# THE POTENTIAL USE OF SLOW SAND FILTRATION FOR THE PRODUCTION OF POTABLE WATER

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## DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of Natal, Durban. It has not been submitted before for any degree or examination in any other University.

Reddy.
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(Signature of candidate)

5th
---------------- day of ---December.-------------------------- 1997

# ABSTRACT

The production of potable water by slow sand filtration was studied with respect to the potable water quality guidelines set by the Department of Health in South Africa. A plain sedimentation tank was used to pre-treat the raw water. During the first half of the study, raw water from the Umgeni river formed the feed water into the plain sedimentation-slow sand filtration pilot plant. Thereafter, raw water from the Inanda impoundment was fed into the pilot plant. The raw water from the Umgeni river was higher in turbidity and microbiological content than that from the Inanda impoundment.

The pre-treated raw water from the plain sedimentation tank formed the feed water into two slow sand filters. One slow sand filter was operated at a filtration rate of 0,1 m/h whilst the other was operated at 0,1 to 0,5 m/h. Both slow sand filters contained sand with an effective particle diameter of 0,3 mm.

Turbidity and microbiological sampling were performed to characterise the filtered water into aesthetic and health criteria respectively. Turbidity was monitored in the raw, pre-treated and filtered water whilst the microbiological content was monitored mainly in the raw and filtered water.

The change of raw water source from the Umgeni river to the Inanda impoundment was suited to a simple treatment process like slow sand filtration. The treatment of *Inanda raw water* was beneficial in terms of slow sand filter operation and filtered water quality. Indications are that *Inanda filtered water* is microbiologically and aesthetically safe even when the slow sand filter is operated at filtration rates as high as 0,5 m/h during *normal filtration* i.e. after *filter recovery*. In addition, the treatment of *Inanda raw water* results in over a 81 % saving in SSF downtime when compared to *Umgeni raw water*. Whereas a filtration cycle time of 2 to 3,5 months results for the treatment of *Umgeni raw water*, the respective filtration cycle time for *Inanda raw water* lasts up to 1 year. Thus slow sand filtration was recommended as a useful treatment process for an impounded water source where natural treatment processes like settling are already taking place.

A slow sand filter feed water turbidity of 7 NTU resulted in the filtered water conforming to both aesthetic and microbiological guidelines. Nevertheless post-disinfection of the filtered water was still recommended, especially during *filter recovery*.

The performance of both plain sedimentation and slow sand filtration was characterised by an increasing trend of treated water turbidity with feed water turbidity. Nevertheless, the performance of plain sedimentation was enhanced at high turbidity feed waters.

A *filter recovery* period of 4 d was estimated for the treatment of *Inanda raw water* by SSF. However, this *filter recovery* estimate of 4 d can potentially be less, especially if post-disinfection is practised. Although it is not necessary to increase the design daily water demand with respect to *Inanda raw water*, an increase of 20 % was recommended. The *filter recovery* period with respect to *Umgeni raw water* exceeded the 21 d generally mentioned in literature. The resultant downtime for the treatment of *Umgeni raw water* was

therefore not practical. Roughing filtration was recommended as a pre-treatment step to slow sand filtration if a river is the only available raw water source.

High filtration rates had more of an operational than a water quality effect on slow sand filtration. The frequency of filter cleanings increased with higher filtration rates. However high filtration rates together with high raw water turbidity and microbiology was detrimental to slow sand filtration with respect to both operation and filtered water quality.

Higher turbidity *Inanda raw water* than *Umgeni raw water* resulted in the filtered water conforming to the *no health risk* turbidity limit. *Umgeni raw water* seems to be composed of clay or colloidal material that passes through a plain sedimentation tank and slow sand filter.

Residence time distribution studies, non-woven filter mat pre-treatment, algal loading effects and suspended solids particle size measurements were recommended for future research work related to slow sand filtration.

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# LIST OF SYMBOLS

| | |
|---|---|
| $a$ | annual growth rate (%) |
| $A$ | cross sectional area ($m^2$) |
| $d$ | days |
| $C_D$ | dimensionless drag coefficient (-) |
| $D_p$ | particle diameter (m) |
| $g$ | gravitational constant ($m/s^2$) |
| $H$ | resistance of clean bed (m) |
| $°H$ | Hazens |
| $h$ | thickness of bed (m) |
| $h_o$ | weir head (m) |
| $k$ | coefficient of permeability (m/h) |
| $n$ | total number of units |
| $q$ | volumetric flow ($m^3/s$) |
| $P_d$ | design population (-) |
| $P_p$ | present population (-) |
| $Q$ | design capacity ($m^3/h$) |
| $R_e$ | Reynolds number |
| $v_s$ | settling velocity (m/s) |
| $v_f$ | filtration rate (m/h) |
| $Y$ | design period (y) |

## Greek Symbols

| | |
|---|---|
| $r_p$ | particle density ($kg/m^3$) |
| $r$ | fluid density ($kg/m^3$) |
| $\phi$ | spericity, angle of slope with respect to horizontal (deg.) |
| $\nu$ | kinematic viscosity ($m^2/s$) |
| $\mu$ | population mean |
| $\sigma$ | population standard deviation |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| AOM | Assimilable organic matter |
| BOD | Biochemical oxygen demand |
| DOC | Dissolved organic carbon |
| EEC | European Economic Community |
| GAC | Granular activated carbon |
| HRL | Health risk limit(s) |
| IHRc | Insignificant health risk for total coliforms |
| IHRe | Insignificant health risk for *E. Coli* |
| IHRf | Insignificant health risk for *F. Strep.* |
| IHRfe | Insignificant health risk for iron |
| IHRmn | Insignificant health risk for manganese |
| IHRs | Insignificant health risk for standard plate counts at 37 °C |
| IHRt | Insignificant health risk for turbidity |
| LAS | Linear alkylate sulphonate (customarily used as an indicator of the presence of foaming agents or detergents) |
| LHRc | Low health risk for total coliforms |
| LHRe | Low health risk for *E. Coli* |
| LHRf | Low health risk for *F. Strep.* |
| LHRfe | Low health risk for iron |
| LHRmn | Low health risk for manganese |
| LHRs | Low health risk for standard plate counts at 37 °C |
| LHRt | Low health risk for turbidity |
| NHRc | No health risk for total coliforms |
| NHRe | No health risk for *E. Coli* |
| NHRf | No health risk for *F. Strep.* |
| NHRfe | No health risk for iron |
| NHRmn | No health risk for manganese |
| NHRs | No health risk for standard plate counts at 37 °C |
| NHRt | No health risk for turbidity |

| | |
|---|---|
| NOM | Natural organic matter |
| PDF | Probability density function |
| PFU | Plague forming units |
| PMF | Pebble matrix filter |
| PRG | Pollution Research Group |
| RDOC | Refractory dissolved organic carbon |
| RTD | Residence time distribution |
| SSF | Slow sand filtration or slow sand filter(s) depending on context. |
| SPC | Standard plate count |
| TCU | True colour units |
| THM | Trihalomethane(s) |
| THMFP | Trihalomethane(s) formation potential |
| TOC | Total organic carbon |
| TON | Threshold odour number |
| TTN | Threshold taste number |
| UHR | Unacceptable health risk |
| USEPA | United States Environmental Protection Agency |
| UW | Umgeni Water |
| WHO | World Health Organisation |
| WRC | Water Research Commission |

