted in contamination of the disinfected water with filtrate that had not been disinfected.

Each lamp was equipped with a pilot light that indicated whether the lamp was operating. This provided the only warning of lamp failure; no automatic isolation of the treated water connection would occur if a lamp failed.

Table 10.2 : Disinfection results for the treated water

(The percentage disinfection and cell concentration are shown for each determinand)

Date	Coliforms		*E. Coli*		Faecal Strep.		Plate counts @ 22°C		Plate counts @ 37°C	
	%	/100ml	%	/100ml	%	/100ml	%	/ml	%	/ml
11/11/93	84,7	21	95,3	4	100	0	0	800	95,1	14
24/11/93	100	0	100	0	100	0	98,5	37	90,8	24
05/01/94	99,8	1	100	0	100	0	68,6	95	84,8	57
15/03/94	100	0	100	0	100	0	61,0	328	76,7	205
25/07/94	100	0	100	0	100	0	99,8	1	100	0
27/07/94	100	0	100	0	100	0	70,0	3	97,9	1
01/08/94	100	0	100	0	100	0	93,8	25	100	0
09/08/94	100	0	100	0	100	0	97,6	9	97,5	6

It can be seen from the unshaded results in **Table 10.2** that significant slippage of micro-organisms through the UV system occurred. It was assumed that this was mostly due to siphoning as no lamp failures occurred during this period. A list of recommendations regarding the lamp control system was sent to Watertek. Appropriate adjustments were subsequently made to the system such that the following operation is achieved :

- The lamps operate continuously during the operation of the plant. This extends the lamp life and disinfects any water that siphons through the system between filtration cycles.
- The flow of filtered water to the UV system is automatically diverted to waste by a pair of solenoid valves that are activated by lamp or power failures.

These modifications effectively prevent undisinfected water from entering the treated water reticulation system in the event of lamp or power failure. However, siphoning can still occur and in addition, the plant continues to operate when the bypass is activated. A large amount of filtered water may be wasted if the operator is not present when a lamp failure occurs.

The results achieved with the modified system (shaded area in **Table 10.2**) show that disinfection of the filtered water was significantly improved and the microbiological quality of all samples conformed to the 1994 Dept. of Health draft guidelines for potable water.

These results were achieved without chlorination and show that UV disinfection systems can be effective. No evidence of contamination due to gradual biofilm growth in the treated water piping was found. Waters disinfected by UV have no protection against subsequent contamination or reactivation of irradiated micro-organisms. Secondary disinfection with chlorine is recommended when waters disinfected by UV enter a reticulation system and are not immediately used. In this regard, the post-disinfection system fitted to the plant was ineffective because the dosing pump did not operate in tandem with the filter feed pump.

10.5.3 Turbidity and Suspended Solids Removal

The turbidity removal achieved during the evaluation period is shown in **Figure 10.3**. In comparison with conventional systems using similar unit operations, the turbidity removal in the clarifier is poor and the filters, which have a polishing function, were removing a large proportion of the influent turbidity load. As a result the filters required daily backwashing during most of the evaluation period. Twice during this period, the filters were found to be badly clogged and the sand had to be manually emptied, cleaned and replaced.

After approximately 3 200 m^3 had been treated, the plant was modified. The modifications included the addition of an in-line flash mixer and electrically powered agitation in the flocculator. It can be seen that the average raw water turbidity after the modifications remained lower than before and this made direct performance comparisons tenuous.

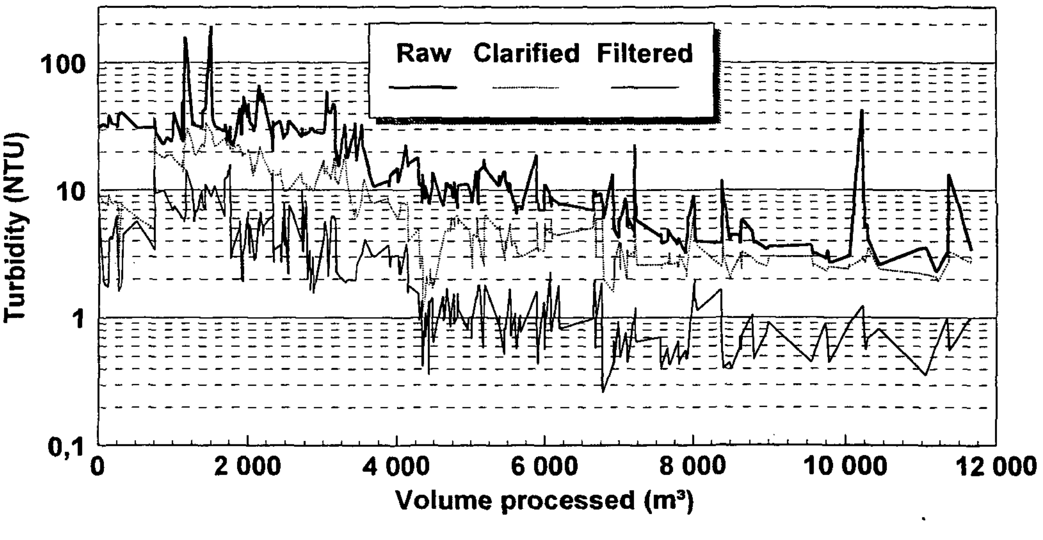


Figure 10.3 : Turbidity removal

Figure 10.4 illustrates more effectively the relationship between raw and treated water turbidity. In spite of the small degree of overlap between the two sets of data it is clear that the modified plant exhibits superior turbidity removal with raw water turbidities up to 50 NTU. It is expected that better performance would also be achieved with higher raw water turbidities.

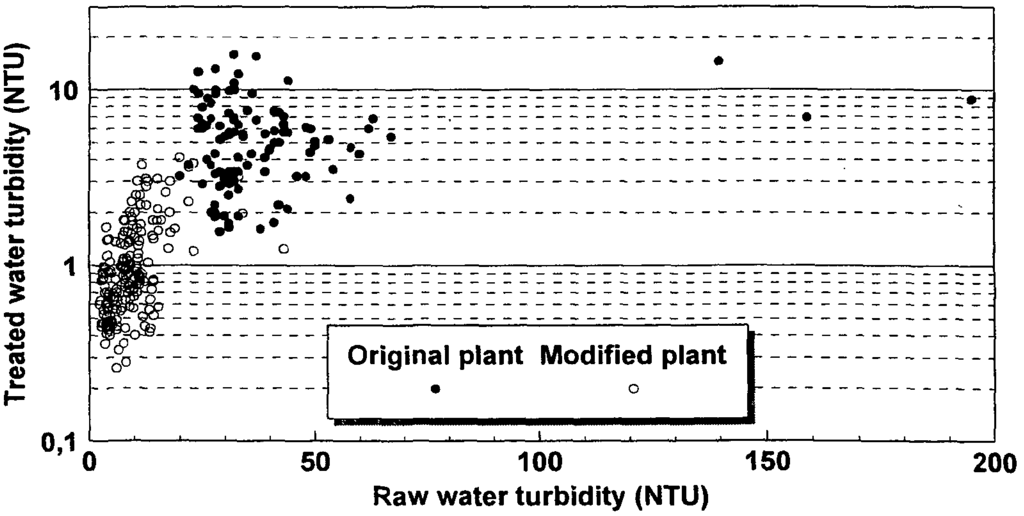


Figure 10.4 : Raw water vs. treated water turbidity

Prior to the modifications, the project staff were unable to achieve treated water turbidities below 1 NTU at any time. Jar tests were carried out for the purpose of optimising the coagulant dose and typically, filtered water turbidities of less than 0,3 NTU were achieved with the jar tests. "Cascade" tests (a modified jar test using clarifier overflow water with no addition of coagulant) gave similar results when the samples were flash-mixed and flocculated. This indicated that insufficient mixing was the cause of poor coagulation and flocculation, leading to poor clarifier performance. Subsequent to the modifications, it can be seen that the treated water turbidity was typically less than 1 NTU although the lower raw water turbidity may have contributed to the improved performance.

The plant produced treated water with a turbidity less than 1 NTU from raw waters with turbidity up to 20 NTU. The performance of the modified plant on raw waters with turbidity in excess of 50 NTU could unfortunately not be assessed during the evaluation period.

Two flowrate related capacity limitations were suggested by operating experience and cascade tests performed on samples drawn from various stages of the process. At low flowrates (below 2 500 ℓ/h) cascade tests on samples drawn from the flocculation tank and the clarifier indicate that insufficient flash mixing (coagulation) has taken place. This is consistent with the fact that the velocity gradient in the flash mixer is a relatively strong function of the flowrate ($G = f_1(Q^{3/2})$). The Gt value (velocity gradient multiplied by residence time) is also a function of the flowrate ($G = f_2(Q^{1/2})$). Operation of the plant at low flowrates is therefore not recommended because turbidity removal is hindered by the inefficient coagulation even though the lower clarifier upflow rate assists the sedimentation process.

At high flowrates, cascade tests indicate that flash mixing is effective but the higher upflow rates in the clarifier result in significant carryover of flocs. A raw water flowrate of 10 m³/h corresponds to a clarifier upflow rate of 5,3 m/h (surface area divided by flowrate). In reality however, flow only occurs in the tube bundle which occupies about 67% of the horizontal cross-sectional area. The effective upflow rate is therefore 8 m/h at full plant capacity, which is high for inclined plate systems. This corresponds to the maximum recommended loading rates for inclined tube systems in several literature sources including Degrémont's *Water Treatment Handbook*,(6ed.) and *Water Treatment Plant Design* by R.L.Sanks, 1978. Proper optimisation of the coagulant dose and mixing energies will be required in order to operate an inclined tube clarifier such rates.

10.5.4 Chemical Requirements

The plant makes use of the following chemicals and other consumable items:

- Chemical coagulants such as alum, ferric chloride or blended polymeric coagulants
- Disinfectant solutions such as sodium hypochlorite
- UV lamps
- pH correcting chemicals and floc aids (these were not used during this evaluation).

Several different types of coagulants were used during the evaluations. These included alum, ferric chloride, ferric chloride/polymer blends and blended polymeric coagulants. When alum and ferric chloride were used, pH adjustment was necessary. The following doses were used for the raw water treated during the evaluation:

- Alum .... 10 to 20 mg/*l* as $Al_2(SO_4)_3.14H_2O$
- Ferric chloride .... 6 to 10 mg/*l* as $FeCl_3$
- $FeCl_3$/polymer blends (Ferrifloc 1010, Ferrifloc 1820) .... 4 to 8 mg/*l* as $FeCl_3$

- Blended polymerics (Zetachem Z464N, Floccotan K10P) ...... 2 to 4 mg/*l*

It is recommended that the following supplies are kept in storage at the plant site:

- Sufficient coagulant for at least one month of operation. All of the coagulants that were used are stable if they are properly sealed and stored.
- No more than one month's supply of sodium hypochlorite. This should be stored undiluted and sealed in a cool dark place. Sodium hypochlorite solutions are usually supplied at 13,5 %(m/v) and have a limited shelf life. The rate of decomposition of sodium hypochlorite is increased by exposure to impurities, heat and light.
- A spare set of UV lamps. When used continuously, the lamps should have an operating life of approximately 9 months.

10.6 Plant Life and Reliability

10.6.1 Materials of construction

Various plastics are used in the plant. PVC pipework, GRP filter vessels and polyethylene tanks will not corrode or impart any undesirable substances to the water being treated. The clarifier, constructed of mild steel plate is the only exception and some surface corrosion became evident on the interior walls of the clarifier during the evaluation. All components have been securely fastened and no breakages or failures related to transportation of the plant were experienced. The shipping container used to house the plant provides good protection from the weather to all internally located components. The container itself developed severe surface rust during the evaluation period and annual painting of the container is recommended.

The following problems related to the design and materials of construction were experienced:

- If the container is not adequately supported, significant warping of the structure occurs when the plant fills with water. This causes difficulties in levelling the clarifier overflow weirs and can cause uneven flow in the clarifier.
- The quartz tubes used in the UV disinfection system are expensive and fragile. Great care is required during cleaning. The tubes are easily cracked if the "O" ring seals are over tightened or if the seal spanner is not properly located during tightening.
- The soft wall plastic tubing used for the dosing lines dilated during the pump pressure strokes. As a result, insufficient pressure was generated in the line to overcome the spring tension in the dosing point check valves and the dose flowrate was significantly reduced. This tubing was replaced with "Polyflo", a more rigid polyethylene tubing used for industrial instrument air lines.

10.6.2 Reliability

Plant and Equipment : During the evaluation, the plant was frequently left running during weekends without operator supervision. Satisfactory performance was achieved except when power failures occurred. However, the sand filters require daily backwashing when the raw water turbidity is higher than 20 NTU.

Control System Components : Due to the frequent switching of the UV system prior to the modifications, the first UV lamp failed after only 500 hours of operation. Several quartz tubes were also cracked during cleaning but only one required replacement. No other incidents of component failure occurred during the evaluations. The UV system was originally designed to operate in conjunction with the filter pump and the lamps were being switched on and off 3 to 4 times every hour. This significantly reduced the lamp life and although warning lamps were provided, there was no audible alarm or emergency shut down facility. For these reasons, the system was rewired so that the lamps would stay on permanently and an emergency shut down facility was fitted to prevent contamination of the treated water supply in the event of lamp failure.

All three dosing systems were fitted with low level switches but these were not wired into the plant's control system. It is therefore possible for the plant to continue operating when the chemicals are depleted and contamination of the treated water will occur as a result. Although this water is still exposed to UV light, disinfection may be considerably less effective due to the higher turbidity. Automatic shut down of the plant based on these alarm switches can easily be incorporated into the control system. In the case of a power failure, the UV system bypass will come into operation and even though raw water may continue to flow into the plant, contamination of the reticulation system will not occur.

The dosing pumps supplied with the plant have a maximum output of 5 ℓ/h and can be accurately adjusted to dose between 10% and 100% of the full-scale flow. The direct use of undiluted coagulants or disinfectant solutions will therefore result in severe overdosing, even at maximum plant flow and minimum dose rate (0,5 ℓ/h coagulant into 10 m^3/h of raw water amounts to a dose of 50 mg/ℓ). During the evaluation, the coagulants were diluted by a factor of 20 to 100 for dosing purposes and accurate records of the dilutions and doses were kept.

All three dosing pumps are fed from 0,2 m^3 tanks. The dosing systems can therefore operate at full flow for at least 40 hours with full tanks. Typically, the dosing pumps were set to operate at flows from 0,5 to 1 ℓ/h and therefore, up to 400 hours of operation can be obtained with full dosing tanks. The post-disinfection dosing system was wired to operate continuously in spite of the cyclic nature of the filter operation. For this reason it was not used since it was impossible to achieve a constant chlorine dose. This system can easily be modified to start and stop in tandem with the filtration system.

10.6.3 Potential for Expansion of Capacity

The filtration system fitted to the plant can accommodate a flowrate of about 13,2 m^3/h (based on a loading rate of 15 m/h) and flowrates up to 14 m^3/h were measured in practice. The local agents for the Willand UV system recommend a maximum flowrate of 8 m^3/h although satisfactory disinfection can be achieved at flowrates up to 14 m^3/h. Based on operating experience and literature sources it is recommended that the maximum design flowrate of 10 m^3/h should not be exceeded in practice. Poor turbidity removal and rapid filter clogging are the likely consequences of operation at higher flowrates. If a flow of treated water greater than 10 m^3/h is required, the installation of a separate additional plant should be considered.

10.7 Servicing, Maintenance and Repair

The operator should be responsible for the maintenance of the plant and its surroundings including the raw water feed and sludge disposal system. Annual painting of the container will be required when the plant is situated in areas with warm humid climates. The operator's manual gives guidelines for the type and frequency of maintenance actions required for other plant components.

Pumps : Two pumps were fitted to the unit that was evaluated but units in the field may have an additional raw water feed pump. Bearings and pump seals require an annual check-up and gland type seals may require more frequent adjustment or repacking. The raw water pump may require more frequent attention due to the abrasive nature of particles that occur in some raw waters.

Dosing pumps : The dosing pumps incorporate a number of components that can become clogged or worn, ultimately affecting dosing precision. These components include the four valves, the foot valve filter and the pump diaphragm. The operator's manual recommends weekly washing of the valves in clean water and replacement of the pump diaphragm every six months. Frequent washing of the valves is important because crystallisation and precipitation have been experienced with some coagulating chemicals and the valve seats are easily damaged by such deposits.

Dosing pump spares are not widely available in South Africa and must generally be ordered directly from the suppliers. Pump service kits are expensive and the importance of frequent dosing pump maintenance should be more heavily stressed in the operator's manual. Operating experience shows that the pump diaphragms typically outlive the valves. Two replacement valves were fitted during the evaluation period. All dosing pump maintenance tasks, except for valve washing, should be performed by a qualified fitter and the pump must be recalibrated when a new component is fitted.

Valves and fittings : While no routine maintenance of pipework is required the plant's pipework incorporates various different valves and other fittings that can wear. The PVC ball and check valves fitted to the plant require an annual check for wear. Worn balls or teflon seals should be replaced. The rotameter used for raw water flowrate monitoring tends to become coated with algae and requires cleaning on a three-monthly basis.

UV System : The operating manual recommends:

- Cleaning the quartz sleeves every six months and replacing them every three years.
- Replacing the lamps after 4500 hours of operation.

Based on operating experience during the evaluation and the lamp manufacturer's information a lamp operating life of 7500 hours can be used. This operating life is based on eight hour cycles of operation. Since the lamps on the plant now operate continuously the manufacturer's quoted operating life can probably be achieved in practice. The recommended cleaning intervals are sufficient but great care must be taken when removing and refitting the sleeves (see **Section 10.6.1**). Replacement of lamps can be performed by the operator but all other UV system maintenance tasks should only be performed by a properly trained technician or fitter.

10.8 Transportation, Installation and Commissioning

10.8.1 Transportation

Any truck fitted with a hydraulic crane and cleats for securing a standard 6 m shipping container will be suitable for transporting the plant. The various process vessels in the plant hold approximately 7 m^3 of water during normal operation so the plant must be completely drained before any attempt is made to lift it. Any containers that are transported in the container with the plant must be properly secured to prevent spillage.

10.8.2 Installation

Installation of the plant at the PEF was delayed by uncertainty about the size of the hoses required for the various inlets and outlets as well as the electrical power connections. These details are all contained in the manual which arrived with the plant. The plant was installed within a day after suitable connections had been purchased. Although the plant is wired to use a 380V three-phase supply, it arrived at the PEF with a 500V three-phase connector attached to the power cable.

During the evaluation period, the plant was moved to another location for a demonstration and then returned a few days later. The design of the plant renders it suitable for relatively rapid deployment or relocation when necessary. If the sites have been properly prepared, the plant can be uplifted, relocated and put into operation within six hours (excluding travelling time).

10.8.3 Commissioning

Although a specific chapter on commissioning is not included in the operating manual, the procedures for start-up and normal operation are well explained. The plant was commissioned by the project staff using the information in the manual. The manual does not provide recommendations for start-up chemical doses or sample calculations for the dilutions and pump settings that may be required. While this did not prove to be problematic for the project staff, such information and examples would be of great benefit to a recently trained operator.

10.9 Costs

10.9.1 Capital Cost

The 1993 cost of the 10 m³/h plant was R91 000. Alternatively the plants can be hired or leased from Watertek (the quoted hiring cost was R185,00/day). A total treatment and supply service can also be negotiated with Watertek.

10.9.2 Operating cost

In addition to the capital cost, the cost of installation and commissioning was quoted as approx. R 19 000 depending on site conditions. Summaries of the operating cost per volume of water produced have been prepared for two plant flowrates (5 m³/h and 10 m³/h) to illustrate the effect of flowrate (see **Table 10.3**). Down-time of 10 % has been included in the estimates where applicable.

Table 10.3 : Summary of operating costs for CSIR package plant

Operating cost components	Specific cost @ 5 m³/h R / m³	Specific cost @ 10 m³/h R / m³
Wages	0,148	0,074
Electricity	0,061	0,039
Coagulants/flocculants	0,016	0,016
Sodium hypochlorite	0,022	0,022
UV lamps	0,027	0,014
Maintenance and repairs	0,054	0,027
Total	**0,328**	**0,192**

Chemical cost : The cost of various polymeric coagulants in 1993 was approximately R 4,00 /kg including the deposit for 25 ℓ plastic drums. These chemicals are dosed at concentrations up to 10 mg/ℓ but during the evaluation polymeric coagulants were typically dosed at concentrations of approximately 4 mg/ℓ. This translates to a cost of approximately R 0,016 /m³. Liquid alum is considerably cheaper than polymeric coagulants (approximately R 0,50 /kg for 48 % solution) but it requires doses between 12 and 30 mg/ℓ. The cost of using alum will therefore be approximately similar to the cost of using polyelectrolytes.

A 28 kg drum (25 ℓ) of 13,5 % sodium hypochlorite solution costs approx. R 41,00 (R10,85/kg Cl). Although chlorination was not used routinely during the evaluation it may be used as a secondary disinfectant in typical field installations. A dose of 2,0 mg/ℓ (as Cl) will also cost approximately R 0,022 /m³.

Subsequent to the modifications, a normal operating life of 7 500 h can be expected from the UV lamps. The lamps will therefore require replacement every 300 days of operation at a cost of R 987,44 for a set of 4 lamps. The specific cost of lamps is therefore R 0,027 /m^3 at 5 m^3/h and R 0,014 /m^3 at 10 m^3/h.

Cost of power : The cost of electrical power is R0,2643/kWh. The plant's power consumption has been estimated at approximately 1,25 kW when operating at 5 m^3/h and 1,6 kW at 10 m^3/h. The specific cost is therefore R 0,061 /m^3 and R 0,039 /m^3 at the two flowrates respectively.

Labour cost : The operator's workload has been estimated at 16 hours per week with wages of R 7,00 /h. The annual cost of wages is therefore R 5 824,00. Annual water production (including down-time) at flowrates of 5 m^3/h and 10 m^3/h is 39,42 Mℓ and 78,84 Mℓ respectively. Since the operator's workload is not significantly affected by the flowrate this results in a wages or labour cost of approximately R 0,148 /m^3 at 5 m^3/h and R 0,074 /m^3 at 10 m^3/h.

Maintenance cost : The maintenance requirements have been estimated at 15 hours per annum by a trained artisan at a cost of approximately R 75,00 /h. The cost of service kits for the dosing pumps and seals or bearings for the filter and backwash pumps will be approximately R 1 000,00 per annum. The specific cost is therefore R 0,054 /m^3 at 5 m^3/h and R 0,027 /m^3 at 10 m^3/h.

11 EXPLOCHEM WATER TREATMENT (Pty) Ltd
FILTREX Direct Upflow Filter

11.1 Introduction

The Filtrex direct upflow filter that was evaluated is a pilot plant designed and built by the Pinetown branch of Explochem Water Treatment (Pty) Ltd, a water treatment company based in Johannesburg. The contact person is Kevin Treffry-Goatley of the Kloof branch in Kwa Zulu-Natal. The telephone number is 031-764 6792 and the fax number is 031-764 6799.

Explochem manufactures Filtrex package plants according to individual customer requirements. A Filtrex package plant with a flowrate of 15 m^3/day, based on this pilot plant is currently operational at the Albert Falls dam in Natal.

11.1.1 Plant design philosophy

Direct upflow filtration has the following features that make it suitable for package plant applications:

- Ease of operation
- Manual or automated operation is possible
- Low operating pressure
- Low maintenance and operating workload
- Low chemical and energy consumption
- Low capital cost

These features have led to the successful application of this technology for rural and small municipal water treatment plants in Russia since the early 1950s (Hamann & McKinney, 1968).

Since flocculation, clarification and filtration all occur within a single filter bed, Filtrex plants can be compact. Plant capacities from 12 m^3/day are easily constructed and scale-up simply consists of increasing the filter bed area. Filtrex plants can be constructed from a wide range of materials with PVC, HDPE and GRP being most suitable for package plants while steel, ferrocement or reinforced concrete can be used for larger scale fixed plants. Filtrex plants are easily automated and low energy costs (in comparison with pressure filtration) are possible as a result of the low operating pressure. If sufficient gravity head is available at the plant site, pumping may not be necessary for filtration.

11.1.2 General description of the plant

The Filtrex process is a multimedia upflow rapid sand filter. The unit installed at the Process Evaluation Facility for this evaluation was a pilot plant consisting of a vertical PVC pipe (height 4 m; diameter 0,3 m) filled with three layers of graded media. The first (bottom), second (middle) and third (top) layers contained gravel, stones and sand respectively (see **Figure 11.1**). Direct upflow filtration is a continuous process and the unit operations involved are coagulant dosing, pumping, flocculation and filtration. Although no disinfection apparatus was installed on the pilot plant, sodium hypochlorite dosing systems are usually used in the commercially built package plants.

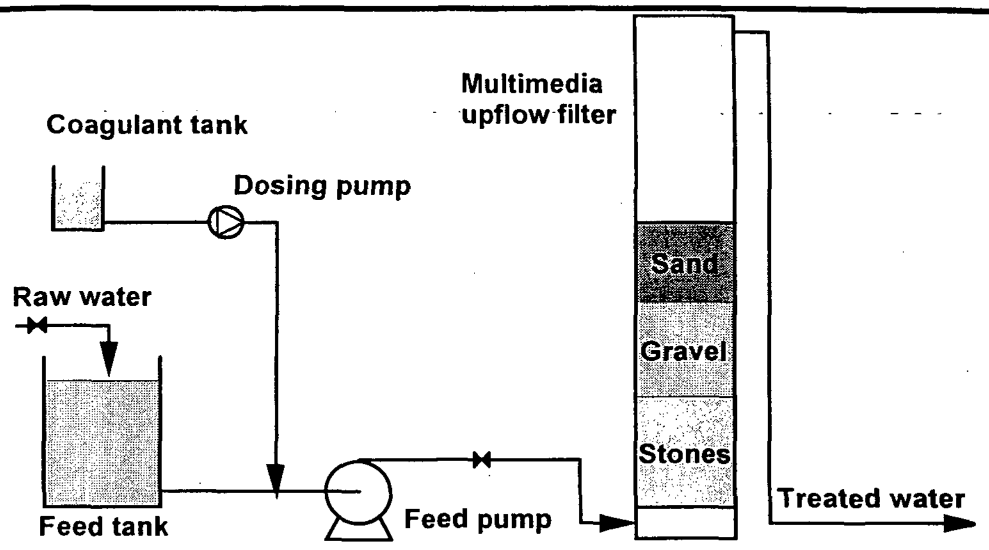


Figure 11.1 : Upflow filter process flow diagram

11.1.3 Process sophistication

A summary of the process components used in the pilot plant is given in **Table 11.1**. The process is relatively simple to operate. During normal operation, the feed flowrate, polyelectrolyte dose and chlorine dose (where fitted) are set at the beginning of the run. Since the flowrate does not decline significantly during filter runs, frequent dose adjustments are not required.

Table 11.1 : Summary of installed equipment in the Filtrex pilot plant

Component	Quantity	Comments
Valves	6	1 x PVC non-return valve on air line 1 x brass gate valve on pump delivery line 3 x PVC ball valves, 1 for sampling, 2 for rotameter selection 1 x brass ball valve for filter drain
Pumps	2	1 x 1,1 kW Primatic centrifugal raw water pump 1 x 0,012 kW Gamma/4-I dosing pump
Filter	1	4 m high, 0,3 m in diameter containing gravel, stone and sand
Tank	2	1 x 1 m^3 GRP feed tank 1 x 25 ℓ plastic drum for polyelectrolyte feed

The filter is washed in the upflow mode and an air scour is required for effective agitation of the filter media. The prototype unit experiences pressures up to 75 kPa (gauge) during filter washing but during filtration, the working pressure at the base of the filter should not exceed 50 kPa. **Table 11.2** summarises the operating and design parameters of the prototype unit.

Table 11.2 : Filtrex design and operating parameters

Parameter	Specification
Energy consumption	2,2 kWh/m^3
Coagulant consumption	1,25 g/m^3
Filtration area	0,07 m^2
Filtration rate	7,0 m/h
Nominal capacity	0,5 m^3/h
Recommended terminal head loss	0,75 m

11.2 Process control system

The Filtrex pilot plant was operated as a constant-rate, variable-head filter. The filtration rate was manually adjusted by means of pump discharge throttling and the polyelectrolyte dose was controlled by means of manual stroke and pulse frequency adjustments on the dosing pump. The filtration cycle length was based on the pressure drop across the media.

11.2.1 Operation and control sequence

Start-up of filter : The chemical make-up procedure, as outlined in the operating manual, should be followed by the operator. This involves dilution of the polyelectrolyte coagulant to an appropriate concentration for the plant. The operator must ensure that all valves are in their correct positions. After starting the feed pump, the coagulant and disinfectant (where fitted) dosing pumps are started up. Turbidity and disinfectant residual are then monitored regularly and appropriate dosing pump adjustments are made until the quality of the treated water is acceptable. All water produced during this phase of operation may be wasted or recycled to the raw water feed tank.

Filter cycle : As soon as water of potable quality is produced the treated water valve is opened and the treated water flows to storage. During the filter cycle, the plant can be operated on demand by a level control system in the treated water reservoir if necessary. Turbidity, chlorine residual and filter inlet pressure are periodically monitored by the operator during the filter cycle. When the filter head loss exceeds 0,75 m (7,5 kPa) the filter cycle must be terminated and the filter washed.

Filter washing : Raw water was used for washing the pilot plant filter but treated water may also be used if necessary. Filter washing proceeds as follows:

- The filter is drained and filled twice.
- Upflow washing with water (60 to 70 m/h) and an air scour (35 m/h) occurs for 5 minutes.
- The filter is water washed (60 to 70 m/h) until the effluent appears to be clear.

The entire filter cleaning procedure takes approximately 20 minutes but longer washing periods will be required if the recommended terminal head loss is exceeded.

11.2.2 Degree of automation

The entire pilot plant was manually operated. The flowrate was controlled by a gate valve located at the pump discharge and a manually controlled coagulant dosing pump was used. The level of the raw water buffer tank was controlled by a float valve.

Complete automation of Filtrex plants (including washing) is technically feasible although it may significantly increase the capital cost of the smaller plants. The following partial automation procedures are recommended as the minimum degree of automation required for reliable, low workload operation of a Filtrex plant:

- An automatic trip based on terminal head loss will prevent overloading of the filter. This is easily installed by linking a manometer mounted level sensor to the feed and dosing pump contactor.
- Flowrate proportional dosing of coagulant and disinfectant solutions is required. This is most economically achieved with a pulse equipped flow meter and compatible dosing pumps or a flow powered metering device.
- A level control system in the treated water storage tank that starts and stops the plant on demand.