# GLOSSARY

| | |
|---|---|
| Appropriate technology | Technology that is suited to the developingcountries. These technologies avoid the mechanisation, instrumentation and automation common in the industrialised world. |
| Developing countries | Developing countries are characterised by an economy that is still agriculturally based rather than industrial. Whereas economies in industrialised countries are mechanised, in developing countries they are labour intensive. These developing countries are located mainly in Africa, Asia and Latin America. |
| Filtered water | Treated water emerging from the slow sand filter. Reference is also made to the water source viz.Umgeni pre-treated water and Inanda pre-treated water. |
| Filter recovery | The period of the filtration cycle when the schmutzedecke is being redeveloped after a filter clean. |
| Heavy turbidity tail | The tapered end of a normal probability density function curve with values higher than the mean and occurring at a low probability. Usually seen as a long drawn out curve on the high turbidity end of the usual bell-shaped curve. |
| Insignificant health risk | Used to define the secondary water quality range less stringent than the no health risk range. This is still a safe range but should not normally be exceeded. |
| Light turbidity tail | The tapered end of a normal probability density function curve with values lower than the mean and occurring at a low probability. Usually seen as a long drawn out curve on the low turbidity end of the usual bell-shaped curve. |

| | |
|---|---|
| Low health risk | Used to define a water quality range that constitutes a minimal health risk to individuals. Several precautionary measures must be taken if individuals are forced to drink this water e.g. medical and hospital personnel should be informed. |
| Maximum permissible limit | Upper limit of acceptable exposure to chemical, micro-biological and biological constituents in potable water. This limit represents a high probability of health effects on potable water users. |
| No health risk | Used to define the primary water quality range and is the limit which ideally should be striven for. The no health risk has a built-in safety factor, and thus no immediate danger exists where this limit is exceeded. |
| Normal filtration | The period of the filtration cycle that occurs after schmutzdecke development or filter recovery. |
| Outliers | Data not following the trend established by the rest of the data |
| Pre-treated water | The raw water, after being pre-treated by plain sedimentation, is referred to as pre-treated water. This pre-treated water is fed to the slow sand filters. Reference is also made to the water source viz. Umgeni pre-treated water and Inanda pre-treated water. |
| Raw water | The untreated water from the river or impoundment that is fed into the inlet of these dimentation tank - SSF plant. Reference is also made to the water source viz. Umgeni pre-treated water and Inanda pre-treated water. |
| Ripening | The period immediately after the SSF start-up when particle accumulation and microbiological occurs to form the schmutzedecke. |

| | |
|---|---|
| Schmutzedecke | The layer, usually about 10 to 30 mm thick, on top of the slow sand filter bed. A high density of micro-organisms living in this layer are responsible for removing or destroying the polluting matter in the incoming water. |
| Unacceptable health risk | Used to define the tertiary water quality range where extreme action must be taken. The range thus represents that level at which serious health effects may occur if the water if the water is consumed for any length of time. |

# 1 INTRODUCTION

Why do so many millions of people in the *developing countries* do not have a sufficient supply of good water, even though it is a basic human need next to food? This was a very emotive question asked by Kankhulugo and Kwaule (1993) in their investigation of water supply in Malawi. Without water people cannot live, with contaminated water their lives are in danger - every day many children die from diarrhoeal diseases.

This chapter gives a brief background to the problem of water supply in South Africa and other *developing countries*. The basics of slow sand filtration (SSF), its history and the need for SSF in the twentieth century are then discussed. The chapter ends with a list of objectives as well as the nature and scope of this investigation on SSF.

## 1.1 BACKGROUND

Kankhulugo and Kwaule (1993) and Ellis (1990) have delved further into the problems of water supply in the *developing countries*. Kankhulugo and Kwaule (1993), in their answer to the above question, suggests some reasons for the dilemma. First, the people concerned do not have enough money to pay for the water as it is produced today. Secondly, they do not understand what constitutes good-quality water or how it can become contaminated. They may even collect good water and then contaminate it themselves. Ellis (1990), in his analysis of the problems limiting the supply and distribution of potable water in the *developing countries*, looks at some of the very practical problems of training, research, planning and design, operation and distribution. He also goes on link bottled water to the problems of water supply in the *developing countries*. Apparently, the professional classes who traditionally provide all the awareness, drive, knowledge and initiative for the provision of municipal developments such as pure water supply now have less incentive to do so. The reason being is that they have good-quality bottled potable water readily available and are no longer so vitally interested.

*Appropriate technology* should include design and engineering concepts that match a nation's ability to build, operate, repair and pay for it. Too often, technology from abroad is imposed on a developing country with unsatisfactory results. For example, water technology advanced of an operating staff's ability or experience, lack of political resolve or financial resources to pay and train staff, or state-of-the-art demands from engineers in *developing countries* who are influenced by industrial technology after seeing it or reading about it in professional journals [Monk *et al*, 1984]. Ellis (1990), however, goes on to comment that *appropriate technology* does not invariably imply low cost simple technology. Although it is often of importance that water treatment works be both inexpensive and simple, the criteria of reliability must always be paramount. It is as ethically wrong for designers to install inexpensive systems that do not work as it is to install an expensive, high-technology water treatment plants that cannot be worked.

The supply of potable water to rural and peri-urban areas is a national development priority in South Africa, being part of its Reconstruction and Development Programme. South Africa is aware of the problems in water supply that have occurred in other *developing countries* and in South Africa itself [Cillie, 1982]. This being one of the main reasons, the Pollution Research Group (PRG) (University of Natal, Durban) and Umgeni Water (UW), with financial assistance from the Water Research Commission (WRC), set about on a project to evaluate package water treatment plants available on the South African market. Small and medium capacity packaged water treatment plants suitable for small communities located in rural and peri-urban areas were evaluated .

Package plants that operate within days of installation can lead to a substantial decrease in the cost of supplying potable water [Voortman and Reddy, 1997]. Smaller local authorities and development agencies sometimes select package water treatment plants for their schemes. An acceptable set of criteria that can apply to these packaged plants to evaluate their suitability for use in rural communities does not exist. Therefore the aim of the abovementioned joint project between the PRG, UW and WRC was to establish such a set of evaluation criteria and to assess package plant technology against these criteria. The slow sand filter (SSF) was the technology against which all the other technologies were assessed.

Examples of some of the performance criteria were:

- raw water characteristics and variability,
- volume of water required and demand elasticity,
- sophistication of operating staff,
- source of power,
- required plant life,
- and service frequency [WRC, 1992].

### 1.1.1 Slow Sand Filtration

Basically, a slow sand filter consists of a box containing:

- a supernatant layer of raw water;
- a bed of fine sand;
- a system of underdrains;
- an inlet and outlet structure;
- a set of filter regulation and control devices [Visscher *et al*, 1987].

The supernatant layer of water, usually about 1 to 1,5 m in height, creates the pressure head that drives water through the bed of filter sand. An initial period of *ripening* wherein particles accumulate within the top few layers of sand granules and microbiological growth occurs to form the *schmutzedecke.* Much of the subsequent particulate material is collected by the *schmutzedecke.* After this initial period, the filter bed operates as a cake filter whereby accumulated material collects on the surface of the sand bed [Hargrave, 1988].

#### 1.1.1.1 A Brief History

Huisman and Wood, 1974, and Baumann, 1978, review the history of SSF. It seems as though the first instance of filtration as a means of water treatment dates from 1804, when John Gibb designed and built an experimental slow sand filter for his bleachery in Paisley, Scotland, and sold the surplus treated water to the public at a halfpenny per gallon [Baker, 1949] (cited in [Huisman and Wood, 1974]). He and others improved on the practical details, and in 1829 the method was first adopted for a public water supply when James Simpson constructed an installation to treat the water supplied by the Chelsea Water Company in London. This filter was operated at a rate of 1,9 to 3,7 $m^3/m^2$.day using about one metre of ungraded sand media to filter raw surface water in runs that lasted for as long as 6 to 8 months [Baumann, 1978]. The filter was cleaned by draining the filter to below the sand surface and scraping off the skin formed on the surface of the sand. This filter was designed specifically for the removal of suspended solids from surface water and was the only water treatment device used (no pre-treatment methods were used).

After the Broad Street incident in London in the early 1850's demonstrated that human disease was related to sewage contamination, there was a general international movement in developed countries to require all potable water to be filtered, generally using English-type SSFs [Baumann, 1978]. John Snow, in his studies of cholera transmission, had also come to the conclusion that the disease was waterborne. In the 1860's and 1870's, Pasteur and others developed the germ theory of disease, and the primary role of the filter shifted from the need to remove solids to the need to remove bacterial pathogens.

Proof of the effectiveness of water filtration was provided in 1892 by the experience gained in two neighbouring German cities, Hamburg and Altona, which drew their drinking-water from the River Elbe. Hamburg delivered its drinking-water untreated except for settlement whilst Altona filtered the raw water before delivering it to the community. When the river became infected from a camp of immigrants, Hamburg suffered from a cholera epidemic that infected one in thirty of its population and caused more than 7 500 deaths. Altona, on the other hand, experienced very few deaths [Huisman and Wood, 1974].

#### 1.1.1.2 The Need for Slow Sand Filtration in the Twentieth Century

A myth has developed that SSF is an old-fashioned process and therefore inefficient, that rapid gravity and other high-rate filtration techniques have rendered it obsolete, and that because it is simpler than recent innovations it is inferior to them [Huisman and Wood, 1974]. In addition, slow sand filters generally have a large land area requirement which cannot usually be justified in large towns and cities where the price and competition for land is high. However, experimental and developmental work in Switzerland [Schalekamp, 1975], Sweden [Bergling, 1981], South Africa [Williams, 1985], Britain [Ellis, 1993], USA [Fox and Lekkas, 1978], India [Raman *et al*, 1981], Brazil [Bernardo, 1991] and other countries has led to some rethinking regarding the application of this technique. In fact Boller (1994), in his paper *Trends in water filtration technology*, states confidently that the trend to use less chemicals and more natural oxidation processes in drinking water treatment will lead to an increase in SSF application.

Owing to remoteness of location and the possibility of non-availability of chemicals, operational neglect, lack of supervision or the breakdown in transport and communications, the risk of failure of any process can never be completely eliminated. A good design of any process should have built into it safety measures to counter any malfunctioning. Public health is the first and foremost consideration of water supply [Hargrave, 1988]. The use of oxidants such as chlorine and ozone for disinfection results in the formation of undesirable by-products from organic compounds present in the water. These by-products include known carcinogens. Boller (1994) predicts that this may lead back to the use of traditional SSF. SSF is therefore an ideal choice of water treatment since it provides natural disinfection and biochemical oxidation by the biological slime layer (called the *schmutzedecke*).

It also meets with the following criteria:

- low capital and operating costs [Logsdon *et al*, 1990];
- simple to understand and operate;

- minimum mechanical and electrical parts;
- low sensitivity to misuse;
- low maintenance and operating time [Cullen and Letterman, 1985]
- and few or no chemical feed systems.

However, pre-sedimentation is necessary since the sometimes high turbidity of surface waters in KwaZulu-Natal exceeds the acceptable limits for direct discharge onto the filters. The United States Environmental Protection Agency (USEPA) guide, *Technologies for upgrading existing or designing new drinking water treatment facilities*, recommends that the influent water to the SSF should be less than 10 NTU.

One of the major arguments against SSF is its large land requirement compared to other more modern treatment processes such as rapid filtration. However, Marx and Johannes (1992) has suggested that this is not necessarily a problem in a developing country where land and labour are normally freely or cheaply available. Land is also not a major problem in the not so populated areas of rural South Africa. Vaillant (1981) when considering countries with a high standard of living, where the cost of land is high, has suggested that the total annual cost (considering depreciation, interest, maintenance and operation, including chemicals, energy and sludge disposal) of SSF need not be higher, due to the long life of SSFs and due to no, or only limited use of chemicals which are generally expensive. Schalekamp (1975) has demonstrated how the Swiss have overcome the large land requirement of slow sand filtration. In Zurich, the filters are enclosed and tennis courts and sport fields are constructed on top of the filters. Vaillant (1981) even goes further to say that the average area required for the treatment of drinking water by SSF lies in the order of 0,05 $m^2$ per person served, whereas parking space requirements for cars nowadays in Europe are of the order of 1 to 2 $m^2$ per person. Thus many of the current objections to SSFs may be overcome.

SSF also fits into the recent interest in package water treatment plants. Package technologies, which are assembled in a factory, skid mounted and transported to the site complete and ready for immediate installation, offer an alternative to the large in-ground treatment technologies [Graham and Hartung, 1988; Goodrich *et al*, 1992]. Package SSF units are now marketed in the United States because of their effectiveness in removing *Giardia* cysts and bacteria [Clark *et al*, 1994].

These package plants seem to be ideal for rural villages characterised by small and isolated communities. Provision of water treatment plants for rural areas have inherent problems. Some of these problems are that:

- small quantities of water are required for thinly populated groups.
- site execution adopting usual course of tendering, supervision, etc. is difficult.
- extremely small sizes of conventional treatment systems are needed.
- skilled operation and maintenance are required for such systems.

Pre-fabricated units have been successfully tried out in India in order to make available potable water to rural villages [Alagarsamy and Ghandirajan, 1981].

## 1.2 OBJECTIVES

The overall objective of this thesis is to investigate the quality of water obtained by slow sand filtration of Umgeni river water and Inanda impoundment water. A general distinction is made between health and aesthetic water quality [DOH, 1994]. Where possible, an investigation is also made on the operating and design parameters that produce water of potable quality.

A more detail list of the objectives is to investigate the relationship between:

- raw water source and the performance of the SSF.
- pre-treated water turbidity and the performance of the SSF.
- raw water turbidity and the performance of plain sedimentation as well as the performance of the entire treatment system.
- bacteria concentration in the raw water and the performance of the whole treatment system.
- turbidity and microbiological content of the raw water.

Other objectives include determining

- the quality of raw and pre-treated water that could be treated to produce potable water by the plain sedimentation-SSF train and the SSF respectively.
- treatment variations that include SSF if potable water quality guidelines are not met.
- the effect of filter cleaning on the filtered water quality.
- the effect of filtration rates on the filtered water quality.
- the effect of the level of microbiological maturity in the filters on the filtered water quality.
- the effect on sampling of the time lag caused by the residence time in the plain sedimentation tank and SSF.

## 1.3 NATURE AND SCOPE OF THE INVESTIGATION

The evaluation of the SSF began in September 1993. The SSF was tested on raw water obtained from the Umgeni river through the Claremont pump station from September 1993 to July 1994. Thereafter the raw water was obtained from the Inanda impoundment.

The turbidity of the raw water often exceeded 10 NTU. This period of high raw water turbidity occurred mainly prior to June 1994. It is for this reason that the design included a plain sedimentation cylindroconical tank that preceded the two SSFs.

The design, procurement, installation and commissioning of the pilot plant took approximately ten months. Experimental work lasted from 1,5 to 2 years. Experimental work consisted mainly of routine water quality monitoring. Observations were made on maintenance and operation of the SSF and plain sedimentation over the long term.

Attention is drawn to the microbiological sampling which occurred only at the raw water entry point and the filter outlet points. A few samples were taken at the actual filter inlet (or sedimentation outlet). Thus the evaluation of microbiological removal is performed on the entire plant and not specifically on slow sand filtration. However, since the removal of turbidity and microbiology by plain sedimentation is low, this evaluation should closely approximate that of slow sand filtration. This type of pilot plant could closely simulate a plant in a rural area that includes a slow sand filter that is preceded by a raw water storage tank (similar to plain sedimentation).

**Chapter 1** has discussed the background and the motivation for the use of SSF. The literature survey on SSF, in **Chapter 2** and **3**, includes comments on the water quality objectives of SSF, appropriate pre-treatment for SSF, the design criteria, the mechanism of biological filtration and the general performance of SSF. Thereafter the thesis gives a description of the pilot plant in **Chapter 4** and the reasoning behind the organisation and analysis of the data in **Chapter 5**. **Chapter 6** discusses the results mainly regarding turbidity and microbiological removal. It also discusses the removal of algae and other contaminants (Fe, Mn and colour), in addition to operational effects. In **Chapter 7**, conclusions are drawn on the objectives set out in this thesis besides recommendations on operation, design and future work to be investigated on SSF.

# 2 OBJECTIVES IN THE PRODUCTION OF POTABLE WATER BY THE PLAIN SEDIMENTATION-SLOW SAND FILTRATION TRAIN

The filtered water emerging from the plain-sedimentation-SSF train must first conform to the established water quality criteria. Water quality criteria, with special reference to South Africa, is first discussed here. Emphasis is placed mainly on microbiological, biological and aesthetic water quality. The type of raw water source that is suitable for treatment by the plain sedimentation-SSF train is discussed next. Other treatment processes that can be combined with SSF to produce potable water is discussed last.

## 2.1 INTRODUCTION

The objectives in the production of potable water by the plain sedimentation-SSF train are:

- to produce clean water that conforms to water quality guidelines.
- to choose a raw water source that slow sand filtration can treat.
- to choose other pre-treatment processes that enhance the potential of slow sand filtration to treat a raw water source.

Some of the other objectives, not discussed here, are:

- to meet the demand of the consumer.
- to maintain a reliable supply of water.
- to ensure that the water supply distribution points of the treatment plant is within walking distance in the case of a *developing country*.

## 2.2 WATER QUALITY CRITERIA

### 2.2.1 Introduction

A comparison of the international approach to establishing water quality show that there are essentially two approaches, namely enforceable standards and guidelines [Fowler, 1992a]. Both the USEPA and the European Economic Community (EEC) adopted a set of standards which address maximum admissible concentrations of water contaminants. The World Health Organisation [WHO, 1984], on the other hand, recognised that uniform water quality standards could not practically be applied throughout the world. However it noted the need for guidance to regulatory agencies on water quality to ensure the maintenance of good health. In 1984 it therefore published drinking water quality guidelines to be used as a basis for the development of standards in each country.