11.2.3 Monitoring of process parameters

Table 11.3 summarises the operating parameters that were monitored during the operation of the pilot plant. Operators in the field are unlikely to have access to jar testing apparatus or turbidimeters; they will have to use a trial and error method for coagulant dose optimisation.

Table 11.3 : Monitoring of process parameters

Parameter	Measurement and Control
Turbidity	Turbidity was measured by means of a Hach turbidimeter and correctional adjustments were made to the coagulant dose.
Pressure	Filter bed head loss was monitored by a manometer connected to the filter inlet.
Flowrate	Flowrate was monitored by means of a rotameter on the pump delivery line..

The manometer used for filter head loss monitoring was inconvenient to use because of its height. Automation of this system of headloss monitoring is therefore strongly recommended. Apart from permitting proportional dosing, a pulse equipped flowmeter will also permit assessment of coagulant and disinfectant consumption, treated water production and monitoring of the plant's actual output capacity.

11.2.4 Effectiveness of the control system

The manual control system used for the pilot plant was effective because minimal fluctuations occurred in the raw water quality and flowrate. However, the manual control system will not be effective when large fluctuations in raw water quality and flowrate occur unless the plant is continually supervised.

Filter cleaning: In **Figure 11.2** it can be seen that the filter pressure drop (head loss) closely follows the solids loading curve over the normal operating range. The head loss across the bed can therefore be used as a reliable indication of solids loading. **Figure 11.2** depicts a run that was terminated after the head loss attained a value of 2 m of water. After approximately 225 hours of filtration the solids load had approached 2 kg. A total backwash time of 1 hour was required. This represents more than twice the downtime and wash water volume that is required for a normal filter wash.

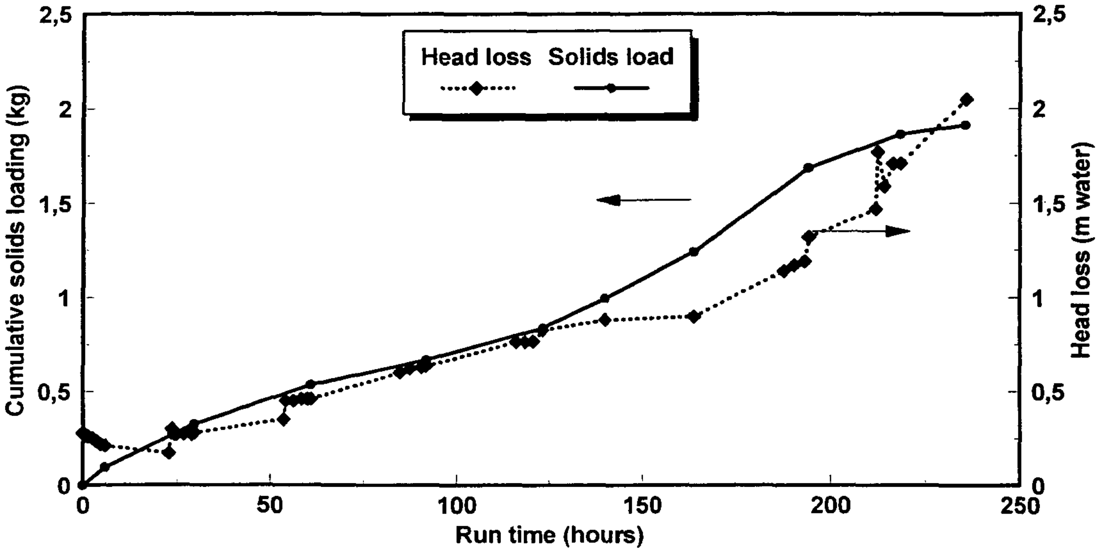


Figure 11.2 : Solids loading and pressure drop for a specific run

11.2.5 Uncontrolled parameters which may affect treated water quality

Rapid fluctuations in raw water turbidity may affect the final water quality. Jar tests may be used to aid the operator in making appropriate dosing adjustments to compensate for such fluctuations.

11.2.6 Susceptibility to demand fluctuations

Treated water turbidity was not significantly affected when the plant was stopped or started in the middle of a filter run. This means that operation on demand, controlled by a reservoir mounted level probe system will be appropriate for Filtrex plants. Direct upflow filters can also be operated over a wide range of filtration rates depending on the degree of filtration required and the composition of the graded filter bed (see **Section 11.6.3**).

11.3 Personnel requirements

A process technician is required to supervise the installation and commissioning of a Filtrex plant and should also be available to give subsequent technical support. A single operator is required and shift operation should not be necessary on package plants fitted with the minimum automation facilities listed in Section **11.2.2**. A suitably qualified artisan will be required for periodic maintenance and repair of the feed pump and dosing pumps.

11.3.1 Workload estimation

Installation and Commissioning : This estimate of the installation workload does not take the site preparation into account (see **Section 11.4**). Installation will involve the erection of a filter unit, filling of the media to correct levels, raw water pump connection and the connection of all pipework and instrumentation. Commissioning involves the calibration of flowmeters and dosing pumps as well as adjustments of level control systems and other automation systems where they are used. In addition, the commissioning period can be used for chemical dose optimisation and operator training. The installation and commissioning of a Filtrex **package plant** on a properly prepared site should not take more than 2 to 3 days. Larger units requiring civil work will obviously take longer to erect.

Routine Operation : Routine operation will involve daily turbidity, water flowrate, pressure drop and coagulant flowrate monitoring. Microbiological monitoring should also take place with a frequency as recommended by the Dept. of Health. The routine operating workload should not exceed 1 hour per day with an additional 30 minutes per week for sampling. Therefore the total operating workload is estimated as 7,5 hours per week.

Maintenance and Repair : The routine maintenance workload is limited to checks on the operation of the control system, valves, dosing pumps, feed pump and other equipment once in every 6 months. Without taking any major repair work into consideration, the workload involved in routine maintenance is estimated as 3 hours every 6 months.

11.3.2 Specific training requirements

An operator with a standard 8 certificate will be capable of operating the plant if provided with a simple operating manual written in his or her home language. The operator will however, require training in:

- Making turbidity measurements, turbidity meter calibrations and proper sampling procedures (especially for microbiological samples).
- Calibration of the chemical dosing pumps, dosing calculations and dose control.
- Control and operation of filter cleaning.

11.4 Infrastructure requirements

Road access : Vehicular access will be required during installation, commissioning and major maintenance work.

Power requirements : Pumps of up to 2 kW can be adequately supplied by a domestic 220 V supply. In plants requiring more powerful pumps, a three-phase 380 V supply is recommended. If a constant and sufficient gravity head is available, normal filtration can occur without pumping but a pump will be required to supplement the flow during filter washing.

Raw water provision : see Section 11.5.1

Treated water reticulation : The Filtrex is not suitable for direct coupling to a water supply point such as a stand pipe. Treated water storage and a reticulation system will be required.

Sludge disposal : Large volumes of washing effluent are produced (approx. 1 m^3 per wash for the pilot plant) and these require disposal. The washing effluent is relatively dilute and the solids removed during washing settle easily. Concentration of the sludge by sedimentation with supernatant recycling is recommended. The reduced volume of thickened sludge can be treated in drying beds.

Chemical storage : A small garden shed will be suitable for the storage of chemicals and the dosing equipment. The storage facility should be cool, dark and dry to prolong the life of the stored coagulants and disinfectants.

Weather protection : All externally situated electrical equipment should be appropriately insulated. The filter bed and all tanks should be covered to prevent contamination by rain, dust and animals.

Site establishment : A level concrete foundation and reinforced slab of about 2 m^2 will be required.

11.5 Performance of the treatment system

The pilot plant was evaluated over a period of 11 months, from January to November 1993. Approximately 3,5 Mℓ of treated water was produced by the pilot plant during this period.

11.5.1 Raw water supply

Head and flowrate : During normal filtration a head of only 5 m is required. The higher flowrates used for backwashing result in a significantly increased pressure drop and a head of at least 10 m should be available at the backwash flowrate. The backwash rate is approximately 70 m/h while during filtration, a rate of 7 m/h is usually used. If a single pump is used, considerable throttling is required during filtration. This wastes energy and is only economically feasible with bed diameters up to 700 mm (Treffry-Goatley, 1994).

Screening : A screen is recommended for removing coarse material (> 2 mm) from the raw water.

Storage capacity : A 1 m^3 tank was used as a feed water balancing tank for the pilot plant. A dam, weir or tank is recommended for feed water storage to ensure continuity of the raw water supply to the plant. A minimum treated water storage capacity equivalent to 2 days production is recommended as this will provide continuity of supply when the plant is down for maintenance or repair.

Quality of Raw Water : The turbidity of the raw water during the period of evaluation ranged from 1 to 120 NTU with coliform and *E.Coli* counts up to 300 /100mℓ. In **Figure 11.4** it can be seen that treated water turbidities below 1 NTU are consistently produced from raw waters with turbidities less than 50 NTU.

11.5.2 Disinfection system

Disinfection was not incorporated in the pilot plant but sodium hypochlorite based disinfection is preferred by Explochem for Filtrex package plants. Based on the treated water quality achieved with the pilot plant, sodium hypochlorite disinfection will be effective if adequate chlorine doses are maintained. Post-chlorination is recommended. The degree of microbiological removal achieved without disinfectant dosing was assessed and results from a typical set of samples are summarised in **Table 11.4**. It can be seen that most algae, coliforms, E.Coli and faecal streptococci are removed by the filtration process while the concentrations of plate count organisms are not significantly reduced.

Table 11.4 : Microbiogical removal achieved with Filtrex process

Determinand	Units	Raw water	Final water	% removed
E. Coli	/100 mℓ	34	1	97
F. Strep.	/100 mℓ	2	0	100
Coliforms	/100 mℓ	34	7	79
HPC @ 37°C	/mℓ	84	50	41
HPC @ 22°C	/mℓ	257	211	18
Algae	/mℓ	1337	0	100

* HPC .... Heterotrophic plate counts

11.5.3 Turbidity and suspended solids removal

In **Figure 11.3** it can be seen that the treated water turbidity peaks coincide with variations in the raw water turbidity. The plant produced treated water with a turbidity below 1 NTU when the raw water turbidity was in the range of 0 to 60 NTU (see **Figure 11.4**).

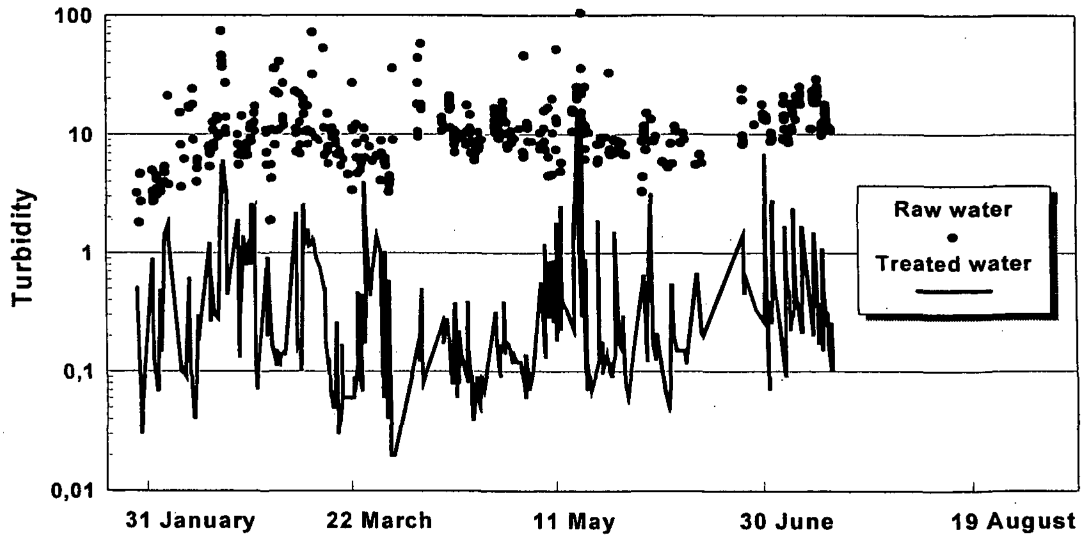


Figure 11.3: Turbidity removal

Treated water turbidities above 1 NTU were produced during the period of filter recovery after cleaning because raw water was used for filter cleaning. This initial filtrate can be either recycled or discarded. Another option is to use treated water for filter washing.

The optimum coagulant dose for the pilot plant was approximately 1 mg/ℓ, significantly lower than the dose used in other package plants and the Wiggins water treatment plant when treating the same water with the same polymer. Optimum filter washing occurred with a water velocity of 70 m/h and an air scour velocity of 35 m/h. Downtime accounted for 2,3 % of the total run time.

Operation at filtration rates higher than 7 m/h will result in shortened filter runs, decreased water recovery and increased operator workload. Turbidity removal may also be affected by operation at higher rates although this was not evaluated on the pilot plant. Water recovery of 97 % was achieved with the pilot plant which compares favourably with the other package plants evaluated. The water recovery can be increased by recycling the settled wash water.

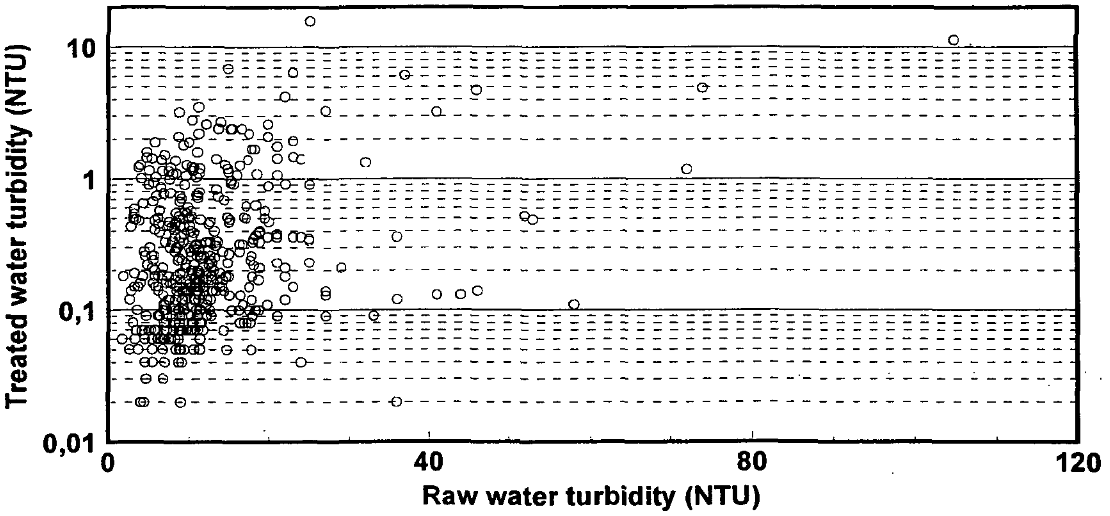


Figure 11.4 : Treated water turbidity as a function of raw water turbidity

11.5.4 Chemical requirements

Three different polyelectrolyte coagulants were successfully used during the evaluation and no significant difference in treated water quality or optimum dose was observed. 2,5 g/ℓ coagulant solutions were used for dosing and doses of approximately 1,25 mg/ℓ were used. This amounted to coagulant consumption of about 0,5 kg/month for the 12 m^3/day pilot plant.

No other chemicals were used for the pilot plant although a disinfectant will be used in the commercially available Filtrex package plants. The required chlorine dose will vary depending on the treated water quality but if post-chlorination is practised, a dose of up to 5 or 6 mg/ℓ may be required for a chlorine residual of about 1 mg/ℓ (as Cl).

11.6 Plant life and reliability

There were no significant failures during the pilot plant's 11 month evaluation period. However, when operated continuously, occasional replacement of one way valves and diaphragms (dosing pumps) or pump seals and bearings (feed pump) will be required. None of the filter components are expected to fail within the lifetime of the plant provided that it is operated correctly.

11.6.1 Materials of construction

The materials used in the construction of the pilot plant are summarised in **Table 11.5** below. The widespread use of plastics will minimise corrosion and maintenance requirements although long-term exposure to the sun and weathering can damage GRP and PVC.

Table 11.5: Materials of construction

Component	Material	Comment
Filter unit	PVC	Corrosion resistant, robust
Piping	PVC	Corrosion resistant, robust
Feed pump	Galvanised Steel	Corrosion resistant, robust
Dosing pump	Polypropylene	Corrosion resistant,
Tanks	Glass reinforced polyester (GRP)	Corrosion resistant

11.6.2 Reliability

Plant and Equipment : There was no significant drop in the flowrate within any 24 hour period. This is the maximum interval for which the plant should be left unattended when the raw water quality is stable. The treated water can be contaminated with untreated water if:

- The chemical tanks are depleted
- The dosing pumps fail
- The treated water isolation valve is not closed during washing.

Dosing system : The pilot plant could operate for up to three days with fully stocked chemical tanks. The existing dosing machinery was adequate when cleaned and calibrated regularly. Since the dosing point was on the pump suction line, a spring-loaded delivery valve was used. During the evaluation, regular calibration of the dosing pump was required, possibly due to worn valves in the pump head.

11.6.3 Potential for expansion of capacity

In a review of upflow filtration processes, Hamann & McKinney, 1968 reported the successful use of upflow filtration rates from 4,8 to 30 m/h for duties ranging from roughing filtration to potable water production. Rates between 4,8 and 12 m/h are usually used for potable water production. *Water Quality and Treatment*, 1990 recommends a maximum filtration rate of 15 m/h for multimedia upflow filters producing potable water. Therefore, it should be possible to accommodate demand fluctuations by increasing the filtration rate as long as adequate turbidity removal occurs.

Since this is an upflow filter the filtration rate cannot increase above the fluidisation velocity of the finest layer of media at the top of the bed. A maximum filtration rate of 12 to 15 m/h (1 m^3/h for the pilot plant) should be observed and proportional dosing will be required. When operated at these higher rates, more frequent monitoring of the treated water turbidity will be required, filter runs will be shorter and head loss development more rapid. If the demand cannot be met by increasing the filtration velocity then additional filter area will be required and this has several consequences:

- The filter washing workload will increase in proportion to the number of individual filter beds.
- The additional beds will use up additional area on the site and this should be considered during the initial planning of the site.
- The pumping energy requirements will increase.

11.7 Servicing, maintenance and repair

Spares, for the repair of mechanical and electrical equipment, are locally available . Pump failure, electrical failure, leaks that will require PVC welding and instrument failures require special skills in order to be repaired. A trained maintenance technician or pipe fitter should be available for emergency situations.

Provision must be made for sand replacement. The operator will require supervision as well as additional labour when changing the sand. The depths and the size of the media need to be carefully checked during replacement.

Raw water pump : A strainer should be added to the plant before the pump as a preventative measure. Bearings and pump seals require an annual check-up and gland type seals may require more frequent adjustment or repacking. The use of mechanical seals is recommended.

Dosing pumps : The dosing pumps incorporate a number of components that can become clogged or worn, ultimately affecting the dose precision. Frequent washing of the valves is important because crystallisation and precipitation was experienced with some of the coagulants used in this evaluation. If the valves are not frequently washed out, the valve seats are easily damaged by such deposits. Pump service kits are expensive and the importance of frequent dosing pump maintenance should be more heavily stressed in the operator's manual. Operating experience shows that the pump diaphragms typically outlast the valves. All dosing pump maintenance tasks except for valve washing should be performed by the maintenance technician. The dosing pump must be recalibrated whenever a new component is fitted or when solutions of different viscosities are dosed.

Valves and fittings : While no routine maintenance of pipework is required the plant's pipework incorporates various different valves and other fittings that can wear out. The PVC ball and check valves fitted to the plant require an annual check for wear. Worn balls or teflon seals should be replaced. The rotameter used for raw water flowrate monitoring should be cleaned to remove algae and grit accumulations.

11.8 Transportation, installation and commissioning

11.8.1 Transportation

Road access will be required for a light delivery vehicle during the installation and commissioning phase. The 4m filter unit has a flange in the centre. Therefore the plant can be disassembled into 2m sub-units, a pump, a tank and the piping for transport. The plant may be difficult to relocate because media removal is a labour intensive task.

11.8.2 Installation

The laying of the foundation and the assembly of the Filtrex unit is labour intensive. Local people should be employed for this work where possible. Installation of the package plant will take about 2 to days on properly prepared sites. Additional time will be required if the site infrastructure and reticulation system is not in place.

11.8.3 Commissioning

Commissioning should not take more than 1 day. An instruction manual was not available for the pilot plant. Since Expolochem builds Filtrex plants to the customer's specification, individual plants may vary significantly and dedicated operating manuals are issued for each plant that is built. The commissioning period can be used for operator training since the plant is relatively simple to maintain and operate.

An important aspect of commissioning is that the filter should be gradually filled with water before the flowrate is increased to the normal operating rate. Chemical dose optimisation, priming and calibration of the dosing pumps is also required. The commissioning of plants fitted with automated control systems may take longer because adjustments to the control system will have to be made.

11.9 Cost

11.9.1 Capital cost

The capital cost of a 15 m^3/day Filtrex plant installed at Albert Falls dam was R 19 750 in 1994 and the capital cost of a 200 m^3/d unit in 1995 was approximately R 165 000.

11.9.2 Operating cost

The total operating cost was estimated at R 1,34 /m^3 for a 15 m^3/d plant and R 0,23 /m^3 for a 200 m^3/d unit. A breakdown of the costs is displayed in **Table 11.6** and it can be seen that significant economies of scale apply to the energy, operating and maintenance costs..

Chemical cost : The average cost of polymeric coagulants in 1994 was R 4,00 /kg. The contents of a 25 ℓ (28 kg) drum of sodium hypochlorite (13,5 % by mass) cost approximately R 41,00 without the container. If polyelectrolyte is dosed at an average of 1,5 mg/ℓ and chlorine at 3,1 mg/ℓ as Cl then the chemical costs will be R 0,01 /m^3 and R 0,033 /m^3 respectively.

Table 11.6 : Estimated operating costs

Component cost	Estimated specific costs (R/m^3)	
	15 m^3/d plant	200 m^3/d plant
Coagulants	0,01	0,01
Disinfectant	0,03	0,03
Electrical power	0,60	0,02
Labour	0,50	0,04
Maintenance and repair	0,20	0,13
Total specific operating cost	**1,34**	**0,23**

Cost of electrical energy : The electricity cost of the pilot plant is based on a consumption of 2,2 kWh/m^3 and Durban Electricity's 1994 'Business and General' tariff of R 0,2643 /kWh. The electrical energy cost was estimated as R0,60 /m^3. This is relatively high in comparison to other package plants using pressure sand filters with higher operating pressures. A single pump was used in the pilot plant for both filtration and washing. The pump was sized for the wash water flowrate and consequently, it was throttled during filtration to restrict the flowrate. As can be seen in **Table 11.6**, the wasted pumping energy significantly contributes to the operating cost of the pilot plant.

Plants built subsequently by Explochem use carefully sized pumps and when bed diameters exceed 700 mm, separate feed and wash pumps are used to reduce energy consumption. For example, a 200 m^3/d unit requires a pump of only 0,2 to 0,4 kW for normal filtration and a backwash pump of approximately 3 to 4 kW which will operate for only 0,5 h/d. This equates to a worst case specific energy cost of approximately R 0,015 /m^3.

Labour cost : The cost of operator labour for the smaller unit was estimated as R 0,5 /m^3 based on a labour cost of R 7 /h and a weekly workload of 7,5 hours. The labour cost is sensitive to the plant capacity and can be significantly lower for plants of larger capacity because the workload does not increase significantly with capacity. For example, the workload involved in operating a 15 m^3/d and a 200 m^3/d plant does not differ significantly and the specific cost of labour will be proportionally lower for the larger plant. Automation can also be used to decrease the operating workload.

Maintenance cost : The annual maintenance cost was estimated as 5 % of the total capital cost of the plant. It was assumed that the plant would operate continuously with 10 % downtime for washing and maintenance. This gave an estimated maintenance cost of R 0,20 /m^3 for the 15 m^3/d plant and R 0,13 /m^3 for the 200 m^3/d plant.

12 JOHNSON'S : Eliminator UV Unit

12.1 Introduction to the Johnson's Eliminator

Johnson's is a Durban based company which manufactures and markets applications for solar energy including water purification systems. Their products are intended mostly for people in remote or underdeveloped communities where conventional electric power is not available. Contact persons are Brian and Clinton Johnson. The telephone number is (031) 327 994 and the facsimile number is (031) 372 434.

The Eliminator is a solar powered ultraviolet (UV) based water treatment system that has a capacity of 0,6 m^3/h and is designed to be portable. Another unit (The Mini-Eliminator) has half the capacity and is usually permanently mounted and used as a disinfection system for groundwater sources.

12.1.1 Plant design philosophy

The unit is designed for use in remote or underdeveloped areas and is portable. It is solar powered and uses no chemicals. The plant is designed to be used in areas where there is little or no infrastructure for water treatment and reticulation.

The unit is simple to operate and maintain. It features push-button operation and routine maintenance is limited to filter cartridge replacement. This is achieved by avoiding the use of chemical dosing systems and complex filter washing procedures.

The plant is housed in a glass reinforced polyester (GRP) housing and consists of a 12V pump, two cartridge filters, a 30 W UV disinfection module, a 12 V lead-acid battery, a 48W solar panel and associated electronic circuitry. The solar panel can be dismantled and packed into the plant housing within minutes and the system transported to a new location.

The unit can be modified to incorporate a reservoir mounted level control system. In areas where gravity feed of raw water is possible, the pump can be disconnected and replaced with an electrically operated valve. This will reduce the power consumption and extend the unit's operating time.

12.1.2 General description of the Plant

The unit is designed for semi-continuous operation in that it can be operated on demand but is a continuous process while in operation. There is no facility for pre-screening of the raw water flow before it enters the pump. There is no clarification process; turbidity removal is by filtration only. **Figure 12.1** shows the plant layout. The plant is designed to operate on demand as follows:

i) The suction line is inserted into the raw water source.

ii) The delivery pipe is inserted into the operator's water container and the plant is switched on by means of a push-button located on the side of the box.

iii) Raw water is pumped through the plant by means of a diaphragm pump and is sequentially filtered though 50 µm and 5 µm cartridge filters before being irradiated by UV light in the disinfection chamber. The flowrate during normal operation is typically 0,6 m^3/h (10 ℓ/min).

iv) When the water container is full, the push-button is released and the unit switches off.

The energy requirement of the plant is approximately 0,19 kWh/m^3. The manual tasks are limited to filter washing and to checking the operation of the lamp and pump. The operator's workload is unlikely to exceed ½ an hour per day. Routine maintenance is limited to occasional cleaning of the Quartz tube in the UV chamber and checking the operation of the electrical components. Routine maintenance tasks include monthly checks on the battery, the solar panel, the UV chamber and the pump. These tasks should not require more than 3 hours every six months.

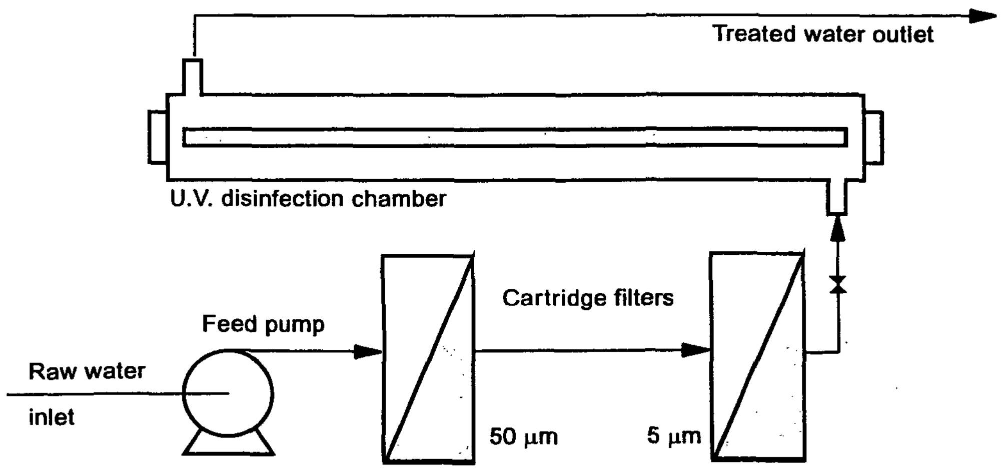


Figure 12.1 : UV unit process flow diagram

12.1.3 Process sophistication

Table 12.1 gives a summary of the process components which are incorporated in the Eliminator plant. Each of these components is described in more detail in the paragraphs which follow the table.

Table 12.1 : Summary of Eliminator process components

Component	Quantity	Description
Pump	1	12V, 85W diaphragm pump with integral pressure switch
Filters	2	Filpro cartridge filters, 50 µm washable and 5 µm wound fibre
Valves	1	½" ball valve, pre-set
UV chamber	1	PVC chamber fitted with 30W, low-pressure mercury vapour lamp
Solar panel	1	12V, 48W solar panel with associated charging circuitry
Battery	1	12V, 75 Ah lead-acid accumulator
Housing	1	GRP box into which the components are fitted

Pump : The diaphragm pump is of the type commonly used in yachts and is self-priming to a height of 2 m above the supply level. It has an integral pressure switch with adjustable cut-off pressure. It supplies a flow of approximately 0,6 m^3/h when the filters are clean.

Cartridge filters : Industrial "Filpro" cartridge filters are used in series for sequential filtration of the raw water through a 50 μm pleated cartridge followed by a 5 μm wound fibre cartridge.

Isolation valve : A ½" stainless steel ball valve is fitted between the filters and the UV chamber. It may be used to isolate the chamber during cleaning and to restrict the flow through the unit so as to ensure that an adequate UV dose is administered to the water being processed.

UV Disinfection Chamber : The chamber is fitted with a 30 W Phillips TUV low-pressure mercury vapour lamp that emits UV light with a wavelength of 254 nm. The lamp fits into a quartz tube (I.D. 27 mm, O.D. 30,5 mm) which runs down the centre of the chamber and the water flows in the annular space formed between the quartz tube and the PVC outer pipe. The chamber is constructed from a length of PVC pipe (90 mm O.D., 82 mm I.D.) with custom-made end fittings and has an internal length of 830 mm. At the operating flowrate of 0,6 m^3/h, the mean residence time of water being treated is approximately 22 seconds.

Solar panel : The solar panel is nominally rated at 48 W, 14 V and the associated charging circuitry is designed for charging a 12V battery. The solar panel is fitted with a collapsible galvanised stand. When erected the frame inclines the panel at 45° to the horizontal. During transport, the panel and folding stand fit into a space in the top of the plant housing.

Battery : A conventional 12 V, 75 Ah lead-acid utility battery provides storage for the electrical energy generated by the solar panel. This battery should be capable of running the unit for approximately 6 hours when fully charged.