The WHO also stated that the judgement of acceptable risk levels is undertaken by society as a whole. Therefore the adoption of the proposed guidelines is for each country to decide. The guidelines were developed assuming lifelong consumption and that specific geographic, socio-economic, dietary and industrial conditions would also have to be considered.

In South Africa too, the Department of National Health and Population Development has adopted a set of water quality criteria, seen as a set of provisional guidelines and not water quality standards, as official policy [DOH, 1994]. These guidelines are based on reports by Kempster *et al* (1980) and Kempster and Smith (1985). The principle on which the guidelines are based, is to put less emphasis on concentration limits such as *recommended limit* and *maximum permissible limit*. An attempt is made to be more pragmatic and to rather impose the concept of health risk ranges for the various water quality parameters. Pieterse (1989) has also traced some of the latest thinking on risk assessment, which is similar to that followed by the Department of Health. Even though four risk concentration areas are defined, it is important to note that, for example, a concentration that nears the upper value of the *insignificant health risk* range, is already inclined to indicate a *low health risk*.

The four health risk ranges on which the criteria are based are [DOH, 1994]:

i) The *no health risk* (NHR) range: This is the primary water quality limit and is the limit which ideally should be striven for. The *no health risk* range has a built-in safety factor, and thus no immediate danger exists where this limit is exceeded.

ii) The *insignificant health risk* (IHR) range: As the *no health risk* range can often be exceeded in practice by one or more determinands in a given water sample, it is necessary to define a less stringent secondary limit, the *insignificant health risk* range. This range is still a safe one, but should not normally be exceeded. Where the concentration of a particular determinand exceeds this limit, the planning/action to reduce the concentration of the determinand should be instituted without delay.

iii) The *low health risk* (LHR) range: This range constitutes a minimal health risk to individuals. When water with a *low health risk* has to be used, special considerations has to be taken into account such as:

- No alternative economic water source is available.
- Composition of the users (e.g. adults, children, expectant mothers and old people) has to be considered.
- Users should be informed and take note of the *low health risk* they may be exposed to.
- Medical and hospital personnel concerned should be informed.

iv) The *greater (unacceptable) health risk* (UHR) range: This tertiary limit is defined as *that limit where extreme action must be taken*. This range thus represents that level at which serious health effects may occur if the water is consumed for any length of time.

The Department of Health [DOH, 1994] has purposefully made the transition from a *safe* to a *hazardous* concentration a gradual one. Therefore the UHR range prevents unnecessary panic when a given determinand's concentration exceeds the LHR range [Pieterse, 1989]. As long as the concentration does not exceed the LHR limit, the parties concerned can take urgent, yet carefully planned and thought-out measures to reduce the concentration of the offending determinant to below the LHR limit. As an interim measure, the UHR range for each determinand has been defined as *twice the IHR range value*. However for certain determinands such as dissolved oxygen, pH and temperature the UHR range values require somewhat different definitions.

In applying the proposed criteria, the UHR range should be treated as a tentative guideline only, and not applied rigidly, except in the case of extremely toxic determinands such as cadmium, lead and mercury, where the risk associated with elevated concentrations is high. For the aesthetic determinands as well as for determinands of low toxicity, where there is only a slight risk at elevated concentrations, the UHR range should be used with discretion, and may be relaxed where circumstances warrant.

### 2.2.2 Microbiological and biological guidelines

Pathogenic micro-organisms exist in most raw water sources, especially surface waters. To protect the public's health, they must be reduced to safe levels that protect the public from infectious outbreaks. Most drinking water problems are of microbiological origin and are caused by inadequate or improper treatment [Drinking Water Health Effects Task Force, 1989].

**Table 2.1: Guideline Values for Microbiological and Biological Quality of Drinking Water [DOH, 1994]**

| Determinand | Units | Health Risk Ranges | | | |
|---|---|---|---|---|---|
| | | None | Insignificant | Low | Unacceptable |
| Standard plate count | /1 mℓ | <100 | 1,000 | 10,000 | 2,000 |
| Total coliform count | /100 mℓ | 0 | 5 | 100 | 10 |
| Faecal coliform count | /100 mℓ | 0 | 1 | 10 | 2 |
| *Clostridium Perfringes* | /100 mℓ | 0 | 1 | 10 | 2 |
| Coliphages | /100 mℓ | 0 | 10 | 100 | 20 |
| Enteric Viruses | /10 mℓ | 0 | 1 | 10 | 2 |
| *Giardia Lamblia* | /2 mℓ | 0 | 2 | 5 | 4 |

As an interim measure, the UHR range for each determinand has been defined as *twice the IHR range value*.

It is not necessary to include all the tests in the routine analysis of drinking-water supplies. Tests for total coliform bacteria and the standard plate count (SPC) should always be undertaken since they are practical and sensitive indicators of unforeseen treatment failure or pollution [DOH, 1994]. The other determinands may yield valuable additional evidence such as the origin of faecal pollution as well as in assessing the efficiency of water treatment processes [WHO, 1984b].

In the case of suspected sewage pollution, it is necessary to have a separate virus identification. Slade (1978), after comparing the removal of *E.coli* and viruses by slow sand filters indicated that the standard *E.coli* test may be inadequate when used as an indicator of low concentrations of viruses in large volumes of water. Roy (1980) has suggested that this observation may imply that viruses may be present in raw water when no faecal coliforms (or other indicator bacteria) could be detected. SSF followed by nanofiltration [Yahya *et al*, 1993] or preceded by rapid sand filtration [Arthur, 1990] is an effective means of removing viruses when considering the fact that viruses are more resistant to chlorine than bacteria.

The final drinking water quality from a treatment plant and that arriving at the consumer's home should conform to the values in Table 2.1. Tapwater, however, may display elevated standard plate counts which may be due to regrowth in the distribution system. Generally these organisms do not constitute a significant health risk. In case of doubt, or if secondary pollution of the distribution system is suspected, some of the other determinands of Table 2.1 should be included for better assessment of the quality of the water.

When total coliform bacteria are isolated from drinking-water, they should be identified because the presence of *Escherichia coli* and/or faecal coliforms are almost conclusive evidence of faecal pollution while other coliforms may be of non-faecal origin [WHO, 1984a; Lorch, 1987].

The WHO (1984b) also recommends that when a sample of drinking-water exceeds the guideline values in Table 2.1 another sample from the same source should be analysed immediately. Tests for additional determinands should be included if considered necessary.

Sanitary surveys are important and should not be neglected in the evaluation of the microbiological quality of drinking-water. This would include inspections to locate potential sources of secondary pollution of water in distribution systems, unforeseen heavy pollution of raw water supplies, pit latrines near boreholes, and the efficient operation of water treatment systems.

### 2.2.3 Aesthetic water quality

**Table 2.2: Guideline Values for Substances Affecting the Aesthetic Quality of Drinking Water [DOH, 1994]**

| Determinand | Units | Aesthetic Impact Ranges | | |
|---|---|---|---|---|
| | | None | Insignificant | Low |
| Colour | mg/ℓ Pt | 20 | | |
| Conductivity | mS/m | 70 | 300 | 400 |
| Dissolved organic carbon (DOC) | mg/ℓ DOC | 5 | 10 | 20 |
| Dissolved Oxygen (% Saturation) | | >70 | >30 | 10 |
| Hydrogen Sulphide | µg/ℓ | 100 | 300 | 600 |
| Methylene Blue Active Substances (MBAS) | mg/ℓ LAS | 0.5 | 1 | 2 |
| Odour | TON | 1 | 5 | 10 |
| pH | pH unit | 6-9 | 5.5-9.5 | 4 or >11 |
| Taste | TTN | 1 | 5 | 10 |
| Temperature | °C | <25 | <30 | <40 |
| Turbidity | NTU | 1 | 5 | 10 |
| Aluminium | mg/ℓ Al | 0.15 | | |
| Copper | mg/ℓ Cu | 0.5 | | |
| Chloride | mg/ℓ Cl | 250 | | |
| Iron | mg/ℓ Fe | 0.1 | 1 | 2 |
| Manganese | mg/ℓ Mn | 0.05 | 1 | 2 |
| Sulphate | mg/ℓ $SO_4$ | 200 | | |
| Zinc | mg/ℓ Zn | 1 | 5 | 10 |

see abbreviation list for undefined symbols    blank spaces - no values were provided in source.