Housing : The housing consists of an open topped GRP box. The floor of the housing incorporates a raised ridge around the battery holder to contain acid spills and several drilled holes for drainage of any water that spills during filter changing operations. Aluminium pop rivets and galvanised bolts are used to secure the various components to the housing. A GRP cover fits over the box and can be locked in place. The outside of the box is fitted with attachments for the suction and delivery pipes, a socket for the external solar panel, four sturdy galvanised handles and a sprung push-button switch for operation of the unit.

12.2 Process control system

12.2.1 Operation and control sequence

The unit's control system is simple and is based on limiting the flowrate to a predetermined maximum value so that an adequate UV dose is administered. The unit is operated by pressing the push-button on the housing. After a delay of about 1 second the lamp lights up and irradiates the chamber. Three seconds later, the pump starts and filtered disinfected water is produced. The purpose of the time delay is to prevent contaminated water from passing through the system without being disinfected. In similar fashion, when the unit is switched off, the pump stops first and the lamps switches off about three seconds later.

12.2.2 Degree of automation

The standard Eliminator plant is totally manually operated but the push-button switch may be replaced with a float switch or other level control system when the unit is used in conjunction with a treated water storage tank.

The associated charging circuitry includes overcharge and discharge protection. These features are designed to extend the service life of the battery by preventing repeated overcharging and total discharge of the battery. The electronic control system also includes an audible alarm which sounds if the UV lamp fails.

12.2.3 Monitoring of the process parameters

Apart from the alarm, no instrumentation is fitted to the plant. The need for filter cartridge cleaning or replacement is judged by monitoring of the flowrate and final water turbidity. Both of these parameters can be simply assessed. If the filters are allowed to become totally clogged, the pressure switch on the pump will activate, and this will serve to warn negligent operators of the need for cleaning.

The purpose of turbidity monitoring is to assess the aesthetic acceptability of the water which can be achieved in the field by means of comparator tests. If the turbidity is high, significant absorption of UV light may occur thereby reducing the effectiveness of UV. In practice it was found that waters with a turbidity in excess of 10 NTU cannot be reliably disinfected with this UV system. This general rule of thumb does not account for dissolved minerals and organics which may absorb UV light.

Monitoring of the disinfection system is more difficult. As UV lamps age, the intensity of radiation emitted by them declines even though the lamp still operates. The Eliminator's alarm system does not monitor UV output intensity. In addition, certain waters tend to deposit a scale or fouling layer on the wetted surface of the quartz sleeve which can also lead to reductions in UV intensity in the chamber.

The operator of the Eliminator has no means of determining the disinfection efficiency of his system and should therefore:

- Keep an accurate logbook of plant operation. Recent versions of the Eliminator incorporate an hour meter in the control system that allows the operator to observe the elapsed lamp operating time and replace lamps at appropriate intervals.
- Open the UV chamber and clean the quartz tube on a three monthly basis. If no significant fouling builds up in this time then the frequency of cleaning may be decreased.

- Regularly submit samples for microbiological analysis by a water authority or commercial laboratory.

By comparison, commercially operated UV units in full-scale water treatment plants incorporate intensity sensors for each lamp and usually include automatically operated standby chambers. The intensity of each lamp's output is regularly recorded and a strict schedule of sleeve cleaning and lamp replacement is followed.

12.2.4 Effectiveness of the control system

The objective of the Eliminator is to produce potable water by means of suspended solids removal and disinfection. The control philosophy is based on flow control to achieve adequate residence time in the UV chamber. This philosophy is effective for controlling the UV dose.

Turbidity removal by the cartridge filters is not significantly sensitive to the flowrate. Since no chemical treatment is used to aid filtration the only way to improve the turbidity removal of the system is to install cartridges with a finer pore size.

12.2.5 Uncontrolled parameters which may affect water quality

There are uncontrolled parameters that may affect the quality of the final water from this plant. In most cases this is not due to shortcomings of the design but rather to consequences of the type of technology used.

Raw water quality cannot be controlled but since no particle coagulation or flocculation occurs, the final water turbidity will be affected by the quantity of particles in the raw water whose size are smaller than the pore size in the filters. Thus raw waters with high colloidal suspended solids will cause higher treated water turbidities than a plant that uses conventional coagulation, flocculation and filtration. This is a consequence of the type of filtration process selected for the unit. The choice of a more effective filtration system would have adversely affected the portability, cost and simplicity of the unit.

The incident solar radiation also cannot be controlled but careful siting and maintenance will allow the unit to make maximum use of the available solar power. The unit's capacity will be affected if it is sited in an area where the amount of direct sunlight is reduced either by shadows or by consistently cloudy weather. In winter the days are shorter and the solar radiation more oblique so the maximum capacity of the unit may be affected by the season. Although the solar panel is not equipped to track the sun, the operator should be aware that the orientation and cleanliness of the panel is important and that seasonal adjustments may be required.

Fouling of the quartz tube due to deposition of scale or suspended matter that passes through the filters will affect the intensity of the UV light in the chamber and reduce the disinfection efficiency. The operator should be aware of the need for routine cleaning of the tube.

Uncontrolled flow can occur if the system operates under gravity feed because the system is not positively sealed when the pump is not operating. This allows water to trickle through the system and will result in water passing through the system without disinfection. Since the treatment system does not remove nutrients or leave a residual disinfectant in the treated water, the possibility of contaminating the treated water with viable organisms exists. In gravity fed applications it will be more beneficial to replace the pump with a solenoid valve which fails in the closed position. Such a valve would consume less power than the pump and therefore allow the unit to operate for longer periods at a given charging rate.

12.2.6 Susceptibility to demand fluctuations

Once the unit has been installed in a particular application, the maximum flowrate will be determined by the suction head and the restrictor valve setting. The flowrate will decline with increasing filter loading thereafter. Demand fluctuations will simply result in the plant being in operation for longer periods when demand is high.

Theoretically, the unit will operate for approximately 7,9 h on a fully charged battery. However, the plant draws power from the battery faster than it can be recharged by the solar panel and the reserve of power in the battery begins to be depleted whenever the plant is operated.

The solar panel will only be effective during periods of bright, direct sunlight. The mean annual peak sunlight hours for productive use of solar panels in Southern Africa varies from 2,8 h/day to 6,5 h/day depending on the latitude and the season (D. Filippa, Grinaker System Technologies). The manufacturers of the panel (BP Solar) use an average of 5,0 h/day when sizing panels for local installations. Recommended panel tilt angles vary between 15° and 55° depending on latitude. The 48 W solar panel fitted to the plant is thus capable of producing an average daily charge of about 14,6 Ah or 240 Wh/day. Normal power consumption is approximately 115 W so it follows that the maximum daily operating time over an extended period is limited to 2,1 h of operation at 0,6 m^3/h yielding approximately 1,3 m^3/day of treated water. This is a long term average value which may be doubled in practice during periods of sunny summer weather.

12.3 Personnel requirements

It is important that one person be appointed as 'operator' of the plant since some of the routine monitoring and maintenance tasks will be inconvenient or too difficult for the ordinary user. The operator should be responsible for:

- Filter cartridge replacement.
- Monitoring of the flowrate to indicate when cartridge replacement is necessary
- Three-monthly inspection of the quartz tube to ensure that no fouling layer is present. The operator should be capable of dismantling the chamber and cleaning the tube when necessary.

- Regular monitoring of the orientation of the solar panel combined with weekly cleaning to ensure maximum capture of incident solar radiation.
- Procurement of consumable items such as spare filter cartridges and lamps.

A maintenance and repair technician will be required for three monthly water quality monitoring and maintenance of the unit. It is envisaged that this technical support group would have responsibility for the maintenance of a number of such units in a given area or be contractually assigned by a regional water authority for such services.

12.3.1 Workload estimation

Installation and commissioning : The installation of this unit can be accomplished rapidly and consists of:

- Assembly and alignment of the solar panel.
- Connection of the unit to the raw water supply.
- Start-up of the unit.

This can be done in minutes at a suitable site and all that is required for commissioning is to set the restrictor valve so that the flowrate is limited to less than 0,65 m^3/h for proper disinfection of the local raw water source. The evaluation of disinfection efficiency will require microbiological analysis which usually requires an incubation period for samples. Results will usually be available 48 to 72 hours after sampling if analysed by a commercial laboratory. Quick methods are available which are useful for field work, producing results in a few hours. The accuracy of these results would have to be checked by submitting samples to a commercial laboratory on a regular basis.

Routine operation : The longest operator tasks are filter cartridge replacement and lamp replacement. Neither of these tasks take more than twenty minutes. The frequency of filter replacement will depend on the suspended solids load in the raw water and plant operating time. The frequency of changing a lamp will depend on the number of cycles of operation but should not exceed three per year. This task can be performed by the operator in 5 minutes.

Maintenance and repair : This is expected to be small and will consist mainly of travelling to the installation and monitoring its operation on a monthly basis. The maintenance workload is not expected to exceed six hours per plant per annum (excluding travelling time).

12.3.2 Specific training requirements

Training of operators : For long term operation of this unit, an operator from the user community will be required for routine tasks as mentioned in **Section 12.3.1** and fault reporting. Training of the operator should concentrate on these aspects. The manufacturers do not offer a formal training course or an operating manual but do undertake to train operators in the basic skills required for operation of the unit.

Training of users : The operator will be required to train users in the proper use of the plant. In practice this plant will typically be situated at a central point close to the raw water source and community members will fetch water from it or it may be installed as a point of entry (POU) system in a private home where the water supply was previously untreated. In either case, the unit will be used at one time or another by all community or household members. These people will require rudimentary training in the use and operation of the unit. The importance of using a clean, uncontaminated container for collection of treated water must be stressed as the treatment system does not leave a residual disinfectant capability in the treated water and also does not remove nutrients from the water. Thus there is potential for regrowth of micro-organisms if a contaminated container is used, especially if the water is allowed to stand for a period of time before use.

A third type of application is the harnessing of an Eliminator unit to a small reservoir and reticulation system. The operator of such an installation should understand the potential that the system has for micro-organism regrowth and be able to apply supplementary disinfection (such as occasional chlorine flushing) in a responsible manner. It should be stressed to the users of the Eliminator that regular disinfection of water containers will still be necessary but that further treatment of the treated water itself should not be necessary.

Training of technical support team : It is assumed that the members of the technical support team for such installations will be familiar with basic water treatment tasks such as replacement of filter cartridges, cleaning and sampling. However they will also require specific training in aspects of battery maintenance, UV lamp replacement, simple troubleshooting and stripping and servicing of the pump used in the Eliminator unit.

12.4 Infrastructure requirements

Since the Eliminator is compact, portable and solar powered, it is ideal for applications where the infrastructure is limited. No electrical power is required and the portability of the unit means that no road access is required. However, due to limited suction head requirements, the plant should be situated within 2 m (vertically) of the raw water source. Facilities for the storage of spare lamps and filter cartridges are built into the housing.

The site preparation will depend on the type of application envisaged by the users. In applications where individual users require access to the plant the following will be required:

- A level stable mounting platform, preferably above ground level and preferably incorporating a small drainage channel. The platform should be positioned that the user has access to the push-button switch and a well drained space for resting water containers during filling.
- Drainage from the platform should re-enter the raw water source downstream of the intake.
- The plant housing should be padlocked so that only the appointed operator has access to it.

In applications where the unit is used to supply a reservoir prior to entering a reticulation system the reservoir and reticulation system must be covered to prevent the entry of sunlight (which can result in photo-reactivation of micro-organisms) and to prevent contamination by dust, bird droppings and insects. Occasional treatment of the reservoir and reticulation system with a small quantity of hypochlorite solution or granules is recommended.

12.5 Performance of the treatment system

The plant was operated intermittently during the period from February 1993 to September 1993 when a water meter was installed on the unit. During the period from September 1993 to April 1994 approximately 35 m^3 of raw water was treated. Typically, the unit was operated for about 20 minutes at a time. The pump motor did not have cooling fins and when the unit was operated for longer periods, the pump motor would tend to heat up significantly and the flowrate would decrease.

12.5.1 Raw water supply

At the Process Evaluation Facility, the plant was supplied with raw water from a tank fitted with a float valve. A constant positive raw water head of approximately 1 m was supplied to the plant. During periods when the plant was not operating, water would continue to flow through the plant. This shows that the plant does not provide a positive seal against raw water pressure when a gravity feed system is used. The use of a fail-safe solenoid valve in place of the pump is recommended for applications where the raw water is available under pressure.

In field applications, screening of the raw water supply will be necessary to prevent the entry of suspended matter that might damage or block the pump diaphragms. A screen or strainer with 2 mm mesh size is recommended. The 12 V pump used on this unit is self-priming for up to 2 m above the source. In permanent installations it may be feasible to mount the pump apart from the housing. However, it is not recommended that the unit be separated from the water source by an elevation of more than 2 m or a distance of more than 10 m because frictional flow resistance in the suction line will contribute significantly to the suction head.

12.5.2 Micro-organism removal

The main advantage of the use of UV light over chlorine or ozone for disinfection of potable waters is that it does not produce reaction products (such as trihalomethanes or taste and odour causing compounds) within the treated water stream. It also does not have the handling problems that are encountered with strong oxidants like chlorine and ozone although the lamps must be shielded during operation.

Samples of raw and treated water were taken on nine occasions between 7 March 1993 and 12 April 1994. The results are given in **Table 12.2** and show that in all cases, 100% inactivation of Coliforms, *E Coli* and Faecal Streptococci occurred. The heterotrophic plate counts remained within the 1994 Dept of Health guidelines in eight out of the nine samples and the out-of-range sample (shaded in **Table 12.2**) was not significantly above the recommended limit of 100/mℓ.

Table 12.2 : Disinfection results

(The percentage disinfection and the residual cell concentration are shown for each determinand)

Date	Sample turbidity	Coliforms		*E. Coli*		Faecal Strep.		Plate counts @ 22°C		Plate counts @ 37°C	
	NTU	%	/100ml	%	/100ml	%	/100ml	%	/ml	%	/ml
07/05/93	7,6	100	0	100	0	100	0	75,9	83	100	0
10/09/93	6,5	100	0	100	0	100	0	99,0	4	91,7	2
17/09/93	7,6	100	0	100	0	100	0	70,1	88	96,3	5
06/10/93	20,0	100	0	100	0	100	0	63,2	21	75,4	35
13/10/93	17,9	100	0	100	0	100	0	75,5	47	92,6	5
02/11/93	7,4	100	0	100	0	100	0	89,3	24	90,9	5
24/11/93	10,0	100	0	100	0	100	0	99,5	12	98,8	3
15/03/94	18,5	100	0	100	0	100	0	80,2	166	94,3	50
12/04/94	37,0	100	0	100	0	100	0	66,7	64	84,2	38

The unit was disinfected by flushing with a sodium hypochlorite solution on two occasions (8 September 1993 and 16 February 1994) Microbiological results from samples taken before and after these dates show no evidence of significant increases in the plate counts with time after flushing. This indicates that no significant biofilm growth occurred in the pipework between the UV chamber and the sampling point (end of outlet hose). No significant difference in disinfection efficiency was observed at different flowrates. Three experiments were performed in which samples of the treated water taken at different flowrates were analysed. A typical result is shown in **Table 12.3**.

Table 12.3 : Typical disinfection efficiency at various flowrates

Sample	Flowrate	Turbidity	E.Coli	Coliforms	F.Strep	Colony counts	
	m^3/h	NTU	/100 ml	/100 ml	/100 ml	/ml @ 22°C	/ml @ 37°C
Raw water	-	29	106	190	30	344	466
Filtered 1	0,33	2	0	0	0	112	0
Filtered 2	0,44	5	0	0	0	63	0
Filtered 3	0,60	8	0	0	0	83	0

These disinfection results were achieved with relatively turbid filtered waters. The turbidity of the samples ranged from 6,5 to 37 NTU with an average of 15 NTU. It can be seen that in general, higher plate counts were observed in the more turbid samples.

Dosing system : Although there are no legislated requirements for the UV dose that must be administered to water to ensure disinfection, an industry standard of 32 mWs/cm^2 is typically used as the basis for sizing UV disinfection equipment.

In order to calculate the UV dose administered by the system, the following basis was used:

- Power output at 254 nm; 9,0 W (Lamp manufacturer's specification for new lamp).
- Lamp represents a linear light source of length 830 mm.
- Quartz tube absorbs approximately 40% of incident UV light (typical of poor quality sleeves).
- Transmittance of water being treated is 90% (typical of values measured during the evaluation with waters of turbidity < 20 NTU)
- UV output intensity equal to 70% of the new lamp value.
- Plug flow occurs in the annular chamber with negligible axial and radial dispersion.
- The flowrate equal to 0,73 m^3/h (maximum flowrate recorded during the evaluation)

Under these conditions the minimum UV dose was estimated as 35,7 mWs/cm^2. At the typical operating flowrate of 0,6 m^3 the estimated minimum dose is 43,4 mWs/cm^2. It can be seen that the Eliminator's UV system exceeded the minimum recommended dose under the conditions in which it was operated during this evaluation. However, it is recommended that the Eliminator plant should not be used when the transmittance (at 254 nm) of filtered water samples does not exceed 85 %.

12.5.3 Turbidity and suspended solids removal

The cartridge filter system has the advantages of portability, simplicity and flexibility. The system is flexible because a wide range of different cartridges are available from several manufacturers and the system will allow specification of suitable cartridges for individual applications. The disadvantages of the cartridge filter system include the relatively low solids loading capacity of the cartridges, poor turbidity removal and the need for disposal of used cartridges.

Since no form of coagulation or flocculation is used, contaminants such as colloidal suspended solids, colour and organic compounds are likely to pass through the filter system. All of these components can affect the efficiency of UV disinfection as a result of screening (suspended solids) or absorption of UV light (suspended solids, colour and organics) which will decrease the radiation dose administered to micro-organisms in the water being treated.

Figure 12.2 shows the relationship between raw and filtered water turbidities during the evaluation period. The turbidity removal performance of the cartridge filter system is relatively insensitive to the flowrate at which the unit operates. However, it can be seen that there is a distinct relationship between the raw and filtered water turbidity. Only 30% of the influent turbidity was removed by the cartridge filter system. **Filtered water turbidities below 1 NTU were not achieved with this filtration system.** The use of this unit for treating raw waters with turbidities in excess of 10 to 15 NTU is not recommended since higher turbidities are expected to severely compromise the disinfection efficiency.

The design of the unit does not preclude the use of raw water pretreatment. In permanent or semi-permanent installations, the feasibility of pre-clarification of the raw water should be investigated, especially if the raw water exhibits high levels of colour, turbidity or organic loading.

This unit could also be used in conjunction with a separate filtration unit in which case the cartridge filters could be removed and the unit used solely for disinfection.

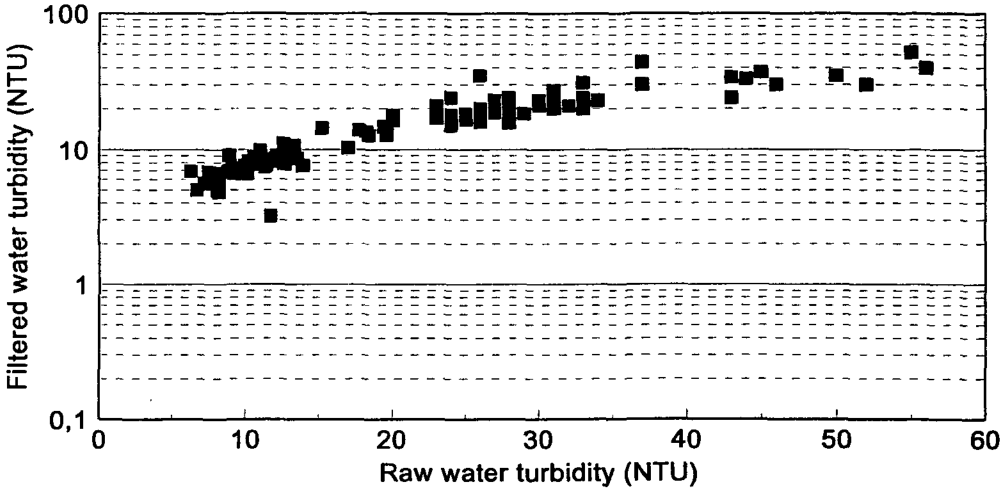


Figure 12.2 : Relationship between raw and filtered water turbidity

During the evaluations the "washable" pleated cartridges become clogged within 2 hours (1,2 m^3) after washing. Various washing methods such as rinsing, scrubbing and backflushing were attempted but none of these methods satisfactorily restored the filtration capacity. The average service life of both types of filter cartridge was approximately 13 hours for plant flowrates of 0,6 m^3/h. The loss of water during cartridge replacement is equivalent to the volume of the cartridge housings (about 2 ℓ each) and the effective water recovery with this process exceeds 99,9 %.

12.5.4 Chemical and consumable requirements

It is recommended that a small quantity of calcium hypochlorite granules is kept by the operator for occasional flushing of the unit. After maintenance or repair work where the possibility exists that contaminated water may have entered or passed through the radiation chamber, a small amount of granular hypochlorite (e.g. a teaspoonful of HTH) should be added to one of the filter bowls. The unit should then be started and the first 100 litres of water discarded. This will ensure that the entire system is properly disinfected before the water is made available to the consumer.

Based on the average operating life of filter cartridges achieved during the evaluation, these will require weekly replacement if the plant operates at maximum capacity (2 hours per day) although this will depend on the raw water quality. It is recommended that one month's supply of cartridges be kept in stock. The housing has facility for the storage of two spare cartridges.

The manufacturers recommend changing lamps after 2000 hours of operation. Operating experience with another UV system that used similar lamps indicates that with 15 to 20 minute cycles of operation, lamps may begin to fail after 500 hours of operation. It is recommended that two spare lamps be kept in stock at all times. The housing is fitted with a holder for a spare lamp and an additional holder can easily be fitted if necessary.

12.6 Plant life and reliability

12.6.1 Materials of construction

The choice of materials used for construction of this unit has been influenced by the need for portability, sturdiness, weatherproofing and reliability.

The housing , pump, filter modules and UV chamber are all constructed from materials which will not corrode. However the long term resistance of the PVC disinfection chamber to intense UV light is uncertain. UV disinfection chambers are conventionally constructed from stainless steel which is considerably more expensive.

Copper pipes of ½" diameter have been used for the interior pipework. All joints are soldered except where brass "Conex" adapters have been fitted for the threaded connections to the hoses, the pump, the UV chamber, the valve and the filter housings. The layout of the pipework is neat and does not obstruct access to any of the components.

Since the system does not operate at elevated temperatures or pressures, the use of PVC or polyethylene pipework may prove to be cheaper and more effective. Some external corrosion of the soldered joints in the copper tubing occurred during the evaluation but no significant quantities of corrosion products (copper, lead or tin) were detected in the treated water. The exterior piping (suction and delivery lines) consists of conventional 12 mm garden hose and associated brass connectors which are durable and widely available.

While the interior wiring is well secured and will not be subjected to wear and tear, the two-core flex leading to the solar panel will be subjected to harsh treatment and the use of a double insulated flex for this purpose is preferable.

12.6.2 Reliability

Plant and Equipment : The pump motor is fully enclosed and does not have any forced ventilation or cooling fins. This pump was designed for occasional use in yachting applications and is not designed for continuous operation. The motor housing heats up considerably after 20 minutes of continuous operation.

In May of 1993 a small amount of leakage from the pump casing was observed. This led to corrosion of the main bearing which eventually seized. The pump was stripped and repaired by the local agents at a cost of R100,25 (June 1993). The diaphragm housing and the bearing were replaced. No estimate of the total pump running time could be made because the unit had been used prior to this evaluation.

The operating life of the UV lamp is uncertain. The output intensity of UV lamps deteriorates with use. The normal operating life of a low-pressure UV lamp is between 7 000 and 10 000 hours (eight hour cycles of operation) according to lamp manufacturers. Deterioration of lamp output is accelerated by the number of cycles of use. In the Eliminator plant, the lamp will be regularly switched on and off and suppliers of the plant recommend changing the lamp every 1 000 to 2 000 hours of use if it is operated intermittently.

Control System Components : The consequences of failure of the various components of the process are outlined in **Table 12.4**. The electronic control circuitry was custom made for this application and did not give trouble during the period of this investigation. The push-button switch was securely mounted to the side of the housing and sealed by a flexible rubber cap. The cap will eventually perish but the switch appears to be of good quality. This switch will be subjected to more physical handling than any other component of the process and may be expected to fail before other components. The solar panel is likely to be mounted in a prominent and exposed position. As such, it may be susceptible to lightning which could result in damage to the electronic control unit . If the panel is mounted in an elevated position (such as in a tree or on a pole) a lightning conductor should be used.

Table 12.4 : A summary of the consequences of component failures

Component	Direct consequence of failure	Effect on water quality
Push-button switch	Unit will not switch on.	Potable water production will cease
Solar panel	Battery charging will not occur	Potable water production will cease when the battery is depleted.
Overcharge protection	The battery will be overcharged resulting in chemical damage to the cells and reduced battery life.	Gradual reduction in battery capacity will result in reduced plant capacity.
Undercharge protection	The battery will be repeatedly discharged and battery life will be reduced.	Gradual reduction in battery capacity will result in reduced plant capacity.
UV lamp	The lamp alarm will sound indicating that the lamp has failed.	Disinfection will cease and contaminated water will be produced if the unit is operated in this state.
Pump	Flow through the unit will cease	Potable water production will cease unless gravity feed is used.
Alarm	No warning will be given of lamp failure	Contaminated water may be produced unwittingly.

12.6.3 Potential for expansion of capacity

The capacity of the unit that was evaluated is restricted by the capacity of the solar panel. This restricts the unit to an average of two hours operation per day. In addition, the diaphragm pump consumes most of the electrical energy used by the unit and tends to overheat if operated continuously for periods longer than 20 minutes. In order to expand the system, the solar panel must be sized correctly and a more reliable feed pump must be supplied. Alternatively a gravity fed system will conserve energy and allow a more continuous operation.

The UV dose administered by the system will decrease in inverse proportion to increases in the flowrate. Significant increases in the flowrate will result in the UV dose falling below the US EPA guideline value. Attempts to increase the flowrate through the plant are not recommended unless the capacity of the UV system is appropriately uprated.

12.7 Servicing, maintenance and repair

12.7.1 Operator maintenance tasks

The operator should be responsible for the following tasks which should be performed on a weekly basis:

- Cleaning of screens on the intake pipe.
- Replacement of filter cartridges when clogging is indicated by reduced flow rate.
- Cleaning the solar panel and checking its orientation.
- Replacement of lamps when necessary.

12.7.2 Maintenance tasks requiring skilled personnel

A suitably trained artisan will be required on a three monthly basis to:

- Check energy capture system, including battery electrolyte levels, charging circuitry and solar panel orientation.
- Check pump motor brushes, bearings and diaphragm.
- Check operation of UV lamps and replace if necessary.
- Check all pipework and repair where necessary.
- Monitor water quality. Periodic microbiological testing of the treated water will determine if the disinfection system is operating effectively.

12.8 Transportation, installation and commissioning

12.8.1 Transportation

When packed for transport the entire unit, including the solar panel and stand, is contained in the housing and has a dry mass of approximately 85 kg. The unit can be transported in the boot of a large car or in a light delivery vehicle. It can be carried by two people but four will be required if it is to be carried for any distance by hand. Four sturdy galvanised carry handles are fitted but these have a narrow grip and are uncomfortable to use.

12.8.2 Installation and commissioning

Installation consists of connecting the suction line to the raw water source, assembling the solar panel and orienting it for maximum solar energy capture. The housing can be locked and the entire unit chained to a fixed object to deter theft or vandalism. This plant does not require commissioning but the raw water at the installation site should have a transmittance exceeding 85% at 254 nm to ensure that the water being treated will receive an adequate UV dose.

12.9 Costs

12.9.1 Capital cost

The capital cost of the unit in July 1993 was approximately R7 150,00. This excludes the cost of any site preparation. The solar panel constitutes approximately 25% of this cost and is the most expensive single component in the process.

12.9.2 Operating cost

The cost of components of the operating cost have been estimated and are summarised in **Table 12.5**. The sum of these individual estimates is the estimated overall operating cost of the unit.

The operating cost is relatively high in comparison to the other package plants evaluated during this project. The high cost is due largely to the small capacity of the unit and the high cost of operating the cartridge filter system. The estimated labour cost is also significant but in most cases, the operators tasks will be performed for free by a member or members of the family unit or small community that operates the unit.

Table 12.5 : Summary of operating costs

Description	Item Cost	Service life	Operating cost
	R (1993)	m^3	R/m^3
UV Lamp replacement	52,00	1200	0,04
50 μm filter cartridge	30,00	7,8	3,85
5 μm filter cartridge	11,25	7,8	1,44
Battery	180,00	>1300	0,14
Maintenance	-	-	0,68
Labour	-	-	0,83
Total			**6,98**

Chemical / Consumable cost : The lamps used are Philips TUV, 30W, low pressure, mercury vapour lamps. The cost of the lamps varies according to the supplier. The manufacturers of the unit quoted R165,00 per lamp (February 1993) while a local electrical supplier quoted R52,00 per lamp.

The lamp manufacturers (Phillips) quote lamp life as approximately 8 000 to 10 000 hours based on 8 hour operating cycles. The lamp life deteriorates with increasing cycles of operation. The Eliminator, with its "on demand" mode of operation, will have a much higher number of cycles and the lamp life can be expected to be less. The manufacturers of the unit recommend replacing the lamps every 2 000 hours of operation and will be installing a clock counter on future units which will enable monitoring of the lamp operating time.

Assuming average flow of 0,60 m^3/h, average operation of 2 hours per day and a lamp life of approximately 2 000 hours a single lamp should treat 1200 m^3 of water at a cost of R0,043 /m^3.

The filter cartridges cost approximately R40,00 each for the washable cartridges and R15,00 for the disposable cartridges (Johnson's, February 1993). The filter cartridge manufacturers (Filpro) quote R30,00 and R11,25 respectively for the same items. The average service life of the cartridges during the evaluation was 7,8 m^3. Filter cartridge cost is therefore estimated at R5,28 /m^3.

Cost of power : No routine operating expenses will be incurred by the solar panel and battery system. The solar panel manufacturers (BP Solar) provide a 10 year limited output guarantee and with normal use, the panel should last longer than 10 years.

When used in motor vehicles, lead-acid batteries are typically exposed to high loads of short duration (starting), a wide range of temperatures and much vibration. Under these conditions their typical service life is between 1 and 3 years. The battery fitted to the Eliminator should experience a significantly less hostile operating environment. With proper care and normal operation it should last for at least 4 years. The cost of a replacement battery in 1993 was approximately R180,00. The long term cost of battery replacements should therefore not exceed R 0,14 /m^3.

Labour cost : The operator's workload should not exceed 1 hour per week. Since this unit is designed as a POU application it will probably be owned and operated by individual families or small consumer groups. The operator may not be paid if his contribution is perceived as a family or community duty. If he is paid (R7,00 /h) the costs will be approximately R0,83 /m^3. This figure is also high in relation to the other plants evaluated because of the relatively lower flowrate.

Maintenance costs : The cost of plant maintenance will depend on the distance travelled by the artisan involved and the repairs performed but should not exceed R300,00 per annum. If the unit operates on a daily basis this equates to approximately R0,68 /m^3 for maintenance. This cost estimate is far higher than the estimated cost of maintenance for the other units evaluated because the capacity of the Eliminator unit is relatively low in comparison.

13 SELECT WATER & ENGINEERING SERVICES Watermaker Package Plant

13.1 Introduction to the Watermaker

The Watermaker plant is manufactured and assembled by Select Water & Engineering Services based in Ferndale, Johannesburg. Contact persons are Paul Mossner or Adrian Parsons. The telephone number is (011) 792 2590 and the facsimile number is (011) 792 3105.

A range of plants with capacities from 2,7 m^3/h to 8 m^3/h with a choice of fully automatic and semi-automatic control systems is available. The plant that was evaluated was nominally rated at 2,7 m^3/h and was fitted with a fully automatic control system.

13.1.1 Plant design philosophy

This plant was designed as an automated application for the use of a powdered coagulant chemical (Watermaker powder) that was developed by Control Chemicals. This powder has several advantages which make it attractive for package plant applications:

- It is easy to handle.
- No preparation or dilution is necessary.
- It is effective over a wide range of raw water turbidities
- It can be moderately overdosed without affecting treated water quality although the recommended dose should not be exceeded.

The plant is limited to operation in areas where suitable electrical power is available. It is intended for use as a complete package water treatment process that can be easily transported, assembled and commissioned by two persons. A batch process incorporating sequential coagulation, flocculation, sedimentation, filtration and post chlorination is used.

The modular construction of the plant consists of commercially available components. Different combinations of settling tank, filter and pump size can be specified for each individual application and subsequent capacity enhancement can be engineered by specifying additional or larger components where necessary (see **Section 13.8.4**).

13.1.2 General description of the plant

The plant consists of a 3,5m^3 glass reinforced polyester (GRP) tank with a conical base, a filter pump, a pressure sand filter, a sludge pump and electrical control panel (see **Figure 13.1**). Apparatus for mixing and chemical dosing is mounted on a cross-member attached to the top of the tank. The plant operates automatically, treating successive batches of raw water as follows:

i) The settling tank is filled with raw water

ii) Watermaker powder is dosed and mixed according to adjustable timer settings

iii) The flocculated water is allowed to stand for a period, allowing sedimentation to occur.

iv) The supernatant water is pumped through a pressure sand filter and disinfected.

v) The residual sludge in the settling tank is pumped out to waste.

The next batch commences as soon as the sludge pump switches off. The cycle time varies between 60 and 80 minutes depending on the timer settings, the inflow rate and the filtration rate. Each cycle produces approx. 3,0 m^3 of treated water and approximately 0,5 m^3 of waste effluent containing sludge.

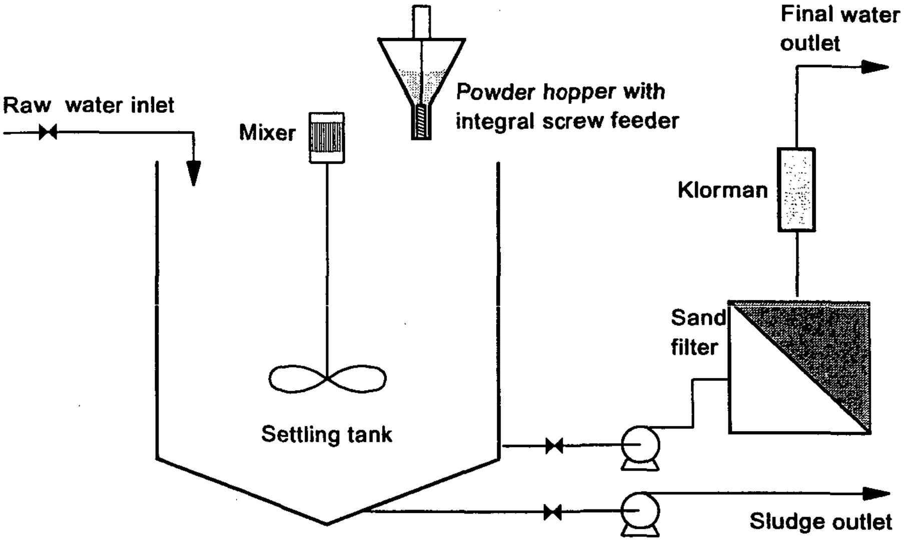


Figure 13.1 : Batch process flowchart

The plant is designed to operate from a 220 V, 16A domestic power point. Average power consumption is approximately 0,24 kWh/m^3 (see **Table 13.1**). The recommended powder dose is 200 mg/ℓ but satisfactory operation was achieved with doses as low as 110 mg/ℓ (see **Section 13.5.3.1**) and each Klorman capsule is capable of treating approximately 180 m^3 of filtered water.

13.1.3 Process sophistication

The Watermaker process is relatively sophisticated in comparison with many package plants but the sophistication is hidden from the operator and the process remains extremely simple to operate. Standard electrical components are used and the automation system provided was reliable.

All timer settings and level control adjustments are made during commissioning and the only adjustment required during normal operation is the adjustment of the chlorine dose. Experienced operators may adjust the timer settings to compensate for seasonal water quality variations. Backwashing of the filter is very simple; requiring only the manipulation of the pump override switch and the multiport valve.

Table 13.1 gives a summary of the number and types of process components incorporated in the design of this plant. Custom-made components include the settling tank, mixer impeller and the combination screw-feeder for the coagulant powder. All custom made components have been constructed from either GRP, stainless steel or galvanised steel and are very robust. All other items are commercially available and can be purchased through industrial equipment suppliers.

Table 13.1 : Summary of process components

Component	Quantity	Comments
Valves	6	2 x PVC ball valves on tank outlets 1 x Brass 8V solenoid valve on inlet pipe 2 x PVC non-return valves on pump delivery pipes 1 x PVC Multiport valve mounted on top of sand filter
Pumps	2	1 x 1,10 kW Speck centrifugal pump (filtration) 1 x 0,75 kW Speck centrifugal pump (sludge removal)
Dosing apparatus	2	1 x conical hopper with screw feeder for powder delivery 1 x chlorinator device on filter delivery pipe
Mixers	1	1 x 1,5 kW mixer with vane type 4-blade impeller
Filters	1	1 x Pressurised rapid sand filter. Diameter 0.75 m.
Tanks	1	1 x 3,5m^3 GRP tank with 30° conical base and open top

Pipework and fittings : Class 16 PVC pipes and solvent welded fittings are used for the pipework system. Appropriately positioned unions allow the plant to be rapidly dismantled into its individual components for transport and relocation. Although UV stabilised PVC is used, the pipework should be painted with a UV resistant paint to improve its service life. Alternatively, the pipework, the filter and the pumps should be housed under a small shelter to shield them from weathering and extend their service life.

The process makes use of six valves of various types:

- Two 63 mm PVC ball valves are used on the supernatant and sludge outlets of the settling tank to isolate the tank when the pumps or the filter are removed for maintenance or repairs.
- A 1¼" brass solenoid valve is used to control inlet flow to the tank. In most installations, a pressurised source of raw water is not available and a raw water feed pump is fitted instead.
- Two 50 mm PVC check valves are used, one on the sludge pump delivery line pipe and another on the treated water outlet line. These valves respectively prevent filter backwash water from entering the settling tank and treated water from draining into the filter and settling tank from the storage reservoir.
- One 50 mm multiport valve (5 port, 6 way) is used in conjunction with the sand filter. This valve uses one control lever to choose between the following six flow configurations for the sand filter:
  i) **Filter;** for normal filtration.
  ii) **Waste;** sends feed water to waste without being filtered.
  iii) **Backwash;** reverses flow in the sand filter during backwashing.

iv) **Rinse;** feed water is filtered but filtrate flows to waste.

v) **Bypass;** allows feed water to bypass the filter. This option allows unfiltered water to enter the storage reservoir which is undesirable. The control lever should be modified to prevent this option from being selected.

vi) **Closed;** prevents flow of water through the valve.

Pumps : Two Speck centrifugal pumps of a type typically used for domestic swimming pools are used. A Raw water feed pump may also be used where the raw water head is insufficient for filling the tank. The pumps incorporate an integral basket strainer with a clear plastic cover which permits inspection of the basket and priming of the pumps. The pumps are used in the following applications:

- **Filter pump:** This 1,10 kW unit pumps clarified water from the settling tank to the filter. It is also used for backwashing and rinsing the filter. It is automatically controlled but a manual override is provided for use during backwashing.
- **Sludge pump:** This 0,75 kW unit pumps sludge from the base of the settling tank at the end of each cycle. It may be possible to use the sludge pump as a raw water feed pump since sludge drainage and feed pumping are never required simultaneously.

Sand filter : The sand filter is manufactured by Colliquip in Johannesburg and is of a type typically used for domestic swimming pools. All modes of operation of the sand filter are controlled by the multiport valve as described above.

The sand used in the filter has an effective diameter (d_{10}) of 0,68 mm and uniformity coefficient (U) of 1,35. These sand specifications are typical of pressure sand filters in potable water treatment. The filter's cross sectional area is 0,44 m^2 and the sand bed depth did not exceed 0,35m in the filter originally fitted.

Dosing apparatus : Two types of chemical dosing apparatus are used:

- The **powder dosing system** consists of a stainless steel hopper with integral screw feeder. The dose is controlled by an adjustable electric timer and dosing is triggered by a level probe in the tank. The rotor of the screw feeder incorporates a scraper which scrapes the walls of the hopper during operation. The hopper assembly is bolted to a galvanised beam which is mounted across the top of the settling tank.
- The **disinfection system** consists of a proprietary in-line calcium hypochlorite dosing device (Klorman®) which is mounted on the filter outlet pipe upstream of the check-valve. The Klorman is constructed from clear PVC and uses cartridges filled with calcium hypochlorite tablets. The device is described in detail in Section 13.5.2.

Mixing apparatus : A stainless steel, four blade vane impeller powered by a 1,5 kW electric motor is used for mixing. The mixer assembly is mounted on the galvanised beam that also holds the powder dosing system. The duration of the mixing cycle is controlled by an adjustable timer and is triggered by the same level probe as the screw-feeder.

Settling tank : The settling tank is constructed from GRP and was manufactured by Mosden Plastics in Durban. The tank has thick (20 mm) reinforced rims at the top and bottom that add structural rigidity during transport and operation of the plant. The upper rim easily supports a man's weight and is also used to mount the transverse beam which carries the mixer and screw-feeder. All PVC pipes and fittings which constitute the inlets and outlets to the tank protrude from strongly reinforced ports in the tank walls.

The tank has four sturdy carrying handles attached to the sidewalls. It can be carried (including the internal piping, the overhead beam , the mixer and the screw feeder) by four men when empty. The location of the handles at waist height on the sides of the tank was not ideal but these handles can be positioned according to the client's specification..

Control and electrical system : The control panel is professionally wired and fitted into a weatherproof housing. A circuit diagram is provided. All other electrical equipment is housed in weatherproof enclosures and is suitable for operation out-of-doors. However, domestic 16A 'cabtyre' cabling is used to feed all the electrical components. This cable is not suitable for exposure to the weather and it is recommended that the external cabling should be properly protected by trunking or sealed conduit.

13.2 Process control system

The control system was designed to provide automatic operation, be simple to optimise, cheap to repair and maintenance free. It uses Omron level probes and timers for sequential switching of the various process components during each cycle. It makes no use of microprocessors, programmable logic controllers or interactive control loops. Three simple settings must be made during commissioning to optimise the mixing, settling and powder timers.

The control panel makes use of conventional modular construction techniques and the timers and level sensor head units can be simply unplugged and replaced if found to be faulty. All the electrical components use a 220V single phase supply. The 8V a.c. signal current used by the level probes is generated by a small transformer contained in the internal circuitry of each level sensor head unit.

13.2.1 Operation and control sequence

In field applications, the treated water is usually pumped to a storage reservoir fitted with high and low level probes that automatically start or shut-down the plant as required. During the evaluation at the PEF, the treated water was pumped directly to the drain and the plant was manually started using the main switch.

For this description assume that the starting point is the moment when Level probe 1 is exposed, thereby switching off the sludge pump and opening the inlet solenoid valve. With reference to **Figure 13.2**, the control sequence works as follows:

i) When exposed, Level probe 1 switches off the sludge pump and opens the inlet solenoid valve, filling the tank with raw water.

ii) When covered by the rising water, Level probe 2 closes the solenoid valve, starts the mixer and screw-feeder timers and reopens the inlet solenoid valve, allowing filling to continue.

iii) When covered by the rising water, Level probe 3 closes the inlet solenoid valve and starts the settling timer.

iv) When the settler timer reaches its pre-set time it starts the filtration pump.

v) The filtration pump transports the clarified water through the filter and when Level probe 4 is exposed it switches off the filtration pump and starts the sludge pump.

vi) The sludge pump continues to operate until Level probe 1 is exposed and the cycle begins again.

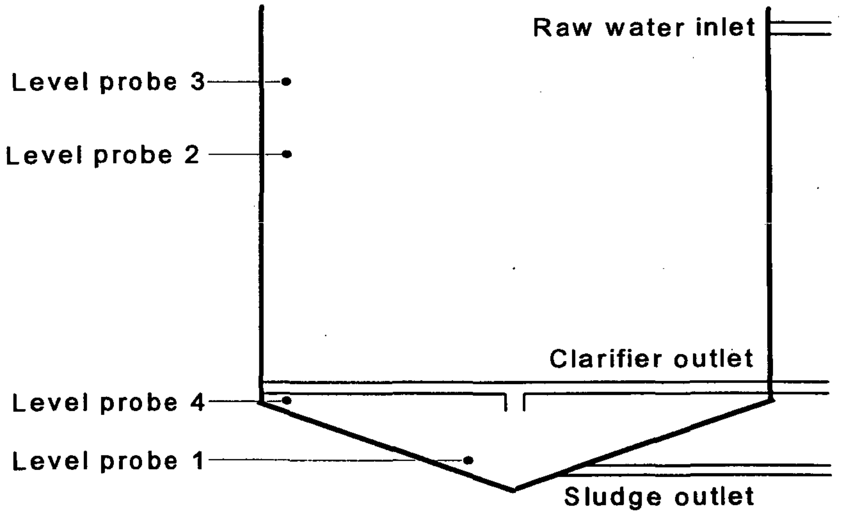


Figure 13.2 : Control system

13.2.2 Degree of automation

Normal operation, consisting of the processing of consecutive batches of raw water based on demand, is fully automated and little operator input is required. Monitoring of process parameters, filter backwashing and other similar tasks have to be initiated by the operator.

13.2.3 Effectiveness of the control system

The control system has been well designed and works effectively. It can be rapidly and simply adjusted to compensate for significant changes in raw water quality. There are no active safeguards against overdosing of chemicals but passive safeguards are inherent in the design; the maximum possible powder dose is approximately 190 mg/ℓ, the powder is self coagulating and the maximum chlorine residual that could be obtained from the Klorman was approximately 4 mg/ℓ as Cl. The powder hopper was deliberately sized for about 1 day's supply of powder. This means that the operator is forced to make a daily visit to the plant. There is no facility for automatic shut-down if the powder or chlorine runs out. Proximity switches were used on early plants to automatically switch off the plants when the powder was depleted but are no longer used. Uncontrolled parameters which may affect Final Water Quality

Parameters which can affect the quality of the treated water and which are not controlled include mixing energy (G-value), the filtration rate of the sand filter and raw water quality.

- Raw water quality obviously cannot be controlled and may exert a strong influence on the final water quality although the powder is relatively insensitive to raw water turbidity.
- Mixing energy is known to affect floc formation and settling rates in clarifiers. Conventional coagulants require a short period of rapid, intense mixing for charge neutralisation, followed by a much longer period of gentle agitation which promotes floc formation. The Watermaker plant used a fixed impeller speed and adjustable mixing duration.
- The filtration velocity in the original sand filter could not be adjusted. Towards the end of the evaluation a second sand filter with a deeper bed was installed and a gate valve on the inlet line allowed regulation of the filter flowrate (see **Section 13.5.3**).

Modifications to the control strategy were attempted in an effort to improve final water quality. These modifications included splitting the powder dosing and mixing into two stages per batch and significant improvements in the treated water quality were obtained (see **Section 13.5.3**).

A critical aspect of the process is the effective dosing of coagulant powder. Should the powder hopper empty completely without being refilled by the operator, or if the screw feeder in the powder hopper fails, or the powder timer fails, insufficient coagulant will be added and unclarified water will pass through the filter into the storage tank. This will significantly affect the quality of the final water.

13.2.4 Susceptibility to demand fluctuations

As long as the demand does not exceed the maximum possible production rate, the control system deals with demand fluctuations by switching the plant on and off. In conventional installations the plant includes a storage reservoir equipped with level probes that switch the plant on or off depending on demand. The degree of buffer capacity can be adjusted by using a larger reservoir or by repositioning the probes. This aspect of the control system effectively uncouples the reticulation system from the treatment process and allows the process to operate on demand at its design flowrate. Since the Watermaker operates in batch mode, no complications arise from starting and stopping the plant on demand as long as each batch is allowed to run to completion before the plant is switched off.

13.3 Personnel requirements

The plant requires daily attention from an operator. Repairs can be affected by a qualified pipe fitter or electrician as required. Further specialised personnel may be required occasionally for water quality monitoring, trouble shooting and mechanical and electrical maintenance.

13.3.1 Workload estimation

The workload involved in installing, operating and maintaining the plant has been estimated from experience gained during the evaluation of the plant at the PEF.

Installation and commissioning : Provided adequate facilities (such as power, raw water supply and final water storage) are available, the components of the plant can be assembled and commissioned in approximately 8 hours.

Routine operation : During routine full-time operation the operator was required for about two hours daily. The operators tasks included:

- Monitoring of turbidity, residual chlorine and filter bed pressure drop on a daily basis.
- Backwashing the filter with a frequency that varied from daily to once every 4 days during full-time operation.
- Refilling the powder hopper (daily) and replacing Klorman cartridges (weekly).
- Cleaning the level probes.
- Control of the chemical inventory and keeping an accurate logbook.

Maintenance and repair : Maintenance of a Watermaker plant will be limited to checks of the mechanical and electrical components (see **Section 13.7.2**) with occasional replacement of pump seals or bearings and should be limited to approximately 6 hours every 6 months. A technician or fitter will be required.

13.3.2 Specific training requirements

As long as technical support is available for monitoring of water quality and decision making with regard to chemical dosing and timer settings, the operator need have no formal training in water treatment although this would be an advantage. The prospective operator will require training in the tasks mentioned in **Section 13.7.1**. Most of this training knowledge can be imparted during commissioning of the unit.

Technical support and maintenance will require an artisan, preferably an electrician who will require additional training and experience in:

- Pump and PVC pipe repairs and maintenance
- Knowledge of sand filter maintenance and operation
- Water sampling procedures
- Troubleshooting and optimisation

13.4 Infrastructure requirements

Road access : Access will be required during installation and for maintenance personnel when repairs or servicing are required.

Electrical power : The Watermaker can be satisfactorily operated from a conventional 220V, 16A domestic power point. However, if a pump is used for provision of raw water to the plant, additional electrical capacity may be required. During filling of the tank, there is a portion of the cycle, immediately after powder dosing, when the raw water pump and the mixer operate simultaneously. A pump of up to 1,5 kW can therefore be accommodated by the existing 16 A connection If a higher current is required during any part of the cycle then additional supply capacity will be required.

Raw water provision : In a permanent installation, the raw water may be pumped to a raw water storage tank or may be abstracted directly from a dam or river supply. Under such circumstances an additional raw water / feed pump would be required. This should be sized accordingly.

Treated water reticulation : The cyclic nature of the treated water flow from the plant precludes direct connection to the reticulation pipework therefore intermediate storage is recommended. The size of this reservoir will be determined by the capacity of the plant and the requirements of the community to be served.

Sludge disposal : A sludge pump is provided and draining of the settled solids is an integral part of the control system. The concentrate contains additional substances not present in the raw water, and may only be returned to the water source if the effluent complies with the Department of Water Affairs and Forestry standards. Under these circumstances, other methods of sludge disposal should be considered. Roughly 14 % of the raw water treated by the plant will be discharged as an effluent containing the settled matter from the sedimentation process (see **Section 13.5.3**). Some facility for disposal of this sludge will be required. Recycling may be feasible in arid areas but otherwise, the sludge should be discharged to the raw water source downstream of the raw water intake.

Chemical storage facilities : The coagulant powder should be stored in a secure dry enclosure such as a roofed shed. The tablets used for disinfection should also be kept in a safe cool dry environment.

Weather protection : It is critical that the electrical controls are protected and should be kept dry. In order to prevent contamination of the water the plant should at least be covered by a roof or enclosed in a shed.

Site Establishment : A reinforced concrete slab measuring about 3m x 4,5m should be cast on the site. This will allow proper mounting of the tank, sand filter, pumps and electrical system. Attention should be given during the planning of the site to the likelihood of future expansion of capacity. Such expansion could take the form of an additional plant, additional treated water storage or increased settling tank size. Any security measures which may be deemed necessary, such as fencing, road access and secured chemical storage should also be in place prior to installation of the plant.

13.5 Performance of the treatment system

The plant was installed and commissioned in January of 1993. A series of experiments were then performed to optimise the powder dose, mixing time and settling time. Further experiments were conducted to evaluate the effectiveness of alternative coagulants and to determine operating parameters for the filter. In September 1993, a water meter was fitted to the treated water outlet and the plant was operated during working hours from September 1993 to October 1994 using the operating parameters determined during the earlier experiments. During this period (September 1993 to October 1994) more than 1,3 Mℓ of treated water was produced by the plant.

13.5.1 Raw water supply

Head and flowrate : The Watermaker requires an average raw water flow of 3 m^3/h. Due to the batch processing system the actual flowrate during filling is much higher (about 12 m^3/h) but it is only required for a short period (about 15 minutes) of each cycle. Gravity feed may be used in conjunction with a solenoid valve on the inlet line provided that sufficient flow occurs and that the valve will not be fouled by suspended matter in the raw water line. If the raw water head is insufficient for filling the tank then a pump will be required (see **Section 13.4**).

Screening : The raw water intake should be screened to prevent ingress of large objects such as leaves and sticks. The Speck pumps used for the plant have integral basket strainers and are ideal for this task. A foot valve should be fitted to the raw water intake as this will aid in priming the feed pump.

Storage / Reservoir capacity : If the plant is situated significantly above the raw water level a positive displacement pump may be required.

Quality of raw water : Raw water turbidity varied between 1 and 4000 NTU during the evaluation but ranged between 20 and 60 NTU for at least 80 % of the batches that were treated.

13.5.2 Micro-organism removal

Disinfection performance was monitored during the period from 17 September 1993 to 14 July 1994 and the results obtained are shown in **Table 13.2.** The sampling tap was located immediately after the Klorman in the outlet line. The position of the sample tap limited the chlorine contact time of samples to less than ten seconds before the chlorine was reduced by sodium thiosulphate in the sample bottles. It was therefore expected that the sample results would not necessarily reflect the true disinfection performance as would be achieved in the treated water reticulation system. Unfortunately it was impractical to use an intermediate container prior to sampling as this method could have introduced additional contamination.

Table 13.2 shows that the free available chlorine residual was adequate for proper disinfection in all cases (provided a sufficient contact time is allowed). In spite of the short contact time (<10 sec, due to plant configuration), the results show that an average 99% reduction in the influent micro-organism counts was achieved. The heterotrophic plate counts at 22°C and 37°C conformed to Dept. of Health guidelines in all cases (the average reduction was 96 %). Indicators of faecal contamination were detected in approximately 50 % of samples and the average reduction was approximately 99 %.

Table 13.2 : Disinfection results

(The percentage disinfection and residual cell concentration are shown for each determinand)											
Date	Coliforms		*E. Coli*		Faecal Strep.		Plate counts @ 22°C		Plate counts @ 37°C		Chlorine residual
	%	/100ml	%	/100ml	%	/100ml	%	/ml	%	/ml	mg/l as Cl
15/09/93	95	17	93,7	11	100	0	99,1	1	89,7	21	0,3
04/10/93	100	0	100	0	100	0	82,5	10	93,7	9	0,5
11/10/93	100	0	100	0	100	0	94,8	10	86,8	9	0,7
02/11/93	100	0	100	0	100	0	88,8	25	90,9	5	0,5
11/11/93	100	0	100	0	100	0	94,9	20	98,2	5	0,9
04/01/94	99,2	45	97,2	45	100	0	92,8	72	91,4	80	0,9
15/03/94	98,8	3	98,4	3	100	0	99,2	7	99	9	1,2
12/04/94	99,1	2	99,1	2	100	0	99	2	100	0	>2,0
19/04/94	99,2	2	99	2	100	0	100	0	100	0	0,6
26/04/94	100	0	100	0	96,7	3	99,9	1	99,8	2	2,0
04/05/94	96,6	6	89,8	6	100	0	100	0	100	0	1,0
17/05/94	99,5	1	100	0	100	0	99,1	2	99,5	1	1,0
18/05/94	100	0	100	0	100	0	100	0	99,8	2	2,0
14/07/94	100	0	100	0	0	1	99,7	3	98,8	7	0,95

The shaded parts of **Table 13.2** indicate samples in which the microbiological quality of the water may have posed a health risk. In all other samples the microbiological quality of the water was acceptable. In typical Watermaker plant installations, the treated water flows into a storage vessel at the head of a reticulation system and adequate chlorine contact time will be achieved, resulting in significantly better disinfection results.

The Klorman disinfection device uses a spring tensioned adjustment to position a capsule containing calcium hypochlorite in the path of water flowing in a pipe (see **Figure 13.3**). A portion of this water is diverted and flows through the capsule where it dissolves some of the calcium hypochlorite before rejoining the main stream.

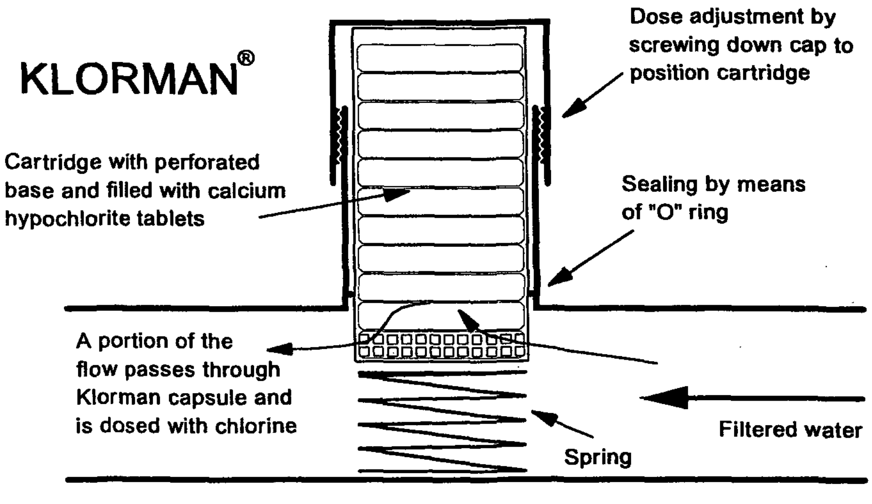


Figure 13.3 : In-line chlorine dispensing system

During settling when there is no flow through the Klorman, the solution in the cartridge becomes saturated with calcium hypochlorite. When filtration begins, an abnormally high dose is administered and the first 50 to 100 ℓ of water produced will typically have a chlorine residual in excess of 4 mg/ℓ. The dose declines rapidly as the cycle continues (see **Figure 13.4**). This effect can result in a distinct chlorine odour in the treated water and more noticeable when the plant is not operated for periods of more than 12 hours. This variation in chlorine dose during filtration also indicates the need for treated water storage in which sufficient mixing of over-chlorinated and under-chlorinated water can occur.

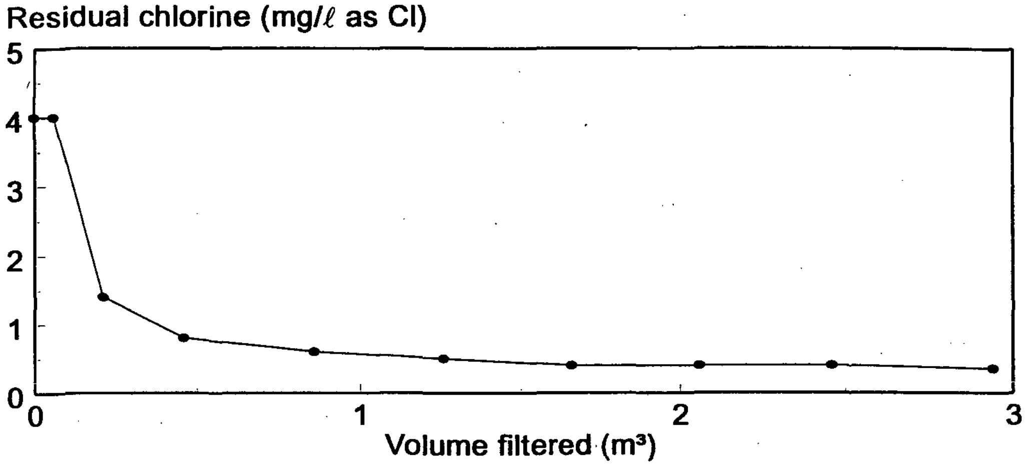


Figure 13.4 : Variation of chlorine residual during batch filtration

Samples taken from the supernatant water in the settling tank immediately prior to the onset of filtration show that the batch sedimentation stage typically removes about 70 % of the influent plate count organisms and 90 % of the influent faecal indicator organisms (these results are not shown in **Table 13.2**).

13.5.3 Turbidity and suspended solids removal.

During evaluation at the PEF raw water turbidities of up to 4000 NTU were recorded but typically, the raw water turbidity was between 15 and 60 NTU. The turbidity removal results (**Figures 13.5** and **13.6**) show that a wide range of raw water turbidities can be effectively treated by the plant with little variation in the powder dose. The operation of the plant was optimised as far as possible by varying the powder dose, mixing and settling times and studying the filter performance.