An aesthetically displeasing source of water may encourage the consumer to use an unsafe supply. In addition, taste, odour and colour may be the first indication of a potential health hazard [WHO, 1984a]. Colour and suspended material in water may affect the domestic use of water e.g. the washing of clothing [DOH, 1994].

Although taste and odour can be produced by inorganic contaminants, they are usually caused by organic material originating from decaying vegetation or from algal activity [Hyde *et al*, 1984]. Chlorination can accentuate the problem, especially if small concentrations of phenols are present. In addition, taste and odour can be formed in the distribution system due to biological aftergrowths or contamination with pipe leachate or corrosion products [WHO, 1984a]. As far as treatment is concerned, Yagi *et al* (1983) have found that slow sand filtration is more effective than rapid filtration in removing odorous compounds caused by algae.

High levels of turbidity can protect micro-organisms from the effects of disinfection and can stimulate the growth of bacteria. Volume 1 of *Guidelines for Drinking-water Quality* [WHO, 1984a], therefore recommends that in all cases where water is disinfected, the turbidity must be low (preferably below 1 NTU) so that disinfection can be effective. In Table 2.2, the DOH has also recommended a *no health risk* turbidity limit of 1 NTU.

Tables of guideline values for inorganic and organic determinands of health significance in drinking water can be found in *Water quality criteria for SA* [DOH, 1994]. Inorganic determinands like Fe and Mn are also used as aesthetic determinands. Fe and Mn over 300 $\mu g/\ell$ and 50 $\mu g/\ell$ respectively give rise to staining, discolouration and taste problems. An organic determinand that is measured frequently is the trihalomethane (THM) which is a useful indicator of undesirable disinfection by-products. The NHR limit, set by the DOH, for THM is 100 $\mu g/\ell$.

## 2.3 RAW WATER SOURCE

### 2.3.1 Introduction

Dependence upon treatment alone to assure safe drinking water in *developing countries* is inappropriate. This is mainly because of inadequate resources as illustrated by the poor record of *developing countries* in operating and maintaining water treatment plants, particularly with respect to adequate disinfection before the treated water enters the distribution system [Schulz and Okun, 1984]. Therefore the raw water source of highest water quality should be selected provided that its capacity is adequate to furnish the water supply needs of the community. Huisman and Wood (1974), however, have noted that in several cities suffering from outbreaks of cholera it was established that the quality of the public water supply was satisfactory but that the quantity was insufficient, so that people were forced to drink from other, unsafe, sources.

As South Africa is a water deficient country, all effluent has to be purified and returned to the rivers of origin. As a result, the quality of water is deteriorating in many areas [DWA, 1994]. The usefulness of SSF, in combination with nanofiltration, in treating secondary wastewater that can be safely disposed off or reused without significant impact, has been investigated by Cluff (1992).

Ground water, surface water and sometime seawater and rainwater are used as sources for community water supply. The careful selection of the source is essential as a measure for preventing the spread of waterborne enteric diseases in *developing countries*. Selection must therefore be based on a detailed survey to ensure that the source is reliable and provides water of satisfactory quality.

### 2.3.2 Ground water

Groundwater is the preferred choice for community water supplies, because it generally does not require extensive treatment and operation is limited to pumping and possibly chlorination [Schulz and Okun, 1984]. Vaillant (1981), however, mentions that groundwater, although hygienically safe, sometimes has to be purified due to the presence of iron and/or manganese resulting from anaerobic conditions in the subsoil. There may also be shallow wells and springs which are contaminated by disposal of solid or liquid waste originating from nearby situated population centres or industries. In addition, natural groundwater may contain too high amounts of fluoride or other toxic substances so that some types of groundwater have to be rejected as possible sources of drinking water. Extensive and ongoing chemical and bacteriological investigations are therefore also required for groundwater before it can be used as a drinking water source.

Seppanen (1992) claims that the most widely-used method for groundwater treatment is SSF. In Finland, both Seppanen (1992) and Hatva (1988) have shown that good purification results were achieved with respect to iron, manganese and ammonia when using slow sand filtration. Pre-treatment, including aeration and contact filtration, is necessary to reduce the iron content of groundwater in order to slow down the clogging process in the SSF [Hatva, 1988]. The removal of iron and manganese occurs due to the activity of living bacteria in the SSF [Seppanen, 1992].

Unfortunately, most of South Africa is underlain by hard rock formations, so only about 5 400 $10^6$ $m^3$ of water per year may be obtainable from groundwater sources [DWA, 1986]. Although groundwater plays a lesser role in the water supply of South Africa than it does in many other parts of the world where extensive primary acquifers are the main sources of water, it is often the only source available to isolated communities, or may be the most cost effective alternative [DWA, 1994]. For example, De Aar meets its supply from boreholes which yield approximately 2,6 $10^6$ $m^3$ per year [Fowler, 1992b].

### 2.3.3 Surface water

Only in cases where groundwater of reasonable quality is not available in adequate quantities or where groundwater abstraction and treatment is too costly, should surface water be used [Vaillant, 1981]. The safety of surface water is generally not reliable from a hygienic point of view. Even if protection zones are established according to high-level criteria and the raw water meets all standards, a disinfection phase should be included obligatory in the treatment system [Vaillant, 1981]. However, Schulz and Okun (1984), maintain that only as a last resort should sources be developed that require chemical coagulation, rapid filtration and disinfection. They go on to say that if river waters are silted, pre-treatment may be provided by plain sedimentation or roughing filters prior to SSF.

Cleasby *et al* (1984), when comparing the treatment of surface water by SSF and rapid filtration, found that SSFs outperform rapid filters operating with alum or cationic polymer as a coagulant.

Some examples of surface water are rivers, streams, impoundments and lakes. In an investigation into the effectiveness of SSF in the United States of America, Slezak and Sims (1984) found that most SSF plants use lakes and dams as raw water sources. A few use rivers or streams. Some of the treatment plants using lakes or dams reported that algae control measures were sometimes required. Also, in a paper on the development of SSF in Europe, Rook (1976) mentions that for many lake waters and some impounded surface waters in which the contents of biorefactory organics remain low, SSF is the best technical means of providing a single step efficient reduction of pathogenic and coliform organisms and bio-oxidation of ammonia and degradable organic matter.

South Africa's average annual rainfall of 500 mm is only 60 % of the world average [DWA, 1986]. The combined average annual runoff of South Africa's rivers is estimated at 53 500 $10^6$ $m^3$ [DWA, 1994]. Owing to the variability and the high evaporation losses from dams, only about 62 % or 33 000 $10^6$ $m^3$ of the average annual runoff can be used cost-effectively with present technology. For instance, in some areas the rivers have periods of up to 10 years in a row of low flow, which must be catered for in the planning and the operation of water supply systems. Although most communities, making use of surface water, rely on dams, the water still requires treatment to reduce turbidity and pathogenic content [Fowler, 1992b].

## 2.4 CHOICE OF TREATMENT PROCESSES

### 2.4.1 Introduction

There are various treatment trains which include SSF. A number of pre-treatment and post treatment alternatives were found in the literature. Collins *et al* (1991), in discussing modifications to SSFs, have suggested three limitations of SSFs. These limitations are as follows:

i) A limited acceptability of raw waters containing moderate levels of abiotic or algal solids.
ii) A limited ability to remove organic precursor materials.
iii) Extensive filter downtimes and ripening periods.

Under these circumstances, therefore, SSFs should then be used in combination with other treatment processes.

Galvis *et al* (1992) have also noted that the raw water sources in many locations in industrialised countries are so deteriorated that a combination of treatment processes is required to meet drinking-water standards. Wolters and Visscher (1989) and Wegelin (1988a) have specifically recognised that SSFs require raw waters of low turbidity. Solid matter retained on top of the sand filter bed will drastically increase the filter resistance, impair biological activity and reduce filter runs. The need to pre-treat the raw water to remove initial turbidity is therefore vital.

Pre-treatment of raw water prior to SSF is especially relevant in South Africa. There are not many raw water sources in South Africa that satisfy the low turbidity and algal concentration requirements of SSF [Haarhof *et al*, 1992].

### 2.4.2 Plain sedimentation

The process of plain sedimentation allows for the removal of suspended solids in the raw water by gravity and the natural aggregation of the particles in a tank, without the use of coagulants. The efficiency of this process, as measured by turbidity removal, is dependent on the size of the suspended particles and their settling rate.