Powder dose optimisation : The manufacturers recommend that a dosage of 200 mg/ℓ should be used. However, during commissioning, the suppliers set the timer to give doses of approximately 110 mg/ℓ. Jar tests were performed with concentrations ranging from 50 mg/ℓ to 300 mg/ℓ. The results of the tests were inconclusive but indicated that concentrations of less than 100 mg/ℓ were ineffective. The settled water turbidity did not fluctuate significantly at concentrations between 100 and 300 mg/ℓ. The screw-feeder timer permitted doses between 20 and 190 mg/ℓ with variations of up to 20% of the prescribed value. The average powder dosage used during the routine operation of the plant was 130 mg/ℓ.

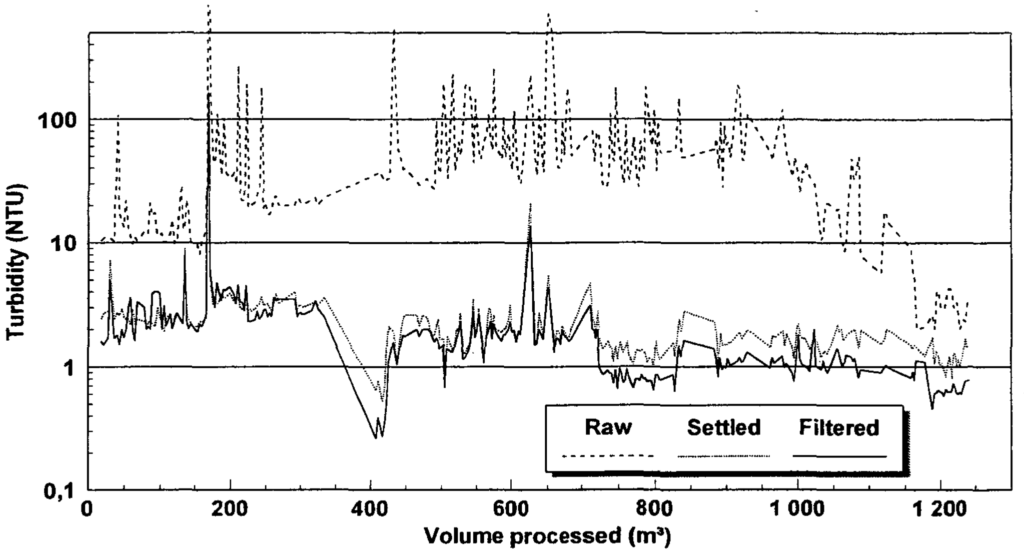


Figure 13.5 : Turbidity removal

Mixing and settling time optimisation : The tank is not baffled. During start-up the water in the tank is quiescent and the mixer motor draws full power until the water's inertia is overcome. This initial period of mixer operation serves to disperse and dissolve the powder and is equivalent to flash-mixing with an estimated G value of approximately 580 s^{-1} and a duration of about 10 seconds. Thereafter, mixing of a more gentle nature occurs because the water in the tank revolves at a similar rate to the impeller and rapid floc formation can be observed. If baffles were used, the high velocity gradients in the vicinity of the baffles would inhibit floc formation.

A range of tests was performed in which the powder dosage, mixing time and settling time were individually varied and the final water turbidity was measured . The objective of these tests was to optimise the operation of the plant by minimising the chemical usage while maximising the throughput and treated water quality. The indicated optimum settings were; a powder dosage of 130 mg/ℓ, a mixing time of 5 to 10 minutes and a settling time not less than 25 minutes. The settling time is difficult to adjust. Settling begins when the raw water flow stops (see **Section 13.2.1**). Mixing begins before this when the powder is added and depending on the inflow rate, may not be complete when the settling timer is activated.

Subsequent to optimisation, it was noted during a power failure at the PEF that considerably improved treated water turbidities were obtained when the mixing and powder dosing were split into two consecutive intervals. This 'split mixing' involved manually overriding the control system to dose half of the normal powder dose, mix for a short period (1 minute), dose the remaining powder and mix for a second period. This procedure consistently gave lower treated water turbidities (**Figure 13.5** - between processed volume of 700 m^3 and 1150 m^3), consistently below 1 NTU.

Filtration performance : Filtration velocities as high as 39 m/h were measured. Filtration rates during normal operation varied between 25 m/h and 33 m/h. These rates are high (literature recommendations vary between 8 m/h and 20 m/h for this type of operation) and it is possible that the pump had been overspecified for this application. The maximum bed depth that could be achieved with the original filter was about 0,35 m. The literature recommends bed depths of 0,6 to 1,0 m.

A deep bed filter was eventually installed in September 1994 and briefly evaluated. It was found that the sand in the smaller filter had become clogged with dirt, especially around the perimeter of the bed. Backwash rates recommended in the literature for such filters vary between 40 and 50 m/h but the highest backwash rate achieved during the evaluation was about 38 m/h and this may account for the gradual clogging of the filter.

Deep Bed Sand Filter : The results achieved with the deep bed sand filter (after 1150 m^3 water had been processed in **Figure 13.5**) operating in single-mixed mode show a significant improvement in treated water turbidity although the raw water turbidities were exceptionally low when the deep bed filter was evaluated.

The deep bed filter was installed with a gate valve on the inlet line so that flow during filtration could be restricted to give a filtration rate of about 12 to 15 m/h. Due to time constraints this could not be fully evaluated and the results from operation at this filtration rate were inconclusive due to the exceptionally low raw water turbidity experienced during this portion of the evaluation period.

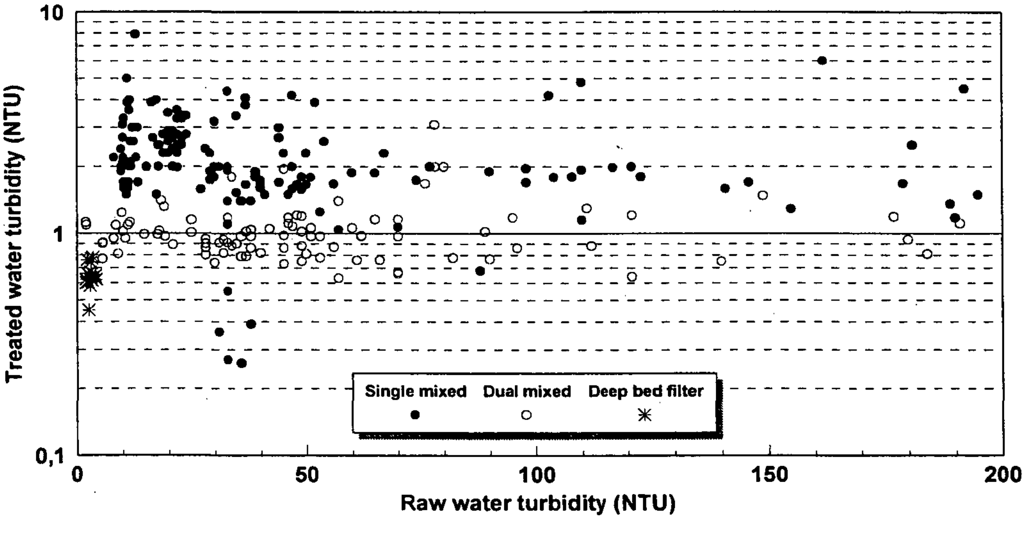


Figure 13.6 : Raw .vs. Final turbidity showing effects of plant modifications

The Watermaker plant, as originally supplied, will generally produce treated water with a turbidity below 2 NTU from raw waters with turbidities up to 500 NTU. However if the plant is modified to incorporate a dual-mixing cycle and the deep-bed filter, treated water turbidities less than 1 NTU should be consistently achieved.

Several batches of very high turbidity water were processed (omitted from the **Figures 13.5** and **13.6** for clarity) and treated water turbidity was not significantly affected until the raw water turbidity exceeded 600 NTU. Raw waters with even higher turbidity can be effectively treated as follows:

- Dose, mix and settle normally but pump out the settled sludge without filtering the supernatant.
- Dose, mix and settle a second time and allow filtration to continue as normal.

A batch of raw water with turbidity in excess of 4000 NTU was treated in this way producing an intermediate settled turbidity of 600 NTU and final turbidity after filtration of 5 NTU.

Sludge disposal : The geometry of the settling tank means that about 0,5 m^3 of sludge is pumped out at the end of each batch and this limits the overall water recovery of the process to about 85 %. The sludge settles rapidly yielding a clear supernatant and a small volume of settled sludge. It is recommended that the effluent is discharged to a settling tank where the sludge and supernatant water can be separated. Thereafter, several options for further disposal may be considered:

- Recycling of the supernatant water may be feasible in arid areas. This option is practised at one existing plant.
- Discharge of the supernatant to the raw water source downstream of the plant intake.
- Discharge of the supernatant water to an irrigation system
- Sludge dewatering by solar evaporation.

Subsequent to this evaluation, the sedimentation tanks were redesigned to include a small cylindrical hopper (∅ 300 mm x h 150 mm) at the base of the tank. This concentrates the sludge and allows more of the supernatant water to be removed, thereby significantly improving the water recovery.

13.5.4 Removal of other micropollutants of health and aesthetic significance

The Dept. of Health's draft guideline for total aluminium in potable water is 150 µg/ℓ. During the evaluation, the treated water consistently exceeded this value, with concentrations varying between 700 and 1000 µg/ℓ. These values exceeded the aluminium content of the raw water (up to 600 µg/ℓ).

Alum is one of the constituents of the Watermaker powder and from these results, aluminium breakthrough is clearly occurring in the process. Unsettled colloidal aluminium particles and flocs in the settled water are fragmented by high shear forces in the pump and are therefore not effectively removed by the filter. The aluminium concentrations detected in the treated water from the deep bed filter varied between 650 µg/ℓ and 750 µg/ℓ. These results show a slight improvement but still exceed the Dept. of Health's guideline values.

The sulphate concentration typically increased from 12 mg/ℓ to 46 mg/ℓ although this is still below the guideline value of 200 mg/ℓ. Iron and manganese were both effectively removed and treated water concentrations were well below the guideline values of 100 µg/ℓ and 50 µg/ℓ respectively.

13.5.5 Chemical requirements

During routine operation the powder dose was approximately 130 mg/ℓ. Each Klorman capsule, containing 700 g of 65% calcium hypochlorite, treated 180 m^3 of water (average dose 1,25 mg/ℓ as Cl).

The powder based dosing system precludes the direct use of coagulants of any form other than dry powders or granules. Several batches were processed by manually adding a liquid blended polymer (Floccotan K10P) in place of the powder. Similar turbidity removals were achieved. This shows that alternative chemicals can be used successfully as long as suitable dosing equipment is fitted.

The Watermaker powder and Klorman capsules are manufactured and distributed in South Africa by Control Chemicals Ltd and alternative equivalent products are not currently available. The chemicals used by the plant can be used as supplied and no preparation, mixing or dilution is required. Both the Klorman capsules and the drums of Watermaker powder should be kept sealed until immediately before use. The Klorman capsules are individually shrink-wrapped and should have a long shelf-life. The coagulant powder is supplied in 50 kg or 200 kg drums. The powder in the 50 kg drums is pre-weighed into packets that can be used to fill the powder hopper. The drums should be kept sealed when not in use as the powder appears to be slightly hygroscopic and its performance may be affected by exposure to humidity.

When completely filled, the powder hopper holds 12,5 kg of powder. This is sufficient for approximately 36 hours of continuous plant operation (32 batches). A single Klorman capsule is adequate for three days of continuous operation (60 batches). The use of post-chlorination minimises chlorine consumption but has the disadvantage that the growth of algae and biofilms in the plant, pipes and filter vessel is not controlled, and may contribute to filter clogging.

13.6 Plant life and reliability

The manufacturer guarantees the installed plant against faulty workmanship and materials for a period of three months after commissioning. The following paragraphs discuss the plant that was tested but the manufacturers will accommodate requests for the use of alternative materials or equipment according to the client's specification.

13.6.1 Materials of construction

Most components including the tank, filter and pump volute casings are of PVC or GRP. All exposed steel components are either galvanised or, in the case of the mixer impeller and hopper, made from stainless steel. The electric motors and gearbox assemblies are protected by epoxy coatings. The water being processed does not come into contact with any metals other than the stainless steel impeller and the level probes. However, corrosion has been observed at the point where the stainless steel level probes are attached to copper wire cables. Galvanic corrosion at this junction may cause malfunctions in the long term but no problems were encountered during the evaluation.

13.6.2 Reliability

The consequences of failure of each of the control system and process components has been assessed and the results are summarised in **Table 13.3**. The control system is not equipped with any alarms or emergency shut-off devices other than overload protection for each of the electric motors There is no system for automatically tripping the pumps if they should run dry or if the filter pressure exceeds normal operating pressures. Provided that the operator visits the plant on a daily basis and diligently applies a monitoring procedure, such features should not be necessary.

Table 13.3 : Summary of the consequences of component failures

Component	Direct consequence of failure	Effect on water quality
Level probe 1	Sludge pump will not switch off, pump will run dry and possibly overheat. The inlet solenoid valve will not open to initiate next cycle.	Water production will cease.
Level probe 2	Timers will not be activated, no powder dosing or mixing will occur and filter pump will not be triggered by settler timer.	Water production will cease.
Level probe 3	Solenoid valve won't close. Dilution of the coagulant by overflow will allow unclarified water to enter the filter when pump starts. If the tank level does not fall, pumping will continue until plant is tripped by level control in storage tank.	Unclarified water will pass through filter into storage tank.
Level probe 4	The filter pump will run dry and possibly overheat. Sludge pump will not start.	Water production will cease.
Powder timer	No coagulant will be dosed but batch cycle will continue.	Unclarified water will pass through filter into storage tank.
Mixer timer	No mixing of coagulant will occur.	Final water quality will drop due to inefficient flocculation.
Settler timer	The filter pump will not start and the cycle will cease.	Water production will cease.
Inlet solenoid valve	• If it fails to close, as for failure of level probe 3 ○ If it fails to open, the cycle will cease.	• As for level probe 3 ○ Water production will cease.
Filter pump	Clarified water will not be pumped to the filter and the cycle will cease.	Water production will cease
Sludge pump	Sludge pump will not start and cycle will cease	Water production will cease
Screw feeder	As for failure of powder timer	As for failure of powder timer
Mixer	As for failure of mixer timer	As for failure of mixer timer

Plant and Equipment : The long term reliability of the plant is assured through use of a simple control system, sturdy construction and high quality components. The custom-made items are well designed and constructed from durable, corrosion resistant materials. Due to the nature of their duty they are unlikely to fail.

The only failures in 8 months of operation have been inlet solenoid valve failures due to blockages in the diaphragm pilot holes (see below). In the event of a power failure all plant activity ceases immediately, all valves fail in the closed position and no contamination of the treated water can occur.

Control System Components : Apart from the need for occasional cleaning of the level probes the control system is robust and reliable. The switchgear, timers and probe units are all locally available and of good quality. No lightning protection is provided. The most expensive single item that could be damaged by lightning is the mixer motor. As this is situated in an exposed position on top of the tank the installation of a lightning conductor and earth strap is recommended.

The raw water entering the plant was controlled by a solenoid valve. The pilot holes in the solenoid valve blocked up on a daily basis during periods of high turbidity after rainfall. On each occasion, the valve was dismantled, cleaned and reassembled; the procedure taking approximately 20 minutes. In typical installations, a raw water pump would be used to supply water to the plant, thereby replacing the solenoid valve, and this problem would not occur. In situations where a valve must be used, it is recommended that a strainer is fitted to prevent such blockages.

13.6.3 Potential for future expansion of capacity

The capacity of the plant can be increased in two ways. Firstly, water production with the existing equipment must be maximised by optimisation of the control settings and upgrading the components that are limiting the production capacity.

Plant optimisation : This can be achieved by :

- Repositioning the level probes to reduce the amount of water wasted during desludging.
- Optimising the timers to give acceptable water quality with the shortest possible mixing and settling times.

A potential capacity increase of about 10% can be gained in this way but operators should not reduce the settling time too much as the increased solids load will result in more frequent filter backwashing which wastes water. During the evaluations it was found that settled water turbidity was typically > 2 NTU when settling times less than 20 minutes were used. This caused rapid filter clogging.

Plant Modification : At present the settling tank geometry and pump intake manifold do not permit more than 85 % of the clarified water to be pumped to the filter. There is scope to improve on the tank geometry which will lead to larger filtrate volumes and more concentrated sludge.

The filter pump and associated sand filter should be seen as a unit. Upgrading the pump to increase the flow will increase the filtration rate, possibly affecting the efficiency of the filter. Larger filters should therefore be used if the pump capacity is increased.

The plant can be successfully adapted to use alternative coagulants and disinfectants by fitting appropriate dosing equipment. Since the plant operates in batch mode, careful attention must be paid to the control and sizing of this equipment if such modifications are made.

13.7 Servicing, maintenance and repair

Most routine maintenance tasks can be carried out by the operator but due to the number of mechanical components used, a fitter or technician will be required once every six months to check on the condition of all mechanical and electrical components.

13.7.1 Operator maintenance tasks

Regular maintenance tasks which can be carried out by the operator include the following:

- Weekly cleaning of the plant to ensure that all electric motors cooling fins are clean and that the fans are working. The indicator lights on the control box must be checked and the pressure gauge, viewing bubble and translucent chlorinator window must be kept clean. The level probes should be cleaned on a biweekly basis.
- Monthly tasks should include the monitoring of the level of sand in the sand filter.

13.7.2 Maintenance tasks requiring skilled personnel

Maintenance of electrical and mechanical components should be carried out by skilled personnel every six months. The following checks should be made with corrective action when necessary:

- Check the operation of the pumps paying special attention to leaks, seals, cavitation noise, bearings and cooling fans.
- Check the operation of the mixer and screw-feeder paying special attention to mounting bolts, gearbox seals and cooling fans.
- Inspect pipework paying special attention to weathering, leaks, 'O' rings and corrosion.
- Electrical system checks for weathering, damage, corrosion and operation of all components.
- General checks on the condition of the plant.

13.8 Transportation, installation and commissioning

13.8.1 Transportation

The plant is transported as a prefabricated unit as individual components and can easily be accommodated by a 3 ton truck with a dropside load-bed or a 1 ton LDV with a 1 ton trailer of suitable dimensions. The total mass of the plant is approximately 500 kg including the filter sand. In spite of this relatively low mass, the size of the settling tank (width 1,9m, height 1,85m) makes it too bulky to be safely transported by a 1 ton LDV (bakkie). Skid mounting is possible and is recommended for units that may be relocated regularly.

13.8.2 Installation

The unit under evaluation was assembled on site from loose pipe lengths and fittings so that the components could be positioned to the best advantage for the individual site layout. Installation and assembly of the plant at the PEF took one day.

Currently, the plants are completely assembled at the factory and disassembled for transport to the site. The level probes in the tanks are also preset in this way to save time. In this way, installation time has reduced to a few hours for properly prepared sites.

13.8.3 Commissioning

No operating or scheduled repair manuals were issued with the plant. Commissioning took two days because difficulties were experienced with earthing of the level probe system. The system functioned properly after a full length earth electrode had been installed. During the commissioning phase most of the fixed settings required for the proper operation of the control system were adjusted by the suppliers. These settings included:

- Settling tank level probe settings (these are now pre-set during manufacture)
- Timer settings for screw-feeder, mixer and settling
- Chlorinator adjustments
- Check valve adjustments

The commissioning period was also used to train the PEF staff in the operation of the plant.

13.9 Costs

13.9.1 Capital cost

The capital cost of the plant installed at the Process Evaluation Facility was approximately R15,000.00 at the time of installation (November 1992). This cost does not include the cost of site preparation or treated water storage.

13.9.2 Operating cost

The operating cost consists of components for chemicals, electrical power, maintenance and wages. Each of these has been individually estimated in the following paragraphs and a summary is presented in **Table 13.4**. The estimates assume average water production of 2,57 m^3/h (20,3 Mℓ per annum) and 10 % downtime for backwashing, maintenance and cleaning. The estimated total cost of water production is therefore R 1,41 /m^3 for raw waters where the turbidity exceeds 50 NTU and R 1,21 /m^3 for lower turbidity waters.

Table 13.4 : Estimated operating costs

Operating cost components	Specific cost (>50 NTU) R/m^3	Specific cost (<50 NTU) R/m^3
Wages	0,252	0,252
Electricity	0,070	0,070
Klorman cartridges	0,190	0,190
Watermaker powder	0,862	0,663
Maintenance and repairs	0,044	0,044
Total	1,410	1,211

These estimates represents the best possible case where the plant operates at full capacity. Idle time due to either unscheduled stoppages or lower water demand will cause the operating cost to rise.

Chemical costs : The cost of the powder (December 1994) is approximately R5,70/kg (including 14% VAT) and the powder was dosed at a rate of 130 mg/ℓ into the raw water during the evaluation (if quantities in excess of 1000 kg are purchased, the price is R 4,00 /kg). Based on a water recovery of

85 %, the cost of powder is R 0,862 /m^3. The plant was able to operate successfully with a powder dose of approximately 100 mg/ℓ when the raw water turbidity did not exceed about 50 NTU. The chemical cost associated with low raw water turbidities was therefore R 0,663 /m^3. The chlorinator cartridges (Klorman Sanitabs) cost approximately R34,20 each and have a service life of 180 m^3. The cost of chlorination was therefore R 0,190 /m^3.

The chemical costs for the powder and Klorman cartridges are significantly higher than the cost of conventional coagulants and chlorine sources. The chemical operating cost can therefore be significantly reduced for the cost of appropriate modifications (see **Section 13.6.3**) and increased operational complexity. The ability to treat high turbidity waters may also be compromised by such modifications. A site specific cost/benefit study should be conducted in cases where these modifications are being considered.

Cost of electricity : The average power consumption for a cycle varies depending on the cycle time and the size of the plant. During normal operation, a volume of 2,7 m^3 can be produced per cycle for which the specific power consumption is between 0,62 and 0,81 kWh. The typical energy consumption is therefore 0,23 to 0,3 kWh/m^3. The cost of domestic 220 V single phase power in 1994 was R0,2643 /kWh. The power cost is therefore approximately R 0.07 /m^3.

Labour cost : The remuneration of the operator would be determined by the organisation responsible for the purchase and operation of the plant. Based on a labour cost of R7.00 /hour, an average daily workload of about 2 hours for each plant, a water recovery of 85 % and a production rate of 2,7 m^3/h operation, the labour component of the operating cost is R 0,25 /m^3.

Maintenance cost : Servicing and maintenance should be limited to the tasks discussed in Section 13.7. The maintenance workload has been estimated at 12 hours per annum at an approximate cost of R 75,00 /h excluding travelling costs. The estimated cost of maintenance is therefore R 0,044 /m^3.

14 VECTOR ENVIRONMENTAL TECHNOLOGIES INC.

Diamond Rain Water Purification Plant (DRWP2)

14.1 Introduction to the DRWP2

The DRWP2 plant is manufactured and marketed by the Vector group of companies based in the USA. Vector representatives may be contacted at the corporate headquarters in Sparks, Nevada, USA (Tel 091 702 331 5524, Fax 091 702 331 5527) or through the local agency, Vector South Africa, based in Verwoerdburg (Tel 012 663 6102/6/7, Fax 012 663 6117). Diamond Rain plants are produced in a range of capacities from 2 gpm (0,454 m^3/h) to 15 gpm (3,4 m^3/h). All of the plants use essentially similar processes. The unit evaluated was the base unit (Model Number DRWP2) which has a capacity of 0,46 m^3/h (10,9 m^3/day). This is sufficient to supply about 400 people at the RDP's minimum service level of 25 ℓ per person per day.

14.1.1 Plant design philosophy

The unit is designed for production of potable water in remote or rural areas where no electrical energy is available. The treatment system makes use of several sequential stages of granular activated carbon (GAC) and cartridge filtration for removal of suspended solids and organic contaminants. Disinfection is by means of a proprietary resin which dispenses iodine into the water. Operation is entirely manual and reasonably simple although frequent replacement of filter cartridges and GAC media may be required. The process is driven by the raw water pressure which should be between 100 and 400 kPa. If the available gravity head is insufficient, a raw water pump will be required.

The DRWP2 unit that was evaluated is a standard basic model and was not specifically designed for South African rural conditions. Vector is able to customise these modular processes to suit individual customer requirements and additional treatment modules are available for the treatment of waters having unusually high turbidity, mineral or organic loads.

14.1.2 General description of the plant

The process layout is depicted in **Figure 14.1**. Raw water entering the plant is 'preconditioned' in a GAC bed before passing sequentially through two cartridge filters (20 µm and 5 µm respectively) which partially remove the suspended solids load. The water then passes through two GAC filtration beds and a second 5 µm cartridge filter which removes any fine carbon particles that may have been carried over from the GAC filters. After filtration the water enters the microbial destruction unit (MDU) where it passes through a proprietary iodinating resin that doses a controlled amount of iodine (up to 4 mg/ℓ) into the water. After iodine dosing the water enters a retention tank system sized for an average iodine contact time of 40 minutes at the rated flow of 0,45 m^3/h. The disinfected water then passes through a 1 µm cartridge filter, a GAC polishing filter and an anion exchange resin bed for the removal of remaining suspended solids, residual iodine and iodide ions respectively.

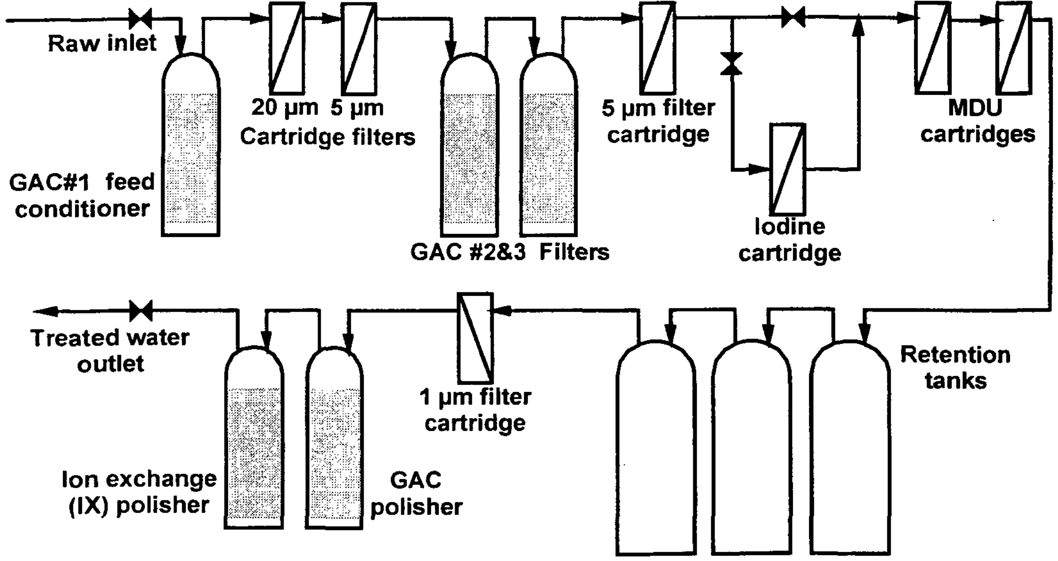


Figure 14.1 : Process flow diagram

The process operates continuously and flowrate is controlled by means of a valve on the inlet system (see **Section 14.2.1**). An iodine analysis kit (based on the leuco crystal violet method) is provided for monitoring free and total iodine concentrations in water samples.

14.1.3 Process sophistication

A breakdown of the installed equipment is given in **Table 14.1**. Due to the extensive use of GAC, cartridge filters of various sizes and ion exchange resins, the process is technologically sophisticated yet it remains reasonably simple to operate.

Table 14.1: Summary of installed equipment

Description	Quantity	Comments
Valves	23	12 x sample taps 5 x 3-way valves (GAC and IX vessels) 4 x ball valves (outlet, drain, iodine recharge system) 1 x needle valve (integral with rotameter) 1 x gate valve (inlet)
Flowmeters	2	1 x rotameter (with integral needle valve) 1 x Kent flowmeter (totaliser)
Filters	9	4 x cartridge filters (1 x 20 µm, 2 x 5 µm, 1 x 1 µm) 4 x 23 ℓ GAC filter vessels 1 x 23 ℓ IX polisher vessel
Tanks	3	3 x 100 ℓ retention tanks (MDU reactor)
Gauges	12	12 x pressure indicators (integral with sample taps)
Disinfectant cartridges	3	2 x MDU resin cartridges (iodine dosing) 1 x iodine cartridge (resin recharge)

Although no calibrations are required, the operator must routinely monitor the pressure drop across each stage. The operator will be required to have an understanding of the function of each unit operation in the process if the plant is to be effectively operated. Monitoring of the condition of the GAC beds will entail regular sampling and total organic carbon (TOC) analysis (see **Section 14.2.3**).

The GAC-beds and the IX polisher are backwashed by means-of-the 3-way valves which are difficult to control. The cartridge filters may be washed by backflushing and gentle scrubbing but this proved to be ineffective (see **Section 14.5.3**) and cartridge replacement is usually required. The recommended maximum working pressure is 400 kPa.

14.2 Process control system

14.2.1 Operation and control sequence

The control philosophy is based on the regulation of flowrate to ensure adequate carbon and iodine contact time. For this reason the unit's rated capacity should not be exceeded. During normal operation this is the only adjustment required since the iodine dosing system operates effectively without the need for calibration or adjustments.

A sample port and pressure gauge situated at the outlet of each stage allows sampling and measurement of the pressure drop across that stage. The pressure drop across any stage can be calculated from the difference between readings shown on the relevant pressure gauges. The need for backwashing or filter cartridge replacement is deduced by comparison of these pressure drops with guideline values in the operating manual. The operating manual describes the backwash and cartridge replacement procedures in detail but is not clear on operating parameters such as iodine residual levels and the MDU recharge procedure.

Control of disinfection is achieved by monitoring the free iodine concentration at the retention tank outlet. As long as the maximum flowrate (0,45 m^3/h) is not exceeded and assuming that plug flow occurs in the retention tanks, the intended contact time will be achieved. If the MDU resin becomes depleted in use, the treated water will not be effectively disinfected. However, total iodine depletion is not likely to occur in the 24 hour period between operator checks (see **Section 14.2.3**).

14.2.2 Degree of automation

No aspects of the plant's operation or control are automated.

14.2.3 Monitoring of the process parameters

The installed instrumentation and the iodine analysis kit is sufficient for proper monitoring of day-to-day plant operation although the pressure drops have to be calculated since they cannot be measured directly. However, the degree of saturation of the GAC media cannot be easily determined. Monthly sampling and TOC analysis of the outlet stream from each GAC vessel is recommended for several months after commissioning to determine the typical service life of each bed for each individual application. Once the service life has been determined, the GAC media can be replaced according to the volume of water treated and the frequency of sampling can be reduced.