Schulz and Okun (1984) have pointed out that plain sedimentation is quite effective in tropical *developing countries* for the following reasons:

i) The turbidity in rivers can be attributed largely to soil erosion, the silt being settleable.

ii) The higher temperatures in these countries improve the sedimentation process by lowering the viscosity of the water.

In addition, Ahmad *et al* (1984) have stated that it is easier to clarify waters of high turbidity than low turbidity.

Both Schulz and Okun (1984) and Ahmad *et al* (1984) recommend plain sedimentation as a pre-treatment method to be used in *developing countries* where skilled operators are in short supply. In the case of SSF, however, its use is limited to where it is possible to reduce the raw water turbidity to 30 NTU or less to avoid too frequent clogging of the sand bed [Schulz and Okun, 1984].

### 2.4.3 Chlorination

Chlorination is necessary as a method of chemical disinfection in order to kill or control the micro-organisms in water which can adversely affect its quality, cause fouling or corrosion of equipment or lead to disease from microbial activity. Di Bernardo (1991) recommends post-chlorination in all treatment trains (see Fig. 2.1) that include SSF despite the fact that SSF can remove a large proportion of the bacterial content of raw water. The limits of the raw water determinands corresponding to treatment technologies of Fig. 2.1 are shown in Table 2.3.

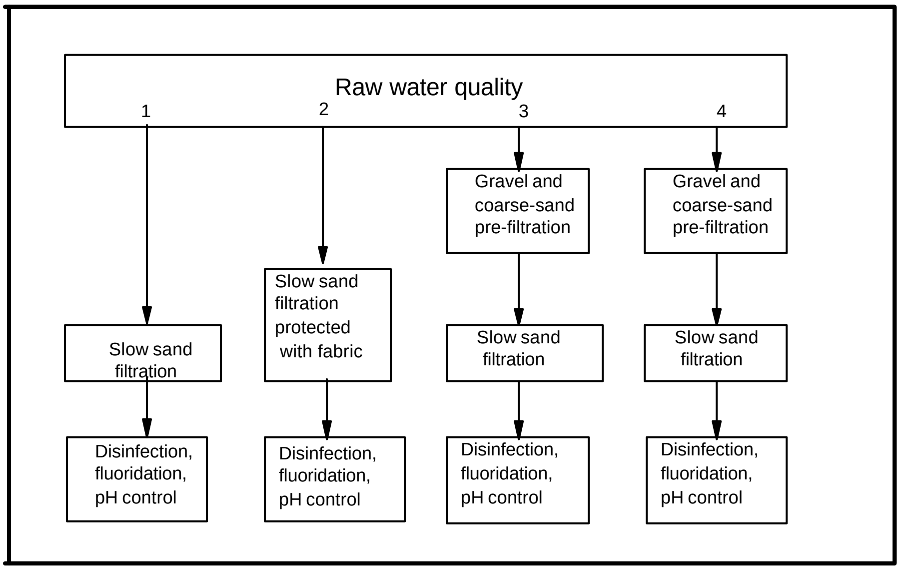


**Figure 2.1: Water-treatment technologies without chemical coagulation - from Di Bernardo (1991)**

**Table 2.0: Suggested limits of raw water parameters - water treatment technologies without chemical coagulation - Di Bernardo (1991)**

| | | Water-treatment technology * | | | |
|---|---|---|---|---|---|
| **Determinand** | **Units** | 1 | 2 | 3 | 4 |
| Turbidity | NTU | 10 | 20 | 50 | 100 |
| True colour | TCU | 5 | 5 | 10 | 10 |
| Total Fe | (mg/ℓ) | 1 | 2.5 | 5 | 5 |
| Mn | (mg/ℓ) | 0.2 | 0.2 | 0.5 | 0.5 |
| pH | | 5,5 to 8,5 | 5,5 to 8,5 | 5,5 to 8,5 | 5,5 to 8,5 |
| Total coliforms | (/100 mℓ) | 1,000 | 5,000 | 10,000 | 20,000 |
| Faecal coliforms | (/100 mℓ) | 200 | 500 | 2,000 | 4,000 |
| TOC | (mg/ℓ) | 1 | 1 | 1.5 | 2 |
| Algae ** | ASU/mℓ) | 250 | 500 | 750 | 1,000 |
| BOD | (mg/ℓ) | 1.5 | 1.5 | 5 | 5 |

* The technologies numbered 1 to 4 correspond to those numbered in Fig. 2.1

** ASU was not defined in source

Bellamy *et al* (1985a) discuss the effect of pre-chlorination on the microbiological activity of a SSF. Originally it was thought that pre-chlorination will destroy the microbiological activity of a SSF. Bellamy *et al* (1985a) have discovered pre-chlorination is acceptable within certain chlorine concentration constraints.

Hargrave (1988) also mentions that chlorinated and unchlorinated slow sand filters demonstrate similar performance.

Post-chlorination is generally recommended for SSF as opposed to pre-chlorination. Slade (1978), in his investigation of enteroviruses in slow sand filtered water, states that adequate post-chlorination is essential to public health since discovering a consistent presence of viruses in this water at concentrations as high as 0,17 PFU (Plague forming units). Pre-chlorination is undesirable if algal numbers in the raw water are high, due to the formation of taste and odour forming chemicals from the contents of lysed cells [Ashitani *et al*, 1988] [Utkilen and Froshaug, 1992] and the formation of trihalomethanes [Steenderen *et al*, 1988] from the released organic compounds.

Experience in South Africa has shown that pre-chlorination is not favoured. Umgeni Water removed their pre-chlorination step after chlorination of raw water containing a bloom of the algae *Anabaena* resulted in taste and odour problems [Joubert *et al*, 1989]. Umgeni Water also found that the performance of their SSFs improved significantly when chlorine dioxide was used instead of chlorine [Pearson, 1989a]. In this instance feed water from the Shongweni impoundment, where algal levels at certain times of the year are high, was treated with chlorine dioxide before a set of SSFs at a plant near Durban.

### 2.4.4 Roughing gravel filtration

There are different types of roughing filters that may be combined with SSF when the raw water turbidity exceeds 10 NTU. The different types can be classified according to their location within the water supply scheme and with respect to the flow direction. There is therefore a distinction between intake and dynamic filters, which form part of the water intake structure, and the actual roughing filters, which are integrated in the water-treatment plant [Wegelin *et al*, 1991]. Roughing filters are further subdivided into down-, up- and horizontal flow filters. Brief descriptions of these filter types can be found in Wegelin (1988a), Wegelin *et al* (1988b) and Galvis *et al* (1993).

In general, horizontal-flow roughing filtration (HRF) is preferred to up- or down-flow roughing filtration. The latter filter types have the operational difficulty of backwashing. However simple draining of the filters has been mentioned by Galvis *et al* (1993).

Basically, a HRF consists of a box filled with different sized gravel through which the water flows in a horizontal direction. Compartments at the inlet and outlet site of the filter box ensure an even flow distribution over the filter cross-section. The flow through the filter is controlled by a discharge weir at the effluent and adjusted in front of the inlet by means of an inlet weir. The size of the graded filter media varies from approximately 20 mm to 4 mm in the sequence of coarse, medium and fine size with 3 to 4 gravel packs [Wegelin *et al*, 1987]. The total length of the filter is in the range of 6 to 12 m. The filter height is limited to 1,5 m to permit easy cleaning. The width of the filter box depends on the capacity of the filter but might generally range between 2 and 5 m.

Successful variations of the basic design of the HRF has been used elsewhere. Australian companies have designed HRFs with a depth of 2,2 m [Drew *et al*, 1987] and they have used gradings with a single gravel size [Fraser, 1988] instead of three different sizes . The performance of the HRFs was not sensitive to the difference in gravel gradings.

Boller (1994) mentions that another idea, which may gain importance in roughing filter design, is the replacement of the coarse gravel with a media with a more favourable surface to volume ratio e.g. plastic chips. Plastic chips performed significantly better than gravel in turbidity removal. In another application [El Basit and Brown, 1986], broken burnt bricks were used as the first stage in a HRF. The other two stages were different gradings of pebbles. A study by Wegelin *et al* (1987) showed that the shape and surface properties of the filter medium had a minor influence on the filter efficiency. Thus, in *developing countries* it should be possible to try cheaper sources of media.

As far as performance is concerned, Galvis *et al* (1993) reported that a combination of roughing filters and a SSF consistently reduced faecal coliforms by the order of 4,9 to 5,5 log units. Wegelin *et al* (1991) mentions that up- and down-flow roughing filters can cope with raw water turbidities of 50 to 150 NTU whereas HRFs can even handle short turbidity peaks of 500 to 1 000 NTU on account of their comparatively long length. Kuntschik (1976) discovered a slight increase in solids removal rate with increased filtration velocity in a HRF on a pilot scale. It appears that the resultant increase in turbulence multiplies the chances of contact between grain surfaces and suspended particles. In a full-scale HRF the suspended solids concentration was reduced by 60 % at filtration rates of 20 m/h.

In South Africa, Williams (1988) has successfully used HRFs consisting of two grades of media. The first metre of the HRF was filled with pebbles, 20 to 50 mm in size. The remaining 11 m length was filled to a 650 mm depth with washed and sieved river gravel, having an effective size of 1,2 mm and a uniformity coefficient of 1,9. The void ratio of this gravel was 40 %. He did, however, go on to recommend a single grade of gravel provided that there was an effective settling tank before the HRF.

Williams (1988) reported that the HRF influent turbidity, during this period, varied widely during the wet season (October to April), with peaks up to 60 NTU. During this period the HRF effluent turbidity followed the influent turbidity, but only exceeded 20 NTU on one occasion. During the dry season (May to September) the HRF influent turbidity was generally below 5 NTU and the effluent was consistently 1 NTU or less. Cleaning of the HRF was recommended during this period since the raw water could be fed directly to the SSF.

### 2.4.5 Upflow coarse-grained filtration

Upflow coarse-grained filtration is also used as a pre-treatment alternative to SSF. It serves well in removing turbidity, colour, iron and manganese. A filter that uses sand of effective size 0,85 mm in addition to the gravel used in roughing filtration was reported by Di Bernardo (1988). Another household upflow filter, the UNICEF filter, consisting of a 250 to 300 mm layer of charcoal of 5 mm grain size sandwiched between two 200 to 250 mm deep layers of fine sand was investigated by Singh and Chaudhuri (1993).

Di Bernardo (1988) reported a significant reduction of turbidity, apparent colour, iron and manganese in the plant that he investigated. Intermediate drainages were used to extend the run length of the filter. At the end of the run the filter was cleaned by several drainages instead of a backwash. One of the disadvantages of this type of filter was its weak attenuation capacity of influent water quality peaks. Nevertheless, Bernardo recommends this type of filter as a pre-treatment alternative for SSF.

The UNICEF filter [Singh and Chaudhuri, 1993] is recommended as an ideal pre-treatment stage to a SSF. It is suitable for use in a packaged water treatment plant used in rural areas. A 40 ℓ raw water tank storage tank placed on top of the 175 to 200 ℓ filter tank. The raw water from the storage tank enters the filter tank at its base through a 12,5 mm diameter hose and pushes upwards through the filter bed. The clean filtered water accumulates above the filter bed and is collected through an outlet hose.

A 600 mm deep sand bed (0,15 mm to 0,45 mm sand size), similar to a slow sand filter, was tested as a polishing filter to the UNICEF filter. The combination produced an effluent with turbidity of 0,5 to 1,5 NTU, heterotrophic plate count of 10 to 40 CFU/mℓ and faecal coliforms below 10 MPN/100mℓ. Singh and Chaudhuri (1993) still recommend that the filter should be tested in terms of its efficiency in removing enteric viruses and protozoan cysts.

### 2.4.6 Pebble matrix filtration

Boller (1994) mentions the pebble matrix filter (PMF) as a new trend in roughing filtration. Whereas a roughing filter consists of gravel or pebbles, the pebble matrix filter, however, consists of a deep layer of pebbles, approximately 50 mm in size, infilled in its lower part by sand less than 1 mm in size. Pebble matrix filtration has been recommended as an appropriate pre-treatment method to SSF by Ives and Rajapakse (1988).

Raw water entering through the top of the pebble matrix filter first passes through the layer of large pebbles and then through the layer of mixed pebbles and sand.

Sedimentation is the dominant removal mechanism in the pebble layer. Removal in the pebble/sand layer is governed by generally-accepted deep-bed filtration mechanisms.

The headloss in the PMF is considerably less than in other conventional filters, which is thought to be principally due to:

i) lens-like cavities formed underneath the pebbles.
ii) boundary effects [Rajapakse and Ives, 1990].

These cavities and boundary flows create secondary (macro) flow paths. Two drainages and a backwash (no air scouring) with raw water are recommended to restore the PMF to its original clean-bed headloss.

At a filtration rate of 0,72 m/h with fine sand ($d_{10}$ = 0,38 mm) the PMF produces an effluent of below 1mg/ℓ suspended solids for most of the run, even with peaks as high as 1 000 to 5 000 mg/ℓ suspended solids at the inlet. Due to occasional peaks, however, the time average suspended solids concentration of the effluent was 5 mg/ℓ. This effluent was then fed to a SSF which performed satisfactorily at 0,18 m/h, producing a filtrate containing below 0,5 mg/ℓ with only a 300 mm headloss after three weeks [Rajapakse and Ives, 1990].

Rajapakse and Ives (1990) recommends PMF as a pre-treatment technique to SSF, especially in tropical areas where rivers may carry several hundred (or even a few thousand) milligrams per litre of suspended solids during monsoon periods. This treatment train could be considered in KwaZulu-Natal since a tropical climate is characteristic of this province.

### 2.4.7 Ozonation

The conventional colour removal process of coagulation, flocculation and separation is inappropriate when used with SSF. SSFs are unable to be backwashed and depend, for effective treatment, on biological activity in the top few centimetres of the filter medium. The use of inorganic coagulant prior to SSF would not only pose problems of rapid headloss development and the precipitation of dissolved residual coagulant deep in the filter bed, where it could remain for several filter cycles, but could also inhibit the proper development of the *schmutzedecke* [Greaves *et al*, 1988]. There is also concern over the formation of disinfection by-products due to the inclusion of chlorination as a treatment step. Consequently there has been interest by Malley *et al* (1993), Rachwal *et al* (1986), Greaves *et al* (1988), Gould *et al* (1984) and others in the use of ozone to bleach coloured humic materials prior to treatment within SSFs and in its disinfection potential, particularly where the replacement of filters would be expensive or inconvenient.

Pre-ozonation followed by SSF is effective in removing colour. Gould *et al* (1984) have reported that an ozone dose of 5 mg/ℓ was required to reduce true colour from 40 °H to less than 12 °H. Greaves *et al* (1988) reported a 20 % reduction in true colour by SSF alone and a 74 % reduction by both SSF and ozonation (from 19,3 °H to 6,6 °H).

An increased TOC removal on pre-ozonated SSFs was attributed to an enhancement by the ozone treatment of the biodegradability of the organic compounds present in raw water [Zabel, 1984]. Ozone is responsible for converting the organic compounds to more biodegradable organic compounds which enhances the ability of the microbiological *schmutzedecke* layer of the SSF to remove them. Other researchers, for example Malley *et al* (1993) and Rachwal *et al* (1986) have confirmed the increased TOC removal by the SSF and ozonation combination.

Rachwal *et al* (1986) reports that during periods of high algal activity above the filter bed, pre-ozonation increased average filter run lengths of SSFs operated at conventional filtration rates from 60 d to more than 90 d before maximum headloss was reached. However, at times of high turbidity, whether due to silt or algal penetration, and during periods of low algal activity, pre-ozonation had no beneficial effect on SSF run length. Zabel (1984) also reports on longer filter runs for raw waters with increased algal activity and generally shorter filter runs otherwise. Malley *et al* (1993) and Gould *et al* (1984) reported that pre-ozonation generally reduced the filter run length of SSFs (no reasons were given). Interestingly, Rachwal *et al*

(1986) have also indicated that acceptable filter run lengths (40 to 60 d) can also be achieved at higher filtration rates of 0,3 to 0,4 m/h with pre-ozonated water.

### 2.4.8 Filter mats

The process of purifying contaminated influent waters by SSFs is principally localised in the top 20 to 30 mm of the sand bed. The rationale of applying a non-woven fabric (NWF) layer on the top surface of the sand filter is to concentrate the major part of the treatment process within the fabric layer, instead of within the top layers of the sand [Mbwette *et al*, 1990]. The reason for this is that the structural properties of non-woven fabrics offer a considerably more efficient filtration medium than sand.