The operator's manual contains a daily logsheet which can be reproduced and supplied to plant operators. Pressure readings, iodine concentrations, flowrates and other observations can be made by the operator on these sheets. If properly utilised, this data logging system will ensure that appropriate monitoring of plant operation occurs and it will provide valuable diagnostic information for the technical back-up personnel.

A small quantity of iodine is required for production of the thyroid hormone in man but large amounts can be toxic. A concentration of up to 2,0 mg/ℓ residual iodide in drinking water will not pose any health hazard (Dept. of Health, 1994) and the guideline value for iodide is 0,5 mg/ℓ. The mechanism of dose control with this iodinating resin is proprietary information and was not disclosed to the project staff. Excess iodine and iodide are effectively removed by the GAC and IX polisher stages respectively. The performance of these stages can be adequately monitored with the test kit. Overdosing of iodine can occur if the iodine recharge valve is opened accidentally but the monitoring procedure should detect such incidents before the treated water quality deteriorates significantly.

14.2.4 Effectiveness of the control system

Generally, if the raw water flowrate does not exceed the maximum permissible flowrate and no malfunctions occur then the control system should be effective. The manual control system relies on a high degree of operator competence and diligence. The iodine analysis is also an integral part of the effectiveness of the process as this will indicate the extent of disinfection and whether the MDU resin is functioning properly. Inaccurate analyses or failure to perform the required analyses will result in inefficient control.

14.2.5 Uncontrolled parameters which may affect final water quality

- Sudden increases in the raw water flowrate will reduce the carbon and iodine contact time. This may result in increased TOC and microbiological levels in the treated water and can be caused by fluctuations in the supply pressure.
- The operator cannot control the dose dispensed by the MDU cartridges. If the excess iodine is not removed in the polisher units, a medicinal taste which may be unpalatable to the consumers will be imparted to the treated water.
- Adsorption of the iodine in the polisher units leaves no iodine residual in the treated water and renders the reticulation system susceptible to contamination and regrowth of micro-organisms. However, the 3-way valve on the polisher unit will allow the iodinated water to bypass the polisher. By adjusting the bypass, an iodine residual can be obtained if necessary but the treated water's taste will be affected.

- It was difficult to obtain accurate results with the iodine test kit as the colour produced in the samples had a different hue to the colour of the reference slide.

14.2.6 Susceptibility to demand fluctuations

If the water demand exceeds the plant's capacity the operator may be tempted to increase the plant flowrate by opening the flow control valve. This should be avoided as the treated water quality may be affected. Vector can supply flowrate restrictors that will prevent the occurrence of excessive flows. The unit can be operated on demand and at lower flowrates than the maximum.

14.3 Personnel requirements

The long term operation of Diamond Rain units will require an operator trained in the tasks mentioned in **Section 14.3.2** and a technician trained in maintenance and troubleshooting procedures. It is envisaged that the operator of a unit or units will be employed by the operating authority while the technician would be employed by the local Vector agents and would be responsible for the technical upkeep and quality control of all units in a particular region. The operating authority may be a private entrepreneur or a local water supply authority.

14.3.1 Workload estimation

The workload involved in installing, commissioning, operating and maintaining the DRWP2 unit is discussed in the following paragraphs:

- **Installation and commissioning :** The installation of the unit takes only minutes once suitable site preparation (as described in **Section 14.4**) has been completed. However, the manufacturers require testing of certain water samples before they will issue a field certification certificate. Certification may require a week.
- **Routine operation :** The operator's average daily workload will be about one hour per day and will encompass the tasks mentioned in **Section 14.3.2**. A single operator could therefore be responsible for the operation of more than one unit in a district.
- **Maintenance and repair :** A monthly or bi-monthly visit by a Vector trained technician is recommended. During these visits the technician would check the operation of the entire plant, take samples for analysis, effect any necessary repairs, replace GAC media, IX resin or iodine cartridges where necessary and deliver fresh supplies of the consumable items required by the plant. This unit should require virtually no maintenance other than media replacement and the workload involved should not exceed 2 hours per month (excluding travelling).

14.3.2 Specific training requirements

Operator training is essential if this plant is to be operated correctly. Although a comprehensive operating manual is provided, the operator of a Diamond Rain system will require training in the following aspects of plant operation and maintenance:

i) Maintaining an accurate logbook.
ii) Replacement of filter and MDU cartridges.
iii) Backwashing of GAC.
iv) Simple analytical measurements for turbidity, iodine and iodide.
v) Diagnostic procedures for assessing plant performance.
vi) Replenishment of GAC and IX resin media.

Technical support personnel will be required to have more detailed knowledge of all unit operations in the process and will require additional training to include:

i) Thorough knowledge of the principles of operation.
ii) The iodine recharge procedure.
iii) Regeneration of resins and GAC media where possible
iv) Repair and modifications to pipework and fittings
v) Sampling and analysis methods.
vi) Problem solving

14.4 Infrastructure requirements

In addition to the capital cost of a plant, expenses are also incurred in the provision of infrastructure that will allow the DRWP2 plant to supply treated water effectively. Additional facilities that may be required include:

- **Road access :** Vehicular access to the site for a light delivery vehicle will be required as the plant cannot be carried by hand or dismantled into more manageable components during transport.
- **Power requirements :** The plant requires no electrical power except where a raw water feed pump may be required to provide sufficient raw water pressure.
- **Raw water provision :** See **Section 14.5.1**
- **Treated water reticulation :** The plant can be operated on demand by connection to a float valve in the treated water reservoir. Secondary disinfection of the reticulation system, either continuously or periodically, can be provided by adjusting the polisher bypass as discussed in **Section 14.2.5.**
- **Sludge and waste disposal :** Vector Venture Corporation recommends recycling of GAC media, MDU resin, iodine cartridges and the ion exchange resin. In countries where an established dealership or agency network exists this may be feasible. At present a limited network of Vector agents is available in the main centres of South Africa and it may not be economically feasible to return spent media for recycling. A separate network is currently available for the recycling of GAC media used by various industries and private users. Used filter cartridges will require disposal as these items cannot be recycled. The relatively low volume of effluent produced by backwashing of the GAC media does not contain additional substances not present in the raw water. It can be drained to a soak pit if the suspended solids content is too high (in terms of Dept. of Water Affairs and Forestry standards) for legal discharge to the raw water source.

- **Chemical storage facilities :** Storage facilities will be required for stocks of replacement media, cartridges, tools and resins. The storage facility should be cool, secure and dry with adequate ventilation to prevent build-up of iodine fumes.
- **Weather protection :** The reinforced flexible hose, the GRP tanks and some of the other plastic fittings unit will deteriorate after several years exposure to sunlight. It is recommended that the unit be situated in shade where possible as this will reduce the effects of the sun on plastic materials as well as reducing the temperature in the cabinet.
- **Site establishment :** The unit should preferably be mounted on a cast concrete slab although a slab made from concrete paving blocks, bricks or any other stable material will be acceptable. The unit should be level and drainage channels should be provided.

14.5 Performance of the treatment system

The plant was operated on raw water drawn from Inanda Dam during the months of July and August in 1994. Raw water turbidity is typically at its lowest at this time of the year and the turbidity of the raw water fed to the plant varied between 3 and 10 NTU. By comparison, in the summer months (December to February) raw water turbidities typically increase to between 10 and 60 NTU. Approximately 160 m^3 of water was treated during the evaluation period.

14.5.1 Raw water supply

- **Head / Flowrate :** The DRWP2 plant requires a continuous raw water feed flow of about 0,46 m^3/h at a pressure between 100 and 400 kPa. Solar powered borehole pumps that can satisfy this feed requirement are available in South Africa and could be used in cases where they are economically feasible. Certain types of hydraulic ram pump may also be suitable for use with the smaller Diamond Rain units although damping of the pump pulsations will be required.
- **Screening :** No provision is made for pre-screening of the raw feed water entering the plant. A basket screen that removes particles greater than 2 mm in size is recommended to prevent blockage of the valves on the GAC pre-conditioning unit especially where raw water is abstracted from small streams or rivers.
- **Storage / Resevoir Capacity :** Raw water buffer storage is only necessary when the continuity of the supply cannot be assured. It is preferable to operate the plant continuously at constant pressure although frequent on/off cycles or fluctuating feed pressure will not significantly affect the plant if a Vector supplied flowrate restrictor is fitted (see **Section 14.2.6**).
- **Quality of Raw Water :** During the evaluation, the raw water source was Inanda Dam with turbidity between 3,0 and 10 NTU. Since waters having turbidity outside this range were not treated, the full range of raw water turbidities that can effectively be treated was not evaluated.

14.5.2 Disinfection system

With new MDU cartridges a free iodine dose of approximately 4 mg/ℓ is obtained. The dose appears to remain steady at this value and then seems to drop off rapidly as the iodine nears depletion. The operator's manual recommends replacing the cartridges when the iodine dose falls below 1 mg/ℓ. An iodine cartridge and iodine recharge facility is built into the plant and the MDU resin can be recharged on site by trained technicians if necessary. However, this procedure requires experience and more specialised analytical equipment than that provided with the plant When this procedure was attempted during the evaluation (using notes supplied by Vector) it was only partially successful and the recharged resin could only achieve a dose of about 2 mg/ℓ. The recharged resin was rapidly depleted and the dose fell below 1 mg/ℓ within two days. In the event of an iodine overdose, the GAC and IX resin in the polisher units will be able to adsorb the excess iodine until saturation occurs but the operating life of the media will be reduced.

The dosing point is positioned after two stages of GAC filtration and three cartridge filters (see **Figure 14.1**). At this stage of the process most of the suspended solids and organic carbon have been removed from the water so the iodine demand of the water should have been significantly reduced. Water samples taken from the retention tank outlet have a characteristic iodine taste and odour but this is removed during the polishing stages and the treated water was palatable. Other tastes and odours were not detected in the treated water from this plant.

Table 14.2: Microbiological results for samples of raw and treated water

RAW WATER										
Date	25/07	27/07	28/07	01/08	10/08	16/08	22/08	29/08	06/09	13/09
Coliforms	14	10	20	16	48	20	2	12	14	6
E.Coli	4	0	4	2	2	0	0	0	2	0
F.Strep.	0	0	2	0	0	0	0	0	4	0
Plate counts (22°C)	472	10	232	404	212	640	252	100	630	280
Plate counts (37°C)	50	48	350	98	90	328	98	52	106	164
TREATED WATER										
Coliforms	0	0	0	0	0	1	0	0	0	0
E.Coli	0	0	0	0	0	1	0	0	0	0
F.Strep.	0	0	0	0	0	0	0	0	0	0
Plate counts (22°C)	0	40	512	>1000	>1000	>1000	0	>1000	121	>1000
Plate counts (37°C)	>1000	>1000	92	4	624	656	0	>1000	166	>1000

With the exception of one sample, all coliforms, *E.Coli* and faecal strep. were inactivated but most samples had heterotrophic plate counts in excess of 1000/mℓ for plates incubated at either 22°C or 37°C (see **Table 14.2**). The breakthrough of coliforms and *E.Coli* occurred a few days after the unsuccessful iodine recharge of the MDU resin. During this period the free iodine concentration in the water entering the retention tank system dropped below 1,0 mg/ℓ and this may have affected the disinfection efficiency.

The heterotrophic plate counts appeared to build up in the week after commissioning of the unit. The plate counts were reduced to zero when the anion exchange resin was replaced but again, the count increased within a week to more than 1000/mℓ. During the last two weeks of operation, a small quantity of iodine (up to 0,4 mg/ℓ) was detected in the treated water samples, indicating iodine saturation of the GAC polisher unit. This could account for the reduced plate counts recorded on 6 September 1994. These results suggest that a significant amount of bacterial activity may occur in the ion exchange polisher and associated piping due to the absence of residual iodine at this point. In spite of the lack of iodine residual in the treated water, better disinfection results were expected. GAC treatment significantly decreased the TOC concentration and should have rendered the treated water less able to sustain regrowth after iodine removal.

These results were achieved with free iodine doses from 1 to 4 mg/ℓ and contact times always in excess of 30 minutes. Since all detectable (leuco crystal violet method) residual iodine and iodide was removed in the GAC and IX polisher units microbial regrowth in the treated water system may occur if no iodinated water is allowed to bypass the polisher unit. It was difficult to obtain accurate results with the iodine test kit due to a colour discrepancy between the samples and the reference slide as mentioned in **Section 14.2.5**. Results of comparative iodide analyses showed that the test kit gave results within 1 mg/ℓ of those obtained with the inductively coupled plasma (ICP) method used by Umgeni Water's central laboratory.

The fresh MDU cartridges supplied with the unit were depleted (dose dropped to 1 mg/ℓ) after treating 35 m^3 of water. Due to the lack of spare MDU cartridges the iodine cartridge was subsequently adjusted to provide a dose of approximately 1,5 to 2,0 mg/ℓ free iodine and after a further 132 m^3 of water had been treated the iodine cartridge was still not exhausted.

14.5.3 Turbidity and suspended solids removal

The standard DRWP2 does not incorporate any coagulation, flocculation or sedimentation steps although these are available as options. In the DRWP2 unit, turbidity removal is by GAC filtration and cartridge filtration alone. Treated water turbidities ranged from 0,34 to 2,00 NTU with an average value of 0,99 NTU. The effectiveness with which the unit can treat waters with turbidity higher than 10 NTU could not be determined but it is reasonable to assume that the filter cartridges will clog more rapidly and that treatment costs will rise significantly with increasing raw water turbidity.

The turbidity removal across each stage was measured on two occasions and from the results in **Table 14.3** it can be seen that the GAC pre-conditioner and 20 µm filter were responsible for the bulk of the turbidity removal. From the graph (**Figure 14.2**) it is clear that the treated water turbidity is sensitive to raw water turbidity increases. In comparison, systems that use chemical coagulation and flocculation are typically less sensitive to raw water turbidity within their normal operating range.

The plant is relatively insensitive to rapid fluctuations in raw water quality or pressure as long as the raw water quality does not exceed the range that can be effectively treated by the plant. This implies that the treated water should flow to a treated water storage tank from which it can be distributed. The level of the treated water tank can be simply controlled by means of a float valve although this will leave the plant fully pressurised when the tank is full.

Table 14.3 : Turbidity removal across process components

Process Component	Turbidity recorded at stage outlet	
	(23/08/94)	(24/08/94)
Inlet (raw water)	2,30	3,30
GAC filter #1	1,50	1,87
20 μm filter	1,29	1,70
5 μm filter #1	1,06	1,94
GAC filter #3	0,90	1,50
5 μm filter #2	0,93	1,47
Retention tank #3	0,90	1,24
1 μm filter	0,61	1,10
GAC Polisher	0,57	1,02
IX Polisher (treated water)	0,54	1,00

The service life of the various filter cartridges has been assessed and the prices of locally produced equivalent cartridges have been used to estimate the associated operating costs (see **Table 14.5** in **Section 14.9**). In practice, the filter cartridge life has been considerably shorter than that suggested by the table of typical values in the operator's manual.

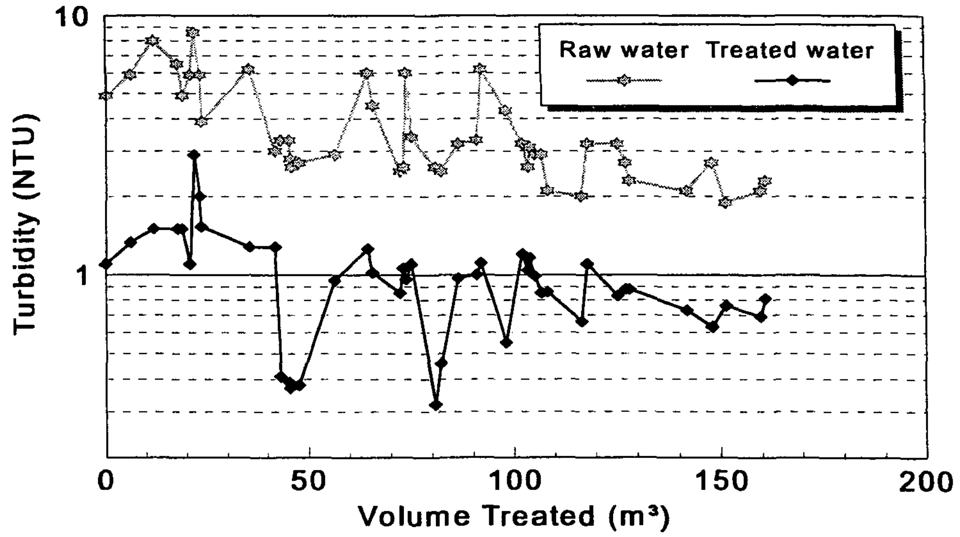


Figure 14.2: Turbidity removal

During the evaluation period, the feed pre-conditioner was backwashed approximately every 20 m^3 and this represented the major loss of water from the process. Water lost during routine maintenance tasks has been estimated as follows:

► Feed pre-conditioner backwash	200 ℓ every 20 m^3.
► Filter cartridge replacement	3 ℓ every 20 m^3.
► Sampling	5 ℓ every 10 m^3.
► Iodex resin replacement	30 ℓ every 60 m^3.
► GAC media replacement	unknown .

These results indicate a total water recovery in excess of 98% for routine plant operation. This compares well with most alternative processes.

14.5.4 Other contaminants

In addition to disinfection and turbidity removal, the removal of other micro-contaminants was also assessed. The results (**Table 14.4**) show that significant removal of aluminium, iron and manganese occurs. Other anions and cations of health or aesthetic significance were not present in the raw water at the Process Evaluation Facility and the overall palatability of the treated water was good.

The iodide concentration in two of the treated water samples (IODP 16/08/94 and IODP 13/09/94) was significantly higher than in the corresponding raw water. This was due to saturation of the IX resin in the polisher unit with respect to iodide ion. The ion exchange resin was replaced shortly after the first of these two samples were taken and the iodide concentration in the outlet then fell below the detection limits until shortly before the second sample was taken. The Department of Health's 1994 draft guideline for iodide in potable water is 0,5 mg/ℓ.

The sulphate result (dark shaded in **Table 14.4**) for the first set of samples indicates that sulphate may be significantly removed when fresh ion exchange resin is present but this result could not be confirmed. The low concentration of sulphate in the treated water may be due to an analytical error. The slight increase in the chloride content of the treated water when fresh anion exchange resin is used indicates that the resin may be chloride charged (if the resin were hydroxide charged, the exchange of just 2 mg/ℓ of iodide with hydroxide ions would cause a significant increase in the treated water pH).

While the plant did not significantly reduce the conductivity or total dissolved solids in the water, removal of colour and organic compounds occurred, presumably as a result of the GAC filters. TOC and colour removal did not appear to deteriorate during the evaluation period. This indicates that the service life of the GAC media exceeds the 160 m^3 of water that was treated during the evaluation.

Table 14.4 : Micro-pollutant removal

Date		28/07/94					16/08/94					13/09/94						
Sample type		Raw	GAC1	GAC3	GACP	IODP	Raw	GAC1	GAC3	GACP	IODP	Raw	GAC1	GAC3	MDU	RET3	GACP	IODP
Colour	°H	-	-	-	-	-	2,2	-	-	-	<1	3,44	3,1	2,82	-	-	3,44	1,3
Conductivity	mS/m	-	-	-	-	-	27,7	-	-	-	27,9	-	-	-	-	-	-	-
Turbidity	NTU	6,5	-	-	-	1,5	2,7	-	-	-	0,38	2,2	-	-	-	-	-	0,75
Total organic carbon	mg/ℓ	4,82	3,92	2,55	2,95	2,11	2,72	2,87	2,28	2,24	1,12	2,58	2,22	1,21	-	-	0,83	<0,7
Total dissolved solids	mg/ℓ	135	142	136	139	127	157	-	-	-	167	138	-	-	-	-	-	140
Suspended solids	mg/ℓ	7,4	5	5	<4	<4	-	-	-	-	-	<4	<4	<4	-	-	-	<4
Aluminium	µg/ℓ	170	-	-	-	108	63	-	-	-	47	58	-	-	-	-	-	27
Calcium	mg/ℓ	14,4	-	-	-	14,2	14,6	-	-	-	14,1	14,2	-	-	-	-	-	13,9
Copper	mg/ℓ	-	-	-	-		<0,05	-	-	-	<0,05	-	-	-	-	-	-	-
Iron	mg/ℓ	0,35	-	-	-	0,13	0,29	-	-	-	0,06	-	-	-	-	-	-	-
Potassium	mg/ℓ	-	-	-	-		3,74	-	-	-	3,6	-	-	-	-	-	-	-
Magnesium	mg/ℓ	7,82	-	-	-	7,83	7,74	-	-	-	7,41	7,5	-	-	-	-	-	7,24
Manganese	mg/ℓ	0,04	-	-	-	<0,01	0,02	-	-	-	<0,01	-	-	-	-	-	-	-
Sodium	mg/ℓ	-	-	-	-	-	31	-	-	-	30	-	-	-	-	-	-	-
Iodide	mg/ℓ	<0,1	-	-	-	<0,1	<0,1	-	-	-	1,3	<0.1	-	-	0,74	1,16	0,71	1,6
Chloride	mg/ℓ	38	-	-	-	41,4	35,1	-	-	-	35,2	35,5	-	-	-	-	-	35
Nitrate	mg/ℓ	0,53	-	-	-	<0,05	0,35	-	-	-	0,36	-	-	-	-	-	-	-
Nitrite	mg/ℓ	<0,05	-	-	-	<0,05	<0,05	-	-	-	<0,05	-	-	-	-	-	-	-
Sulphate	mg/ℓ	19	-	-	-	0,49	19,9	-	-	-	20,6	18	-	-	-	-	-	18,2
Soluble react. phosphate	mg/ℓ	-	-	-	-	-	8	-	-	-	9	-	-	-	-	-	-	

Key :

GAC1 ...... water filtered in GAC#1 filter

GAC3 ...... water filtered in GAC#2 & GAC#3 filters

GACP ...... water filtered in GAC polisher unit

IODP .... treated water outlet from ion exchange polisher

MDU .... water dosed with iodine by MDU cartridge

RET3 .... water exiting retention tank system

14.5.5 Chemical requirements

Table 14.5 shows the typical service life of the various media, chemicals and filter cartridges that are used in the treatment process. The shelf life of all consumable items used by the plant will exceed six months if properly stored. Iodine in particular must be properly sealed while in storage. All chemicals and media are supplied in the form in which they will be used and no preparation is required. The operators manual describes the safety precautions that should be observed in each case as well as providing instructions for the proper disposal or recycling of used media. All equipment and tools required for media replacement (buckets, funnels, keys etc.) were supplied with the unit.

Some of the media and chemicals used by the plant are available from other sources. These include:

- **GAC.** Many types of GAC are available in South Africa. If locally available products are used, the particle size and adsorption properties should be similar as far as possible.
- **Anion Exchange Resin.** A strong base anion exchange resin was used in the test unit. Suitable alternative products are available from several manufacturers in South Africa.
- **Filter cartridges.** Locally produced filter cartridges of similar specification are available.
- **Iodine.** The iodine recharge cartridges can be refilled with iodine crystals. If an alternative source of iodine crystals is used, the purity of the product should be sufficient for potable water use.

The MDU resin used for iodine dosing in this system is a proprietary product and no alternatives are available on the local market. While it is possible to replace the iodine based disinfection system with alternative disinfection systems this would detract from the advantages of the current system.

Table 14.5 : Approximate service life of cartridge filters and other media

Description of item	Average volume treated (m^3)	Comments	Suggested inventory
GAC #1	>150	not replaced during evaluation	1 bag
20 µm filter cartridge	25,3	not washable	6 cartridges
5 µm filter cartridge #1	24,8	not washable	6 cartridges
GAC #2 and #3	>150	not replaced during evaluation	1 bag
5 µm filter cartridge #2	148	not washable	1 cartridges
MDU Cartridges	22	recharging procedure is complex	6 cartridges
Iodine cartridge	>150	not replaced during evaluation	1 cartridge
1 µm filter cartridge	33,8	not washable	4 cartridges
GAC polisher	>120	not replaced	1 bag
IX polisher	60	regeneration *in situ* is not possible	1 bag

All of the various chemicals are stable in their supplied form with the exception of the IX resin and the iodine crystals. The IX resin must not be allowed to dry out during storage. The use of a rigid sealed container is recommended because the plastic bags tend to be holed in transit and the resin eventually dries out. The iodine cartridges should be stored in impermeable sealed containers (preferably glass) because iodine gas that sublimes from the crystals tends to permeate through plastic containers. The storage facility should be well ventilated because iodine vapour is very corrosive when it is allowed to build up in a confined space.

14.6 Plant life and reliability

The quality of construction and the choice of materials used in the manufacture of this plant is exemplary and only one related problem occurred during the evaluation (see **Section 14.6.2**).

14.6.1 Materials of construction

The reinforced PVC hose used to connect the various stages will be damaged by continuous exposure to direct sunlight and the resins generally used for GRP tanks are also susceptible to weathering. Algae growth may occur in the hoses and filter bowls if the side covers are removed during full-time plant operation. If the plant is operated in direct sunlight with the side covers fitted, its internal temperature may become significantly higher than the ambient water temperature. For these reasons it is recommended that the plant is situated in shade and operated with the side covers in place.

14.6.2 Reliability

Plant and Equipment : The plant should not be left unsupervised for more than 24 hours at a time because several undesirable effects can occur within this timespan. These effects include filter clogging which will reduce the flowrate and MDU resin depletion which may result in ineffective disinfection of the treated water.

No component failures occurred during the evaluation period. Apart from the rotameter and the flowmeter, none of the control system components would be particularly expensive to replace, or difficult to source in the unlikely event of their failure. However, the three-way valves used on the GAC and IX filters are only available through the local Vector agents.

Control System Components : Problems were experienced with the needle valve and rotameter used for flowrate regulation. The rotameter float became jammed on two occasions by grit carried over from the GAC #1 filter after backwashing. This float is aligned in the riser tube by a central stainless steel rod which must be removed to unblock the float. The PVC end cap on the rotameter has a small Allen key socket which was stripped during the first attempt at removing the cap. Grit also affected the regulation of flow with the needle valve and the use of a diaphragm valve (Saunders type) on the inlet to the plant would provide adequate flow control with less chance of blockages occurring.

14.6.3 Expansion of plant capacity

The production of treated water may be maximised by ensuring that the plant runs at full capacity with minimum downtime. This can be achieved with operator diligence and careful scheduling of maintenance tasks. The housing of the DRWP2 unit is too small to permit installation of larger retention tanks and GAC filters which would allow a higher maximum flowrate to be used. The maximum recommended flowrate should therefore not be exceeded. Increasing the raw water feed pressure to the maximum allowable value (400 kPa) will allow maximum loading of the filters to be achieved and will extend the filter runs. If the demand for water still exceeds the available production, the installation of a larger DRWP plant should be considered.

14.7 Servicing, maintenance and repair

The operating manual discusses the servicing and maintenance of the unit in detail. It explains which tasks can be performed by the operator and which should be carried out by a Vector technician.

It is recommended that repairs, the iodine recharge and replacement of GAC and IX resin should only be performed by a Vector trained technician. The operator should assume responsibility for backwashing of the GAC filters and the replacement of filter cartridges when necessary.

The 3-way valves, GAC filter vessels, retention tanks and polisher vessels are not locally available and replacement of these items locally will be difficult. The glass reinforced polyester tanks and filter vessels should be pressure tested if they are locally repaired.

14.8 Transportation, installation and commissioning

14.8.1 Transportation

The DRWP2 unit can be transported by a light truck (1 ton) or a small trailer (½ ton). The other plants in the range may require larger vehicles for transportation. The current design of the housing makes provision for lifting by forklift only. The attachment of lifting eyes, allowing the use of an overhead crane or other lifting tackle, is recommended.

The plant is transported in the fully assembled state and all components are well secured to the housing. The design of the unit renders it suitable for rapid relocation when necessary. The use of simple hose connections means that the unit can be disconnected and ready for transport within minutes. If the plant is to be relocated, all vessels should be drained to reduce the weight of the unit.

14.8.2 Installation

The unit can be installed on a prepared site within minutes of delivery if suitable hose connections and sufficient raw water pressure are available.

14.8.3 Commissioning

Commissioning of the DRWP2 unit includes the following tasks:

i) Installing the filter cartridges, MDU canisters and the iodine canister.
ii) Filling the GAC tanks with GAC media.
iii) Filling the IX polisher with ion exchange resin.

iv) Opening the raw water valve and bleeding all air from the system.
v) Checking the operation of all valves and instruments.
vi) Noting the initial pressure drops across all stages of the process.
vii) Analysis of samples from each stage of the process for field certification purposes. This certificate signifies that the plant is operating correctly and is producing water of potable quality at the time of handover to the customer.
viii) Handover of the unit to the customer.

The total time required for commissioning of the plant is determined largely by the time required for analysis of samples as the other commissioning tasks can be completed within 3 hours. It is important to note that operator training should occur before commissioning of the unit. It would be an advantage for new operators to have seen an existing plant in operation prior to being entrusted with the operation of a new plant. At present the operator's manual is only available in English. Since the operator's home language is likely to be one of the indigenous South African languages, the translation of key sections (at least) of the manual into some of the more common local languages (Afrikaans, Sotho, Xhosa, Zulu) is recommended.

14.9 Cost

14.9.1 Capital cost

In March 1995, the maximum suggested retail price of the DRWP2 unit was US$ 16 083,54 (excluding shipping). At the prevailing exchange rate of R 3,60 /US$ the equivalent Rand price was R 57 900,74. The installed cost will include the additional costs of shipping, delivery, commissioning and site preparation but the quoted retail price is negotiable on the quantity of units ordered.

14.9.2 Operating cost

An operating cost of R 4,01 /m^3 has been estimated (see **Table 14.6**) on the basis of continuous plant operation at maximum flowrate with an estimated 10% downtime.

Table 14.6 : Estimated operating cost for DRWP2 plant

Operating cost components	Specific costs	
	R/m^3	US $/gal
Chemicals and consumables	2,81	0,00295
Electricity (if used for a pump)	0,21	0,00022
Labour	0,70	0,00074
Maintenance and servicing	0,50	0,00052
Total operating cost .... (pumped feed)	**4,22**	**0,00442**
.... (gravity flow)	**4,01**	**0,0042**

The cost of operating a raw water feed pump has also been estimated. The maximum operating cost (including power for a small centrifugal pump) would be R4,22 /m^3. These estimated operating costs (based on the evaluation at the PEF) agree well with Vector's quoted range of operating costs for this unit (R 1,23 /m^3 to R 5,42 /m^3). These estimates comprise the following cost components:

Chemical and media cost : The operating cost for replacement of filter cartridges, media and other chemicals has been estimated from the prices of locally available equivalents and the service life obtained during the evaluations. These estimates are summarised in **Table 14.7** with US Dollar equivalents based on an exchange rate of R 3,60 /$ which prevailed during evaluation of the unit in March 1995.

Table 14.7 : Estimated cost of consumables for DRWP2 plant

Consumable item	Service life m^3	Cost of item Rands (1994)	Treatment cost R/m^3 (US $/gal)
20 micron filter cartridges	25,3	24,80 ea.	0,98 (0,00103)
5 micron #1 filter cartridges	24,8	11,85 ea.	0,48 (0,00050)
5 micron #2 filter cartridges	148,0	11,85 ea.	0,08 (0,00008)
1 micron filter cartridges	33,8	12,70 ea.	0,38 (0,00040)
GAC #1 media (filter 1)	>160,0	4,00 /kg	0,12 (0,00013)
GAC # 2 & 3 media	>160,0	4,00 /kg	0,12 (0,00013)
GAC polisher media	125,0	4,00 /kg	0,14 (0,00015)
Iodine	~ 2,0 g/m^3	191,40 /kg	0,38 (0,00040)
IX resin regeneration (12- 15 *l*)	60,0	7,50 *	0,13 (0,00014)
Estimated cost of consumables for DRWP2 system			2,81 (0,00295)

* Estimated cost of regeneration chemicals per batch

Cost of electrical energy : The raw water pressure available at the Evaluation Facility, together with a gate valve used for control, was used to drive the water through the package plant and no electrically powered devices were used. A pump may, however, be required for field applications if sufficient gravity head is not available. As an example, a small (0,37 kW) centrifugal pump will be oversized for the flowrate, resulting in a power cost of R0,21/m^3 (flowrate, 0,46 m^3/h; Commercial power tariff is R 0,2643 /kWh).

Labour cost : For operation in rural areas in Southern Africa the DRWP2 plant will require approximately 1 h/day of operator attention at an estimated rate of R 7,00 /h. The specific cost of wages is therefore R 0,70 /m^3.

Maintenance cost : The technical backup and maintenance cost has been estimated at 2 h/month at a rate of R 75,00 /h. The specific cost associated with maintenance is therefore R 0,50 /m^3. The cost of media and other items used by the technician has been included under chemicals and consumables.

15 Slow Sand Filtration

15.1 Introduction to the pilot slow sand filter (SSF)

A pilot scale slow sand filter (SSF) was designed and built by the project staff at the Process Evaluation Facility. The plant was based on pilot scale SSF studies reported by Graham (1988) and was operated in accordance with slow sand filtration practice. Although the plant under investigation is a test plant, various sizes can be manufactured depending on the required water capacity. The linear velocity through the filter is a critical parameter and subsequently the cross sectional area of the filter will vary according to the required capacity.

15.1.1 Plant design philosophy

Slow sand filtration has been widely used in Europe and the USA for more than 200 years, both as a stand alone water treatment process and as a filtration step within more sophisticated processes. SSF is commonly used to treat a relatively clean raw water with low concentrations of suspended solids. The literature indicates that SSF is most effective when the feed water turbidity is less than 10 NTU. The microbiological removal by slow sand filtration is reported to be excellent.

SSF was considered to be appropriate as a rural water treatment technology for the following reasons:

- The systems are simple to build and operate.
- Inexpensive to operate - with no chemical addition.
- Minimal operational problems are experienced.
- Easily prefabricated as a package plant.
- Easily manufactured from locally available materials.

Slow sand filters are operated within a narrow range of flowrates. In order to realistically evaluate the performance of slow sand filtration and determine the costs of operation, two SSFs were constructed and operated at different flowrates.

A limiting factor in the operation of a SSF is the pressure drop across the filter bed which reduces the flowrate and is caused by the build-up of a skin or thin cake of suspended matter (*schmutzdecke*) removed from the raw water. For this reason a pretreatment system was also constructed to reduce the amount of suspended matter accumulating in the filters.

15.1.2 General description of the plant

The pilot plant comprises of a pretreatment system followed by two sand filters (see **Figure 15.1**). The design and operating parameters of the pilot plant are similar to previous pilot plant studies (see **Table 15.1**).

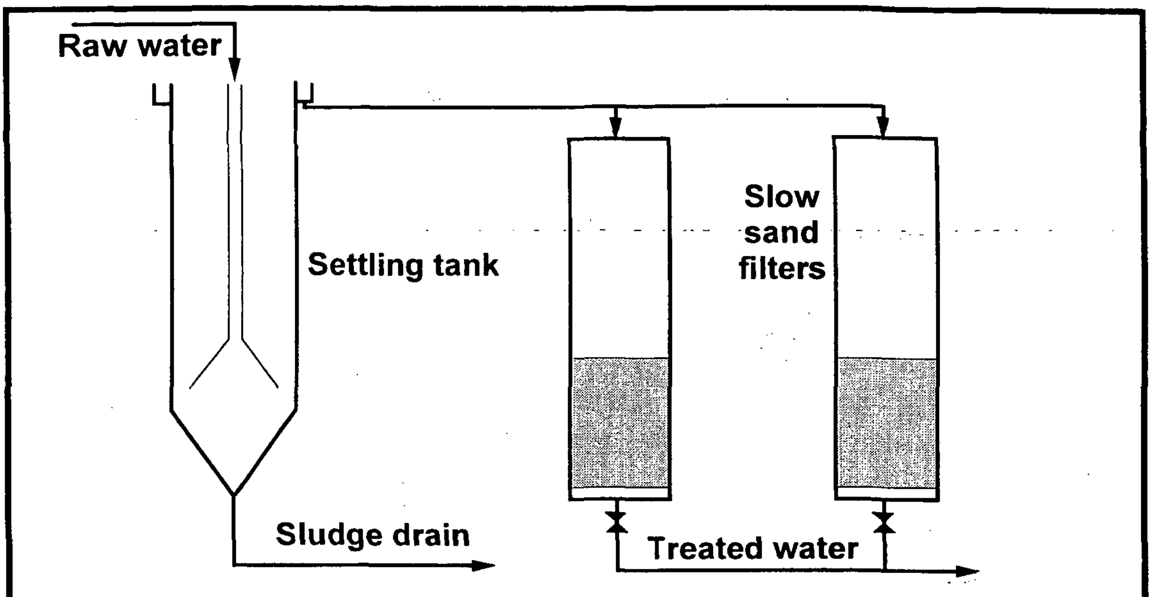


Figure 15.1 : Slow sand filter process flow diagram

The raw water is pre-treated by means of a cylindroconical upflow sedimentation tank, which allows for separation of silt and suspended matter. The sludge was drained from the bottom of the settling tank on a regular basis. The overflow from the sedimentation tank is fed to two sand filters which are operated at different flowrates (0,1 m/h and 0,2 m/h). The flowrate through each filter is manually controlled by valves on the filter outlets and measured on a variable area flowmeter.

Table 15.1 : Design parameters

Parameter	Specification (per filter)
Clarification step :	
Upflow rate (m/h)	0,3
Annulus area (m^2)	0,15
Detention time (h)	6,67
Filtration step :	
Filtration area (m^2)	0,116
Filtration rate range (m/h)	0,1 to 0,3
Nominal capacity (ℓ/h)	10 to 30
Recommended terminal head loss (m)	1,9

15.1.3 Process sophistication

Table 15.2 shows a summary of the components and equipment fitted to the SSF package plant.

Clarification process : Clarification is not aided by coagulants or flocculants. In a cylindroconical sedimentation tank the raw water enters a draft tube that extends to the base of the sedimentation tank. Water flows down the draft tube, and up into the annulus (area between draft tube and filter shell). The settling rate of solid matter (assuming the density of soil particles to be 1121,4 kg/m^3) in the water was estimated as 0,8 m/h. The tank was therefore designed for an upflow velocity of 0,3 m/h, less than half of the settling velocity.

Table 15.2 : Summary of slow sand filter components

Component	Quantity	Comments
Valves	9	7 x PVC ball valves, 3 for sampling and 4 for isolation 2 x diaphragm valves
Instrumentation	2	2 x rotameters for flow monitoring
Filter	1	The following specifications are as designed : 2 x 400 mm by 2,94 m long filter units, each with 0,3 mm sand 1,4m high (top) 0,8 to 1,5 mm sand 6 cm high 2 to 4 mm stones 6 cm high 5 to 12 mm stones 6 cm high 15 to 30 mm stones 6 cm high (bottom)
Clarification	1	450 mm (w) 2,9m (h) cylindroconical settling tank

Disinfection Process : Micro-organism removal is achieved by many types of predatory organisms located in the upper levels of the filter bed, as well as a reduction in nutrients in the lower levels of the bed. Micro-organisms in a slow sand filter produce various substances that act as chemical or biological poisons to intestinal bacteria, resulting in a substantial reduction in the number of E. Coli, and an even greater proportional decrease in pathogens (Huisman and Wood, 1974).

Filtration Process : No calibrations were required for the operation of the filters. The rotameters had to be adjusted to their respective flowrates, of 10 ℓ/h and 20 ℓ/h, which decreased as the pressure drop in the filter increased. The flowrate adjustments were undertaken only once a day as large fluctuations in raw water turbidity did not occur.

The filters were operated with a head of 1,4m of water (14 kPa) during the first 12 months of operation but it was increased to 1,9m of water (19 kPa) thereafter. Raw water was available at 2 bar pressure. Power for pumping will be required if the raw water head at the site of the plant is insufficient.

15.2 Process control system

The filtration velocity is a critical variable that affects final water quality. The control system involves adjustment of the filter outlet flowrate to maintain the setpoint filtration velocity.

A constant head of water is maintained above the bed by a fixed level of water above the media. This is achieved by means of a float valve. Control of feed water flow can also be used for SSF but in this case, the depth of water above the bed will vary.

15.2.1 Operation and control sequence

The flowrates are pre-set during normal operation (20 ℓ/h and 10 ℓ/h on SSF1 and SSF2 respectively) by adjusting the filter outlet valve. As colloidal matter and solids are filtered, the filter slowly becomes loaded, the head loss increases and the flowrate drops. One of the operator's daily tasks is to adjust the flowrate accordingly.

Eventually, after 2 to 6 months of operation, the pressure drop across the filter bed exceeds the available head and the flowrate cannot be maintained. When this happens, filter cleaning is necessary. The filter is isolated and drained of water. The top layer of sand (*schmutzdecke* - top 2 to 3 cm) is scraped off, removing the fouling layer from the filter. The filter is then reassembled and filtration is continued. The sand which is removed should then be washed, sterilised and stored for future use.

The cycle of filtration and scraping can continue for up to 4 years before reaching a limiting depth of 0,6m of sand. At this stage the filter sand is removed and washed. All the sand accumulated from previous scrapings is then returned to the filter and the reconditioned filter is recommissioned.

15.2.2 Degree of automation

The water level in the filter and sedimentation tank was maintained by float valves. No other automation of the process was used.

15.2.3 Monitoring of process parameters

Turbidity was monitored on a daily basis. Microbiological sampling was performed once a week during normal operation. After the removal of the *schmutzdecke* however, disinfection efficiency is usually affected. During this time, sampling should be more intensive. Since microbiological sampling will not be possible on a regular basis in rural areas, post disinfection with chlorine will be necessary after *schmutzdecke* removal. The length of the disinfection period will depend on the raw water quality.

Flowrates were monitored by means of rotameters located on the filter outlet. Flowrate monitoring was important to ensure that the filtration rates were within the range of 0,1 m/h to 0,3 m/h (Huisman and Wood, 1974).

15.2.4 Effectiveness of the control system

The constant-head, variable-flow control system that was used required minimal supervision because the raw water quality fluctuations were mainly gradual and seasonal. The levels in the filters were maintained by float valves. The control system was therefore very effective.

15.2.5 Uncontrolled parameters which may affect final water quality

Sudden increases in raw water turbidity, to over 10 NTU, resulted in deterioration of the final water quality. Increases in raw water turbidity resulted in increases of the final water turbidity to between 1 and 3 NTU (see **Figure 15.2**). This range of turbidity is in the 'insignificant health risk area' as defined by the Department of Health's Draft Guidelines, 1994.

During periods after filter cleaning, the disinfection capabilities of the slow sand filter may not be adequate, resulting in the need for chlorination of the final water. The chlorination should be undertaken in the final water reservoir, and not into the raw water as the biological growth in the sand will then also be destroyed.

15.2.6 Susceptibility to demand fluctuations

As the effectiveness of the process is determined by the filtration rate, the Slow Sand Filtration system will not be able to meet demand fluctuations. The flowrate could be increased slightly but never beyond 0,3 m/h without compromising the final water quality. If there are periods of high demand , sufficient final water storage should be provided such that the filter is able to cope with the average daily demand.

15.3 Personnel requirements

A supervisory service was required during the installation and commissioning phase. The availability of a technician may become more important if a raw water pump is needed as part of the process, although a single operator should be sufficient. Technical support is necessary especially when analysis of microbiological and other chemical content is performed.

15.3.1 Workload estimation

Installation and commissioning : The installation and commissioning of the SSF depends on the size of construction. A SSF constructed of corrugated iron sheeting may take 1 to 2 weeks to install. SSFs constructed of concrete or membrane-lined earthen berms may take 1 month to install. The installation phase involves the erection of the filter unit, erection of a clarification unit (if necessary), filling of media to correct levels and the connection of pipework and instrumentation. Commissioning involves the gradual filling of clarification and sedimentation units with water as well as the start-up of the plant and the initial period of maturation of the filter bed.

Routine operation : Daily turbidity and flowrate monitoring will take 20 minutes per day whilst microbiological sampling will take another 20 minutes per week. The total operator workload during routine operation is therefore approximately 3 hours per week.

Maintenance and repair : Maintenance tasks should take place approximately once every 4 months. The tasks involve removal of the *schmutzdecke* layer, cleaning of rotameters, removal of blockages in the float valve and other repair work. These tasks will take approximately 10 hours (estimated from operating the pilot plant). The maintenance workload is therefore approximately 30 hours per annum.

15.3.2 Specific training requirements

The operator requires special training in

- turbidity monitoring and filtration rate monitoring

- checking raw and filtered water levels and maintaining an accurate logbook
- microbiological sampling
- *schmutzdecke* removal
- post-disinfection after *schmutzdecke* removal and during high filter inlet turbidity occurrences (above 10 NTU).
- observations of algae development, rising *schmutzdecke* and unusual weather conditions

15.4 Infrastructure requirements

Road access : Package slow sand filters will generally be assembled on site. Road access will be required for transporting building materials and personnel as well as earthmoving equipment.

Electricity requirements : Slow sand filters do not require electrical energy although electricity may be necessary for pumps (raw water, reticulation, chemical dosing) and other equipment.

Raw water provision : See **Section 15.5.1**

Treated water reticulation : Since slow sand filtration is a continuous operation a reservoir suitable for a days production of clean water is necessary for buffer storage. Peak demand periods occur during mornings and evenings.

Sludge disposal : Although no sludge is produced by the process, an area for this purpose should be located near the filter. This area will be required to wash and store the sand that is removed with the *schmutzdecke*. Storage of the filter sand is necessary as it can be reused when replacing the sand in the filter bed

Chemical storage : A proper chemical storage shed is required for storage of a disinfection chemical such as sodium hypochlorite when disinfection is used.

Weather protection : The filter should preferably be covered to prevent sunlight from enhancing the growth of algae in the filters, resulting in possible tastes and odours in the final water.

Site Establishment : The establishment of a site will involve ground levelling and preparing a proper foundation if the SSF is to be constructed of concrete. Mechanical earthmoving equipment may be necessary and trenches will be required for laying piping and drainage systems.

15.5 Treatment system

15.5.1 Raw water supply

Head and flowrate : Approximately 1,5 to 2 m of water head is required.

Screening : Screening is very important for the success of a slow sand filter since coarse material (e.g. leaves) will reduce the filter runs considerably. However a settling tank or a raw water buffer storage facility may also serve to remove any coarse material.

Storage / Reservoir capacity : Both raw and clean water storage tanks, each with a 48 hour storage capacity, are necessary.

Quality of Raw Water : Only 31 % of raw water samples were below 10 NTU. The general turbidity range during the period of evaluation was between 0 and 4000 NTU with 97 % of raw water turbidity in a range between 0 and 100 NTU.

15.5.2 Micro-organism removal

Samples were submitted for microbiological analysis on a weekly basis during the period of evaluation. **Table 15.3** shows the number of samples with analyses below or equal to the limits set out in the Department of Health Guidelines (**Appendix 2**). Only the limits conforming to no health risk (NHR) and an insignificant health risk (IHR) are displayed. In addition, the coliform results are discussed in detail because they show the poorest removal of all the indicator organisms.

Although the literature recommends a feed water turbidity (clarified water was used as feed to the SSFs) of less than 10 NTU, a feed water turbidity of 15 NTU was used to differentiate the performance of SSFs with respect to high and low turbidity waters. Approximately 60 % of all microbiological samples were taken when the feed water turbidity was less than 15 NTU and over 60 % of microbiological samples taken were within the NHR limit. The heterotrophic plate count (HPC) at 37°C was an exception.

Table 15.3 : Micro-organism removal

	FEED WATER TURBIDITY LESS THAN 15 NTU				
	Coliforms	***E. Coli***	**F. Strep**	**HPC @ 22°C**	**HPC @ 37°C**
	% of samples below No Health Risk limit				
Filter 1	68	89	94	72	11
Filter 2	82	100	100	81	73
	% of samples below Insignificant Health Risk limit				
Filter 1	100	95	100	100	89
Filter 2	100	100	100	100	100
	FEED WATER TURBIDITY GREATER THAN 15 NTU				
	% of samples below No Health Risk limit				
Filter 1	15	62	77	54	8
Filter 2	29	50	86	50	21
	% of samples below Insignificant Health Risk limit				
Filter 1	62	69	85	92	92
Filter 2	71	71	86	100	71

In the case of Coliforms, for example, 68 % and 82 % of the samples analysed conformed to the NHR limit for SSFs 1 and 2 respectively when the feed water turbidity was below 15 NTU. Only 15 % and 29 % of the samples analysed conformed to the NHR limit for SSFs 1 and 2 respectively when the feed water turbidity was above 15 NTU. Therefore microbiological removal was significantly better when the feed water turbidity was below 15 NTU.

With the exception of the HPC at 37°C, 95 to 100 percent of samples conformed to the IHR limit when the clarified water turbidity was below 15 NTU.

It was also observed, from **Table 15.3**, that the microbiological removal was relatively better in SSF2 than in SSF1. This occurred despite the fact that both filters were run within the recommended range of filtration rates between 0,1 m/h and 0,3 m/h. SSF 2 operated at half the filtration rate of SSF 1 therefore the contact time available for microbiological removal in SSF 2 was twice that of SSF1.

F. Strep counts conforming to the NHR guideline occurred in 94 % and 100 % of samples from filters 1 and 2 respectively. This can be attributed to the low counts of F. Strep in the raw water.

The microbiological content of the treated water from both filters did not conform to the guideline values during filter ripening and filter recovery periods. Filter ripening (microbiological maturation) occurs during the first month after plant start-up. A filter recovery period is the time taken for the filter to re-establish a mature microbiological layer on the sand surface, after *schmutzdecke* removal The filter recovery period was in the range of 4 to 5 days at clarified water turbidities below 15 NTU and approximately 3 to 4 weeks at clarified water turbidities above 15 NTU. Post-disinfection with chlorine is recommended during the filter ripening and filter recovery periods.

15.5.3 Turbidity and suspended solids removal

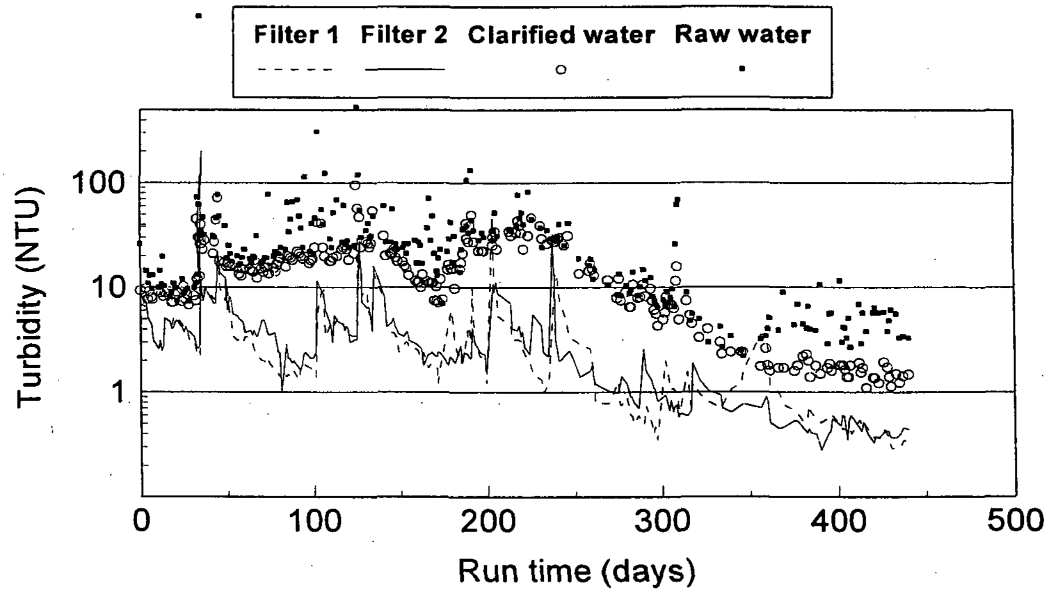


Figure 15.2 : Turbidity trends for pilot slow sand filters

The turbidity of the water entering a slow sand filter should be less than 10 NTU (Graham,1988). **Figure 15.2** shows the general turbidity trends during the entire evaluation period and it can be seen that satisfactory turbidity removal only occurred when the clarified water turbidity was below 10 NTU. The clarified water turbidity was < 10 NTU in the first 30 days of operation but turbidity breakthrough occurred at this stage because filter ripening was still in progress. From **Table 15.4** one can also observe that the clarified water turbidity was below 10 NTU in 40 % of the daily grab samples.

Table 15.4 : Summary of turbidity removal

% of Raw Water samples < 10 NTU	% of Clarified Water samples < 10 NTU
30,6	39,8
% of Treated Water samples below No Health Risk limit (< 1 NTU)	
SSF1	**SSF2**
24,3	25,7
% of Treated Water samples below Insignifcant Health Risk limit (<5 NTU)	
SSF1	**SSF2**
81,2	82,5

The turbidity guideline values for drinking water are listed in **Appendix 2**. A filtrate turbidity of below 1 NTU was typically achieved when the turbidity of water entering the filters was below 10 NTU. Approximately 24 % and 26 % of filtrate samples from SSF1 and SSF2 respectively, conformed to the NHR limit. Just over 80 % of both filtrate samples conformed to the IHR limit. Therefore there was no significant difference in turbidity removal performance between SSF1 and SSF2 even though the filters operated at different rates.

Instances where a filtrate turbidity above 1 NTU was produced, despite a feed water turbidity below 10 NTU, can be attributed to the initial 'ripening' period and subsequent recovery periods after filter scraping. An increase in the raw water and clarified water turbidities to over 10 NTU generally resulted in an increase in final water turbidity.

The clarifier was most effective when operated with raw water turbidities above 100 NTU. In this range, 70 to 99 % of the influent turbidity was removed. The water recovery was approximately 96 % (3 months filter run, 4 days recovery) for clarified water turbidities below 15 NTU. At clarified water turbidities above 15 NTU the water recovery decreased to 77 %. A water recovery of 100% may be feasible if post disinfection of the final water is applied during the filter recovery periods.

15.5.4 Chemical requirements

The system was operated without chemicals. However chemical treatment may be required when turbidities increase above 10 NTU (due to seasonal changes or geographical locations). A coagulant will be required at the clarification stage in order to reduce raw water turbidities to below 10 NTU.

Post disinfection is advisable especially during filter recovery periods and high raw water turbidity periods (above 10 NTU). Pre-disinfection is not advisable since the micro-organisms within the filter media will be destroyed.

15.6 Plant life and reliability

If the turbidity of the water fed to the filter is maintained below 10 to 15 NTU, 4 to 5 years of operation should be possible before replacement or reconditioning of the filter bed is required. Sand replacement is generally carried out once the bed depth has been reduced to 0,6 m as a result of periodic *schmutzdecke* removal.

15.6.1 Materials of Construction

The filters can be constructed from concrete, bricks, membrane lined earth berms or ferrocement. Package SSF plants constructed from cylindrical galvanised steel tanks (Potapak) are available and their life will be limited by the aggressivity of the raw water to galvanised steel.

15.6.2 Reliability

Plant and equipment : The plant can operate for a week without supervision if the fluctuations in raw water quality are minimal. The slow sand filter cannot handle a shock load of suspended solids in the raw water. One particular example was when a final water turbidity of 200 NTU resulted after the raw water turbidity had increased to 4000 NTU after a severe storm. Inflow to the plant should be temporarily stopped when such situations occur.

Control system components : Both flow indicators and inlet valves require periodic cleaning. The flow indicators on the pilot plant became fouled with solid matter and algal growth after 6 months and cleaning on a three monthly basis was necessary. The inlet valves also become clogged with sediment from the raw water after a period of time and require occasional flushing.

15.6.3 Potential for expansion of capacity

SSF volumetric capacity should not be increased by increasing the filtration rate as this reduces the contact time in the filter bed, causing a deterioration in the treated water quality. Additional filter area is required if a SSF is unable to meet the demand for water. The recommended method for expanding capacity is therefore to build additional filter units that operate in parallel with the existing system. This will improve the continuity of the treated water flow during system maintenance.

In normal practice, SSF can be operated at rates up to 0,3 m/h. However, when treating raw waters with high turbidity, operation at the maximum rate reduces the length of the filter runs and extends the recovery period. If raw water turbidities exceed 10 NTU for more than two months of the year, pretreatment of the water (reducing the turbidity to < 10 NTU) will permit more effective operation at rates up to 0,3 m/h.

15.7 Servicing, maintenance and repair

Raw water pump : If a pump is used, bearings and pump seals require an annual check-up and gland type seals may require more frequent adjustment or repacking. The raw water pump may require frequent attention due to the abrasive nature of particles that occur in some raw waters. The use of mechanical pump seals is recommended.

Dosing pumps : A disinfectant dosing pump may be installed to disinfect the treated water either during the period of filter recovery (after the *schmutzdecke* scraping) or permanently. The suction-valve strainer should be regularly inspected. The valves also require cleaning and maintenance at least every 6 months. These tasks can be performed by the operator with the aid of an instruction manual.

Valves and fittings : Valves and fittings, especially those on the inlet side of the filter, require periodic cleaning when they become blocked with solid matter.

Media cleaning : Cleaning operations of the SS form the major part of the maintenance workload. The removal of *schmutzdecke* occurs once every 3 to 6 months and replacement of the sand bed is necessary every 4 to 6 years.

15.8 Transportation, installation and commissioning

15.8.1 Transportation

The plant should be accessible by road for the transport of building material during installation and commissioning. Technical support or supervisory personnel (e.g. for microbiological sampling and analysis, checking of logbooks, etc.) may also visit the plant at regular intervals.

The size of the filters will dictate the transportation requirements. It is possible to manufacture smaller plants in a workshop and transport them to the site as packaged units. Once erected however, these plants will be difficult to relocate, and subsequent transportation is unlikely.

15.8.2 Installation

The local people may be used, under supervision, for building of tanks, transport of media and laying of pipes. The length of time from purchase to full scale operation of the plant will depend on the size of the plant and the time taken by the local people for the construction of the plant.

15.8.3 Commissioning

Commissioning will involve the filling of raw water into the pretreatment tanks and the Slow Sand Filter supernatant reservoir. Commissioning also incorporates the time taken for 'ripening', which takes approximately a month. During this time the filtrate is drained to waste.. Microbiological sampling should occur more regularly (twice weekly) in order to determine the exact completion of the 'ripening' stage. The 'ripening' process can be accelerated by 'seeding' the filter with active material removed from an existing filter.

The filter should be filled from the bottom to drive out the air bubbles from the interstices of the sand thus ensuring that the whole cross-sectional area is available for filtration. This is continued until the sand bed is covered by a sufficient depth of water to prevent it being scoured or disturbed by turbulence from the admission of raw water. Raw water is then admitted through the inlet above the media.

15.9 Cost

15.9.1 Capital cost

The cost of a SSF constructed of a cylindrical steel tank was difficult to determine. The cost of a Slow Sand Filter (1978), with a covering, that was constructed of concrete was 805 US $/m3/day. The cost of a Slow Sand Filter (1978), without a covering, that was constructed of a membrane-lined earthen berm was 108,5 US $/m3/day (USEPA 1990)

The costs were projected to 1993 using a Marshall and Swift index value of 966,9. The 1978 Marshall and Swift index value was 554 (Peters and Timmerhaus, 1988).

The 1993 capital cost of a concrete Slow Sand Filter, with a covering, is R 4215 /m^3/day. The cost of a membrane-lined earthen berm Slow Sand Filter, without a covering, is R 568 /m^3/day. Packaged SSF units are not available locally (as far as it is known).

15.9.2 Operating cost

Due to the low capacity of the SSF pilot plant, operating cost estimates based on the pilot plant were unrealistically high. An attempt was made to calculate realistic operating costs based on the literature and the experience obtained during operation of the SSF pilot plant. An estimated operating cost of R 0,11 /m^3 was calculated for a 10 m^2 SSF which is the smallest size that is likely to built for a community water scheme.

Table 15.5 : Estimated operating cost (1994)

Component cost	Estimated specific cost (R/m^3)
Chemicals	negligible if supplementary disinfection is not practised
Electrical power	not applicable
Labour	0,11
Maintenance and repair	negligible
Estimated total	**0,11**

Chemical Cost : A chemical cost may be appropriate if one considers the cost of sand replacement, which occurs approximately once in 5 years. However this cost should be negligible if recycled sand (from the scraping of the filters) is used. An approximate cost of R0,03 /m^3 will be incurred if chlorination of the filtered water is practiced.

Power Cost : The SSF should ideally be fed by gravity from the raw water source. However, pumping costs will be incurred if gravity feed from the raw water source to the plant is not possible. In addition, pumps may also be necessary for elevation of the treated water to a reservoir supplying a reticulation system. These costs will be site specific and have not been considered here.

Labour Cost : The workload for routine operation such as adjustment of flowratesand water quality monitoring was 2,67 hours per week for the pilot plant. This routine operation workload will not increase significantly as plant capacity increases. However, the workload related to *schmutzdecke* removal will be directly proportional to filter bed area. Huisman and Wood reports a labour requirement of 75 man-hours for the cleaning of a 2000 m^2 SSF. A SSF of 2000 m^2 operating at a filtration velocity of 0,1 m/h will produce 200 m^3/h. If filter scraping occurs every three months, an additional labour cost of R0,0012 /m^3 will result at an unskilled labour cost of R 7,00 /h, . If raw water tubidities increase and the periods between filter scraping are reduced to three weeks, the additional labour cost could increase to R 0,005 /m^3.

According to these criteria, the total labour cost for the SSF **pilot** plant was estimated as R2,78/m^3. Using the same criteria, a more realistic estimate of R 0,11 /m^3 was calculated for a 10 m^2 SSF with a capacity of approximately 1 m^3/h (sufficient for up to 960 people at the RDP minimum supply level). The equivalent labour cost for a 100 m^2 SSF is approximately R 0,02 /m^3.

Maintenance Cost : The maintenance cost was based only on resanding operations. The cost of having to wash and recycle sand was considered negligible as this will occur only once every 4-6 years.

16 References

BALDWIN D A, 1981, The chemistry of swimming pool disinfectants, *CHEMSA*, **8**(5)

BARROT L P, Graham N J D and LLOYD B J, 1994, Further Evaluation of an on-site chlorine gas generator (Moggod) for small-community water disinfection in developing countries, *Aqua - Journal of Water Supply Research and Technology*, **43**(4).

BAUMANN E R, CLEASBY J L and LaFRENZ R L, 1962, A Theory of Diatomite Filtration, *Journal AWWA*, **54**(9)

CARLSSON F H H, 1994, Chemical aspects of the use of cyanuric acid stabilisation of chlorinated swimming pool water, *Water Sewage and Effluent*, **14**(1)

CARLSSON F H H, 1994, Environmental and human health aspects of the use of cyanuric acid stabilisation of swimming pool water, *Water Sewage and Effluent*, **14**(4).

CLARK, R M, GOODRICH, J A and LYKINS, B W, 1994, Package plants for small water supplies - the US experience, *Aqua*, **43**(1).

C.S.I.R, (No publication date given), *Manual on Water Purification Technology*, CSIR Technical Guide K73.

DEGRÉMONT, 1991, *Water Treatment Handbook*, 6 ed, Lavoisier Publishing.

Department of Water Affairs, 1986, *Management of the Water Resources of the Republic of South Africa*, Government Printer, Pretoria, Republic of South Africa.

Department of Water Affairs and Forestry, 1994, White Paper entitled "Water Supply and Sanitation Policy".

Department of Water Affairs and Forestry, 1991, Water Quality Management Policies and Strategies in the Republic of South Africa.

GALVIS G, FERNÁNDEZ J and VISSCHER J T, 1993, Comparative study of different pre-treatment alternatives, *Aqua - Journal of Water Supply Research and Technology*, **42**(6).

GANDILHON A and TAMBO N, 1992, An experimental study on a membrane ultrafiltration process for drinking water production, *Aqua - Journal of Water Supply Research and Technology*, **41**(4).

GOODRICH J A, 1994, Small Systems Research in the United States, Drinking Water Research Division, Risk Reduction Engineering Laboratory, United States Environmental Protection Agency.

GOODRICH J A, ADAMS J Q, LYKINS B W, 1994, Ultrafiltration Membrane Applications for Small Systems, Drinking Water Research Division, Risk Reduction Engineering Laboratory, United States Environmental Protection Agency.

GRAHAM N J D, 1988, *Slow Sand Filtration - Recent Developments in Water Treatment Technology*, John Wiley, Chichester.

HAMANN C L and McKINNEY R E, 1968, Upflow Filtration Process, *Journal AWWA*, **60**(9).

HANEY B J and STEIMLE S E, 1974, Potable Water Supply by means of Upflow Filtration, *Journal AWWA*, **66**(2).

HUISMAN L and WOOD W E, 1974, *Slow Sand Filtration*, World Health Organisation.

LaFRENZ R L and BAUMANN E R, 1962, Optimums in Diatomite Filtration, *Journal AWWA*, **54**(7).

LANGE K P, BELLAMY W D, HENDRICKS D W and LOGSDON G S, 1986, Diatomaceous Earth Filtration of Giardia Cysts and Other Substances, *Journal AWWA*, **78**(1).

LORCH, W (editor), 1987, *Handbook of Water Purification*, 2 ed, Ellis Horwood.

OEBEN R W, HAINES H P, IVES K J, 1968, Comparison of Normal and Reverse Graded Filtration, *Journal AWWA*, **60**(4).

PETERS M S and TIMMERHAUS K D, 1981, *Plant Design and Economics for Chemical Engineers*, 3 ed, Mc Graw-Hill.

PONTIUS, F W (editor), 1990, *Water Quality and Treatment : A Handbook of Community Water Supplies*, 4 ed, Mc Graw-Hill.

SANKS, R L (editor), 1978, *Water Treatment Plant Design for the Practicing Engineer*, Ann Arbor Science.

SCHULZ, C R and OKUN, D A, 1992, *Surface Water Treatment for Developing Communities*, Intermediate Technology Publications.

SHUVAL H, FATTAL B, NASSAL A, LEV O and PEDAHZUR R, 1994, The study of the synergism between oligodynamic silver and hydrogen peroxide as a long acting water disinfectant, Paper presented at the IWSA International Specialised Conference on Disinfection, Kruger National Park, South Africa.

TREFFRY-GOATLEY K, 1994, Explochem Water Treatment (Pty) Ltd, Personal communication.

U.S.E.P.A., (No publication date given), *Technologies For Upgrading Existing Or Designing New Drinking Water Treatment Facilities*.

WHITE, G C, 1992, *Handbook of Chlorination*, 3 ed, Van Nostrand Reinhold, New York.

APPENDIX 1 Evaluation Testing Methodology Checklist

1.1 Introduction to the Plant

- Provide the name and address of the manufacturer as well as the names of contact persons in the manufacturer's organisation.
- Mention the capacities of the range of plants available from the manufacturer and state explicitly which model was evaluated.

1.1.1 Plant design philosophy

How has the process layout and the choice of components been affected by compromises on the following desirable features:

- modular plant design
- low maintenance requirements
- automated operation
- low workload
- conventional technology
- chemical free operation

1.1.2 General Description of Plant

The description should include:

- a flow diagram
- the manufacturer's specifications and performance claims where applicable.
- the type of process (batch or continuous) and the unit operations involved .
- the type and approximate quantity of consumable items required for operation of the process.

1.1.3 Process sophistication

The following aspects should be evaluated:

- The number of valves, pumps, control loops, electrical switches and circuits used.
- The number of calibrations and settings that need to be made.
- The maximum working pressure and the power consumption (kWh/m^3) of the process.
- The level of sophistication and additional risks of failure introduced by the complexity.
- The type of cleaning methods in use.
- The number of custom made components that can only be repaired or replaced by the supplier.
- Comments on each component discussing its suitability in terms of type, capacity and materials of construction where relevant.

1.2 Process Control System

1.2.1 Operation and Control Sequence

This section should include a detailed description of the control system and operation of the plant. Diagrams should be used if necessary

1.2.2 Degree of Automation

The degree of automation and the reduction in manual workload that results from automation of the following aspects of the plant is discussed:

- Automation of chemical dosing, replenishment and calibration.
- Control of the duration and intensity of mixing.
- Control of flowrate, retention time, sludge removal and turbidity monitoring in clarification equipment and filters.
- Control of level and flow in the reticulation system.

1.2.3 Monitoring of process parameters

The following features of the monitoring system are to be assessed:

- Superfluous or insufficient instrumentation:
    i) The instrumentation should accurately reflect the state of the plant.
    ii) The system should alert the operator to alarm conditions.
- Operator decisions that cannot be directly inferred from instruments and which require specialised testing equipment (e.g. jar test apparatus).
- Parameters that require routine monitoring and recording to give an indication of performance.

1.2.4 Effectiveness of Control System

Comments on the effectiveness of the control system in maintaining adequate quality and quantity of treated water with reference to results.

1.2.5 Uncontrolled parameters which may affect treated water quality

This section of the evaluation must determine if:

- The controlled variables effectively produce potable water.
- Alternative control strategies or modifications will improve the process control.
- Standardised checks exist that the operator can perform to indicate control system malfunctions.
- Safeguards against overdosing of chemicals are provided by either passive or active means.
- The control system or its components limit the throughput of the process.
- The process produces a residual that will suffice for disinfection of the reticulation system.

1.2.6 Susceptibility to Demand Fluctuations

The following factors must be assessed:

- The effect of the automation system on the susceptibility of the plant to demand fluctuations.
- The susceptibility of plant components to demand fluctuations.
- The effectiveness of automated facilities for shut-down or reducing the flowrate as well as the effect on treated water quality of operation at flows greater than the design capacity.

1.3 Personnel Requirements

The personnel requirements need to be reflected in three main categories:

- operations
- maintenance
- technical support.

A thorough evaluation is made of the workload and required level of competence for each category of personnel.

1.3.1 Workload Estimation

Installation and Commissioning: The workload involved and the type of expertise required is estimated. Estimates should be based on the time taken to install the units at the Process Evaluation Facility.

Routine Operation: The workload and personnel resources required for routine operation are determined from operating experience and include estimates of the workload involved in :

- Sampling
- Analysis and monitoring
- Backwashing
- general cleaning duties
- administration
- make-up of chemical stock solutions

Maintenance and Repair : Assess the workload involved in:

- Routine maintenance and servicing including calibration of instruments.
- Replacement of membranes or filter modules and periodic cleaning of clarifiers and sand filters.
- Painting and general repairs to perished or weathered equipment.

1.3.2 Specific Training Requirements

- Determine the educational or skill level required.
- List the additional training required to enable the operator to effectively:
  - i) replenish chemicals
  - ii) report faults
  - iii) manipulate the controls
  - iv) take samples
  - v) perform simple cleaning and maintenance

vi) determine chemical dosages.

- Determine the availability of training and operating manuals in the operator's home language.
- Details any specific training requirements for the artisans who will be involved in maintenance.

1.4 Infrastructure Requirements

The aim of this section is to determine the level of additional facilities that a package plant customer will have to provide. These include:

- Road access
- Power requirements
- Treated water reticulation system
- Sludge disposal
- Chemical storage facilities
- Site establishment
- Weather protection

1.5 Performance of the Treatment System

1.5.1 Raw water supply

The plant's requirements with respect to its raw water supply needs to be assessed. These requirements include:

- Head and flowrate
- Screening
- Storage/Reservoir Capacity
- Quality of Raw Water

1.5.2 Micro-organism Removal

The effectivenees of micro-organism removal must be addressed with regard to:

- Maintenance of a residual
- Consumption of disinfectant
- Ease of maintaining dose concentrations.
- Safeguards against over or under dosing
- Disinfection by-products
- Positioning of dosing points
- Taste and odours caused by disinfection
- Results of microbiological tests

1.5.3 Turbidity and suspended solids removal

Results obtained from operation of the units will be presented and discussed in terms of:

- The range of raw water turbidities that can be treated to produce acceptable potable water.
- The relationship between raw and final water turbidity.
- The relationship between turbidity removal and chemical consumption.
- The proportion of suspended solids removed by clarification and filtration processes
- Optimisation of the plant and the sensitivity of the plant to setpoint changes
- The susceptibility of the plant to demand and raw water quality variations.
- The water recovery that the process can achieve.
- Long term decline in the performance of filters and membrane modules.

1.5.4 Chemical Requirements

The following points are discussed:

- The types and quantity of chemicals and other consumable items required by the process.
- Recommended minimum inventory levels based on consumption, shelf life and availability.
- The degree of preparation of chemicals and special safety precautions or storage requirements.
- The use of alternative chemicals is discussed and where possible, their viability.
- The stability of the diluted chemical dosing solutions.

1.6 Plant Life and Reliability

The purpose of this part of the evaluation is to determine if the life of the plant as a whole will be prejudiced by a particular component or design fault.

- The expected operating life of the plant as well as the expected operating life of filter modules, membranes, tanks, pumps, valves, electrical switchgear is estimated.
- The terms of any guarantees offered by the manufacturers are also stated.

1.6.1 Materials of construction

The materials of construction play an important part in the life of a package plant. For any particular duty, the material chosen for use:

- Should have suitable physical properties (strength, toughness, thermal and chemical tolerance)
- Should be appropriately coated or treated to minimise corrosion, weathering and wear and tear.
- Should not interact with other adjacent materials in a way that will accelerate corrosion or wear.
- Should not impart undesirable corrosion products or toxic compounds to the water being treated.

Certain design characteristics apply to package plants for rural and peri-urban water treatment applications that can affect the choice of materials. These characteristics include:

- **Transportability:** This has an impact on tank and pipework design:
    - Lightweight tanks with sufficient durability to withstand the stresses of repeated relocation are required.
    - Pipework should be constructed in such a way that it can be dismantled, relocated and reconnected quickly and cheaply.
- **Low maintenance:** In many of the user communities, persons suitably trained for maintenance of plant machinery will not be available. Therefore:
    - Plant components should be of the low maintenance type.
    - The requirement for spares and consumable items such as filter cartridges and pump spares should be as low as possible
- **Cost:** Third world communities typically are not affluent and cannot afford large outlays for capital and operating expenses.

- **Weatherproofing:** Many package plants will not be sheltered in use and be should be able to operate reliably in the outside environment. Consequently:
    - Electrically powered devices should be appropriately insulated.
    - Weatherproof low maintenance coatings and treatments should be used.

In this part of the evaluation all process components are discussed in terms of how well they meet these requirements. The degree of overdesign (resulting in excessive cost) and underdesign (resulting in compromised performance and reduced operating life) is also assessed.

1.6.2 Reliability

The reliability of the plant and its control system is assessed The following aspects are considered:

- The length of time for which the plant can run without supervision.
- Incidents of failure during operation and the provision of standby capacity.
- Circumstances under which untreated and undisinfected water can enter the potable water reticulation system.
- Facilities for automatic shutdown in the event of power or component failures.
- Components that seem inappropriate for their tasks. Alternatives should be suggested.
- The delicacy of instruments or automation devices where this restricts the range of potential applications for the plant.
- The possible effects on final water quality of control system or process component failures.

1.6.3 Potential for Expansion of Capacity

The potential for increasing plant capacity must be assessed and include:

- Analyses of physical constraints in the existing process and estimates of the relative costs of increasing capacity by removing these constraints.
- Comments on the effect of increased capacity on the workload and operating skill requirements.
- The effect of expansion on utility requirements such as storage space, stock inventories and electrical power requirements
- Where a modular design approach has been used; the consequences of adding further modules to increase capacity must be assessed, noting instances where existing equipment can be shared.

1.7 Servicing, Maintenance and Repair

The servicing and maintenance requirements are assessed including:

- Pumps, valves, pipework and instruments
- Maintenance schedule provided by suppliers.
- Availability of spares from suppliers and alternative sources.
- Maintenance tasks requiring special skills or tools.
- The feasibility of entrusting the operator with certain maintenance tasks.

1.8 Transportation, Installation and Commissioning

1.8.1 Transportation

The following aspects will need to be addressed:

- The size and type of vehicle required for transport of the plant.
- The degree to which the plant can be dismantled for transport.
- The suitability of the design for relocation after installation.
- Special precautions required for protection of delicate components during transport.

1.8.2 Installation

The following aspects must be addressed:

- the extent to which local people can be involved in the installation of the unit.
- the length of time from purchase to full scale operation of the plant.

1.8.3 Commissioning

A description of the commissioning process is based on the actual commissioning of the units at the PEF. The following points need to be highligted:

- *The time required for commissioning.*
- The degree of operator training that is offered and the consequent extra costs incurred.
- The degree of optimisation of the plant achieved during commisioning.
- The effectiveness of instruction manuals.

1.9 Cost

All prices quoted must be linked to dates so that they may be adjusted from price indices by future readers.

1.9.1 Capital Cost

The capital cost of the plant (including installation and commissioning) is to be obtained from the manufacturer or supplier. The capital cost of ancillaries such as modifications to power supply, sourcing of raw water supply, site preparation and additional water storage will be site specific and is not estimated here. The future reader may estimate such costs from the discussion of infrastructure requirements that are included with each evaluation and must be aware of these potential additional expenses. Determination of unit costs over a range of output capacities allows comparison of the operating expenses of different types of plant.

1.9.2 Operating Cost

The operating cost of each unit must comprise of labour, chemical, energy and maintenance costs. Each of these will be estimated to give the reader an appreciation of the cost per unit volume of water produced by each plant. The sensitivity of these costs to variations in plant capacity should also be estimated where possible.

APPENDIX 2 Department of Health, 1994 Draft Guidelines for Drinking Water Quality

Four different health risk areas are defined for contaminants. These definitions are summarised here for convenience:

The no health risk area : The primary water quality limit. There is a built-in safety factor and no immediate risk to health exists if this limit is exceeded.

The insignificant health risk area : This area still represents safe potable water but the specified limits should not be exceeded. Immediate action should be instituted to reduce the concentration of determinants that exceed this limit.

The low health risk area : Water falling in this category may constitute a minimal health risk to individuals. Various considerations apply to the use of such waters:

- ► There should be no economically viable alternative source.
- ► Vulnerable consumers (expectant mothers, children, the elderly) must be considered.
- ► The consumers and local medical personnel must be informed of the risk.

Waters where the contaminant concentrations exceed the limits of this area fall into **the greater (unacceptable) health risk area.** Waters of this quality may cause serious health effects and extreme action must be taken to find an alternative supply or improve the water quality immediately.

Tables A2-1 to **A2-4** list contaminants of health and aesthetic significance together with the concentrations at which the various risk levels occur. **Tables A2-5** and **A2-6** list recommendations for the frequency of sampling for the listed contaminants.

Table A2 - 1 : Guideline values for microbiological and biological quality of drinking water

Determinands	Units	Health risk ranges			
		None	Insignificant	Low	Greater
Standard plate count	/mℓ	<100 *	1000	10000	
Total Coliforms	/100 mℓ	0 *	5	100	
Faecal Coliforms	/100 mℓ	0 *	1	10	
Clostridium perfringes	/100 mℓ	0 *	1	10	
Coliphages	/100 mℓ	0 *	10	100	
Enteric viruses	/10 ℓ	0 *	1	10	
Giardia lamblia	/2 ℓ	0 *	2	5	

* In 95 % of annual samples

Table A2 - 2 : Guideline values for substances affecting the aesthetic quality of drinking water

Determinands	Units	Aesthetic risk ranges			
		None	Insignificant	Low	Greater
Colour	mg/ℓ Pt	20			
Conductivity	mS/m	70	300	400	
Dissolved organic carbon	mg/ℓ DOC	5	10	20	
Dissolved oxygen	% Satn.	>70	>30	10	
Hydrogen sulphide	µg/ℓ	100	300	600	
Methylene blue active substances	mg/ℓ LAS	0,5	1,0	2,0	
Odour	TON	1	5	10	
pH	pH units	6 to 9	<5,5 or >9,5	<4 or >11	
Taste	TTN	1	5	10	
Temperature	°C	<25	<30	<40	
Turbidity	NTU	1	5	10	
Aluminium	µg/ℓ Al	150	500	1000	
Copper	mg/ℓ Cu	0,5			
Chloride	mg/ℓ Cl	250	600	1200	
Iron	µg/ℓ Fe	100	1000	2000	
Manganese	µg/ℓ Mn	50	1000	2000	
Sulphate	mg/ℓ SO_4	200	600	1200	
Zinc	mg/ℓ Zn	1,0	5,0	10	

Table A2 - 3 : Guideline values for inorganic and radioactive substances of health significance in drinking water

Determinands	Units	Health risk ranges			
		None	Insignificant	Low	Greater
Aluminium	mg/ℓ Al	0,15	0,5	1,0	
Ammonia	mg/ℓ NH_4	1,0	2,0	4,0	
Barium	mg/ℓ Ba	0,5	1,0	2,0	
Boron	mg/ℓ B	0,5	2,0	4,0	
Bromide	mg/ℓ Br	1,0	3,0	6,0	
Calcium	mg/ℓ Ca	150	200	400	
Cerium	mg/ℓ Ce	1,0	2,0	4,0	
Chlorine (free residual)	mg/ℓ Cl	0,2 - 5	<0,2 - >5		
Chloride	mg/ℓ Cl	250	600	1200	
Copper	mg/ℓ Cu	0,5	1,0	2,0	
Fluoride	mg/ℓ F	1,0	1,5	3,0	
Total hardness	mg/ℓ $CaCO_3$	20-300	<20 or >650	1300	
Iodide	mg/ℓ I	0,5	1,0	2,0	
Lithium	mg/ℓ Li	2,5	5,0	10	
Magnesium	mg/ℓ Mg	70	100	200	
Nitrates	mg/ℓ N	6	10	20	
Phosphate	mg/ℓ P	0,1	0,25	2,0	
Potassium	mg/ℓ K	25	50	100	
Rubidium	mg/ℓ Ru		5,0		
Silica	mg/ℓ Si		18,0		
Sodium	mg/ℓ Na	100	400	800	
Sulphate	mg/ℓ SO_4	200	600	1200	
Strontium	mg/ℓ Sr	2,0		10	
Uranium	mg/ℓ U	1,0	4,0	8,0	
Antimony	µg/ℓ Sb	50	100	200	
Arsenic	µg/ℓ As	100	300	600	
Beryllium	µg/ℓ Be	2	5	10	
Bismuth	µg/ℓ Bi	250	500	1000	
Cadmium	µg/ℓ Cd	10	20	40	
Chromium	µg/ℓ Cr	100	200	400	
Cobalt	µg/ℓ Co	250	500	1000	
Cyanide	µg/ℓ CN	200	300	600	
Gold	µg/ℓ Au	2	5	10	
Lead	µg/ℓ Pb	50	100	200	
Mercury	µg/ℓ Hg	5	10	20	
Molybdenum	µg/ℓ Mo	50	100	200	
Nickel	µg/ℓ Ni	250	500	1000	
Radium	µg/ℓ Ra		1		
Selenium	µg/ℓ Se	20	50	100	
Silver	µg/ℓ Ag	20	50	100	
Tellurium	µg/ℓ Te	2	5	10	
Thallium	µg/ℓ Tl	5	10	20	
Thorium	µg/ℓ Th		0,5		
Tin	µg/ℓ Sn	100	200	400	
Titanium	µg/ℓ Ti	100	500	1000	
Tungsten	µg/ℓ W	100	500	1000	
Vanadium	µg/ℓ V	250	500	1000	
Yttrium	µg/ℓ Y		1		

Table A2 - 4 : Guideline values for organic substances of health significance in drinking water

Determinands	Units	Health risk ranges			
		None	Insignificant	Low	Greater
Aldrin/Dieldrin	µg/ℓ	0,2		2	
Atrazine	µg/ℓ	2,5		25	
Propazine	µg/ℓ	8		80	
Chlordane	µg/ℓ	1		10	
D, 2, 4-	µg/ℓ	10		100	
DDT	µg/ℓ	2		50	
Endrin	µg/ℓ	0,2		1	
Heptachlor	µg/ℓ	0,1		1	
Lindane	µg/ℓ	2		5	
Malathion	µg/ℓ	50		100	
Methoxychlor	µg/ℓ	10		1000	
Parathion	µg/ℓ	0,1		1	
Toxaphene	µg/ℓ	5		5	
T, 2, 4, 5-	µg/ℓ	1		10	
TP, 2, 4, 5-	µg/ℓ	10		30	
Polycyclic aromatics	µg/ℓ	0,2		5	
Total THM	µg/ℓ	100			
Chloroform	µg/ℓ	2		18	
Dibromochloromethane	µg/ℓ	2		24	
Bromodichloromethane	µg/ℓ	2		20	
Bromoform	µg/ℓ	3		38	
Trichloroethylene	µg/ℓ	14		144	
Diethyl phthalate	µg/ℓ	23,4		234	
Dimethyl phthalate	µg/ℓ	17,3		173	
Dibutyl phthalate	µg/ℓ	14,3		143	
Butyl benzene phthalate	µg/ℓ	20,3		203	
Bis (ethylhexyl) phthalate	µg/ℓ	15,1		151	
Di-iso-butyl phthalate	µg/ℓ	0,042		0,42	
Benzothiazole	µg/ℓ	2		20	
1, 3 Isobenzofuran-dione	µg/ℓ	6		60	
Octadecanol	µg/ℓ	0,06		0,6	
Phenol	µg/ℓ	0,9		9	
2-Chlorophenol	µg/ℓ	1,5		15	
2-Nitrophenol	µg/ℓ	2,5		25	
2, 4-Dichlorophenol	µg/ℓ	2,5		25	
p-Chloro-m-cresol	µg/ℓ	5,5		55	
2, 4, 6-Trichlorophenol	µg/ℓ	1,9		19	
2, 4-Dinitrophenol	µg/ℓ	0,14		1,4	
4-Nitrophenol	µg/ℓ	0,9		9	
4, 6-Dinitro-o-cresol	µg/ℓ	0,14		1,4	
Pentachlorophenol	µg/ℓ	0,5		5	

Table A2 - 5 : Recommended frequency for the testing of inorganic determinands in drinking water supplies

Group A	Group B	Group C	Group D	Group E
Daily	Monthly	Quarterly	Annually	Every 5 Years
Calcium *	Arsenic	Barium	Antimony	Other potential elemental pollutants
Chlorine (free residual)	Lead	Cobalt	Bismuth	
	Selenium	DOC	Lithium	Unusual elements
Colour	Cadmium	Molybdenum	Thallium	Radioactive elements ⅄
Conductivity *	Mercury	Nickel	Tin	
Odour	Silver	Sodium		
Dissolved Oxygen	Cyanide	Vanadium		
pH *	Gold **	Boron		
Taste		Chromium		
Temperature *		Copper		
Turbidity		Fluoride		
Alkalinity *		MBAS		
Aluminium †		Nitrate		
Ammonia †		Potassium		
Chloride †		Zinc		
Total hardness †		Phenols ‡		
Iron †		Hydrogen sulphide ‡		
Magnesium †				
Manganese †				
Sulphate †				

Note:

* Measured to estimate the corrosive potential of the water

** Only in gold mining areas, otherwise Group D

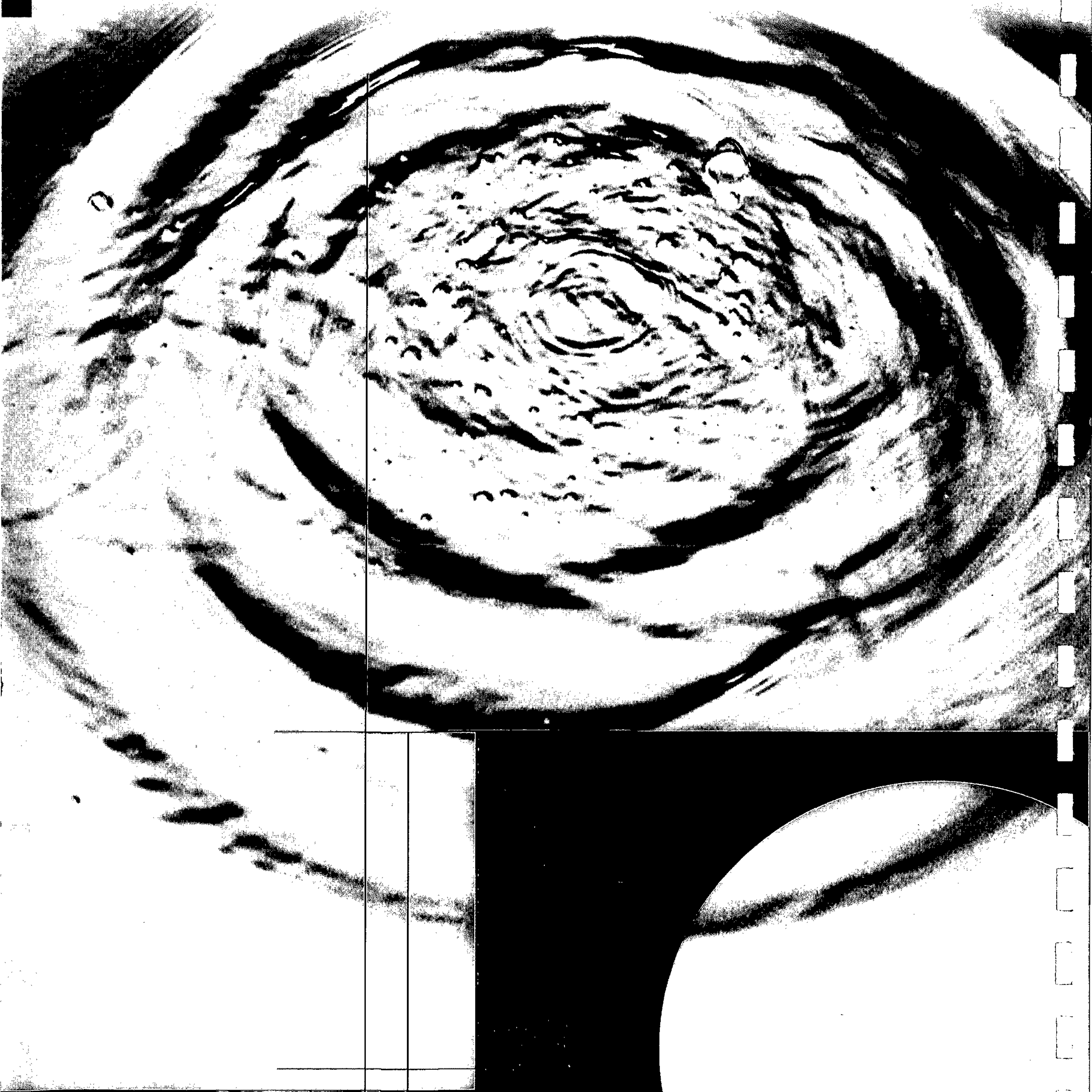
† If not used in the treatment process, these determinands should fall under Group C

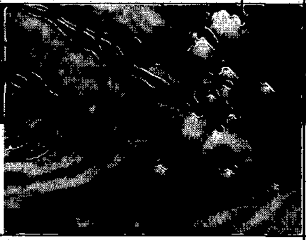
‡ Only if taste and odour problems occur

⅄ As complete an analysis as possible on raw and treated water using a combination of suitable muli-element screening techniques

Table A2 - 6 : Recommended frequency for the microbiological testing of drinking water supplies

Population Served	Minimum number of samples
More than 300 000	1 every day
100 000 to 300 000	20 every month
25 000 to 100 000	10 every month
10 000 to 25 000	3 every month
2 500 to 10 000	2 every month
Less than 2 500	1 every month





Water Research Commission

PO Box 824, Pretoria, 0001, South Africa

Tel: +27 12 330 0340, Fax: +27 12 331 2565

Web: http://www.wrc.org.za