Graham and Mbwette (1990) attempted to specify the non-woven synthetic fabric layer in terms of specific surface area and thickness of the fabric. Mbwette (1989), in work done for his PhD thesis (cited in [Graham and Mbwette, 1990]), has shown that a maximum run time ratio can be achieved using a 30 mm layer of fabric having a specific surface area in the range of 13 000 to 15 000 $m^2/m^3$. The run time achieved with the fabric protected SSF was 8 times that of the SSF alone. For fabrics of significantly lower surface areas, particle penetration through the fabric occurs leading to headloss accumulation in the sand. Alternatively, fabrics of high surface area (>20 000 $m^2/m^3$) have a very high filterability so that rapid headloss development occurs in the fabric leading to run time ratios of less than unity.

The overall physical and biological treatment performance of conventional SSFs is very high so that application of NWF matting appears to make a negligible improvement to this [Mbwette and Graham, 1988; Mbwette *et al*, 1990]. Rachwal *et al* (1986) has reported that in the Thames Water Authority region up to 70 % of direct operational costs for SSFs are associated with filter cleaning and resanding. Subsequently, Mbwette *et al* (1990) have shown that the use of filter mats has potential economic benefits. The use of filter mats are able to reduce the depth of the sand filter significantly and thus the capital cost. Other benefits of using filter mats [Mbwette and Graham, 1988; Mbwette *et al*, 1990] are as follows:

i) Longer filter run times (an increase of 400 % compared to conventional SSF).

ii) A simpler filter cleaning arrangement involving the removal and washing of the fabric only.

Mbwette *et al* (1990) have also shown that the filtration rate can be doubled from 0,15 to 0,3 m/h whilst still maintaining a viable filter run time.

### 2.4.9 Surface amendments

The use of layers of clinoptolite [McNair *et al*, 1987] and granular activated carbon (GAC) [Fox *et al*, 1984; Schalekamp and Bakker, 1978; Thames Water, 1994] on the surface of a SSF has been investigated in improving its performance.

Clinoptolite is an ammonium-selective zeolite usually used as an ion exchange material in the treatment of industrial and municipal wastewaters. McNair *et al* (1987) investigated the use of 80 mm of clinoptolite on the surface of a SSF. The clinoptolite-amended SSF operated for longer periods of time e.g. in winter the clinoptolite-amended filter operated for 80 d compared to the 58 d of the SSF. The clinoptolite-amended SSF achieved these longer run times at higher filtration rates (0,35 and 0,75 m/h) than the SSF (0,2 m/h). Particle removal (2,4 to 100 μm) was also superior in clinoptolite-amended SSF at these high filtration rates.

Whilst Fox *et al* (1984) and Schalekamp and Bakker (1978) investigated a surface layer of granular activated carbon (GAC), Thames Water (1994) investigated the effect of a sandwich layer of GAC within a SSF. Thames Water proposed that 75 to 200 mm of GAC between layers of normal SSF sand, so that the upper sand layer would protect the GAC from the incoming particulate load while the lower layer would prevent GAC fines and biological entities from entering the filtrate.

Fox *et al* (1984) discovered that the GAC-amended filter, despite its large effective particle size of 0,6 mm, provided better turbidity control than the ordinary SSF. Effluent turbidities were typically less than 0,5 NTU and often less than 0,1 NTU. The filtration cycle time for the GAC-amended filter was also longer. As far as organic compounds are concerned, the mean TOC and seven-day THMFP (THM formation potential) removals in the GAC-amended filter were 88 and 97 % respectively. Thames Water (1994) confirmed the GAC's ability to absorb organics. In addition, Schalekamp and Bakker (1978) found that the use of a GAC surface layer of 100 mm resulted in a fivefold improvement of SSF run time.

### 2.4.10 Microscreening

Both Bergling (1981) and Syrotynski and Stone (1975) recommend the use of a microscreen to pre-treat surface waters with a high load of algae and other microscopic matter prior to SSF. Bergling (1981) successfully used a 5 µm microscreen whilst Syrotynski and Stone (1975) reported on the use of a 35 µm microscreen.

Syrotynski and Stone (1975) reported that microscreening demonstrated the following performance:

i) An average reduction of 90,4 % in the concentration of plankton micro-organisms.

ii) An average reduction of 44,6 % in the concentration of total microscopic count (plankton plus amorphous matter).

iii) A more uniform concentration of plankton micro-organisms and total microscopic count than that present in raw water.

Both Bergling (1981) and Syrotynski and Stone (1975) have indicated that microscreening prior to SSF increases the filter run length considerably. Bergling (1981), in fact, found that the filter run length could be doubled. This consequent reduction in the number of filter cleanings reduces the labour and material costs significantly thus making microscreening an economically viable proposition.

# 3 SLOW SAND FILTER PROCESS THEORY AND DESIGN

This section delves into the actual SSF process. A discussion is carried out on the mechanisms of filtration. In addition, the effect of filtration variables such as raw water quality, filtration rate, temperature and composition of media are discussed .

This section also covers a brief discussion and description of the design of the plain sedimentation tank. A more detail and methodical discussion and description of the SSF plant then follows.

## 3.1 THEORY OF BIOLOGICAL FILTRATION

### 3.1.1 MECHANISMS OF FILTRATION

In general, the literature on SSF emphasises the engineering design and operation aspects rather than the process design. However, Huisman and Wood (1974) and Schmidt (1978) have reviewed the processes in sufficient detail. In South Africa, Potgieter (1991) has also reviewed these processes briefly with some good illustrations.

Bellamy *et al* (1985b) have found that the events in a SSF are as follows:

i) Removal within the sand bed.

ii) Adsorption of convected bacteria on the biofilm attached to the grains.

iii) Metabolism of convected bacteria.

iv) Synthesis of attached bacteria.

Huisman and Wood (1974) have categorised these events as follows:

i) Transport mechanisms.

ii) Attachment mechanisms

iii) Purification mechanisms.

Although these mechanisms are described separately the division between them under actual working conditions are not clear cut.

#### 3.1.1.1 TRANSPORT AND ATTACHMENT MECHANISMS

The principal processes by which particles are transported into contact with the sand grains consist of the following:

i) Straining, or screening.
ii) Sedimentation.
iii) Inertial and centrifugal forces.
iv) Diffusion.
v) Mass attraction (Van der Waals force).
vi) Electrostatic and electrokinetic attraction.

The main forces that attach the particles in place, generally referred to as adsorption, once they have made contact with the sand grain surfaces are as follows:

i) Electrostatic attraction.
ii) Van der Waals force.
iii) Adherence.

Poynter and Slade (1977), in their study of virus removal by SSF, indicated that physical activities such as gravity, diffusion and adsorption are important in bringing the particles into contact with the sand surface. Williams (1987), in his attempt to determine the effect of removing suspended matter from the water without any biological action, filtered samples of raw water through sterile glass-fibre filter paper. After comparing results to those of a SSF he then concluded that the primary bacteria removal processes in SSF are screening and adsorption of suspended particles and bacteria in the *schmutzedecke* and sand bed. Microbiological and biochemical processes can then take place on the organic matter and bacteria retained in the filter.

Straining removes those suspended particles that are too large to pass through the pores of the filter bed [Huisman and Deazevedonetto, 1981]. Bellamy *et al* (1985a) confirmed that the larger particles causing turbidity are more easily removed than the smaller particles. Thus straining is a more plausible mechanism in the removal of larger particles and it takes place almost exclusively at the surface of the filter.

The surface area of the sand grains per unit volume of filtering material is so large, that a slow sand filter acts as an extremely effective sedimentation unit [Vaillant, 1981]. Sand grains, having a porosity of 38 % and an average diameter of 0,25 mm, has a gross surface area of 15 000 $m^2/m^3$ [Huisman and Wood, 1974]. The large surface area combined with the low rate of filtration gives a very low surface loading. The settling efficiency will, therefore, be so high that even small particles can be completely removed.

Bellamy *et al* (1985b) discovered that a decrease in the size of the filter media did not necessarily bring about a 100 % removal of coliform bacteria. They therefore supported the hypothesis that adsorption is an important removal mechanism, and not straining, because higher removals would be expected with the larger surface area of the smaller sand size. Ellis (1987) also showed that straining was not the only filtration mechanism when he discovered that the ratio of $BOD_5$ removed to that of suspended solids removed through the whole depth of the filter was 0,72 for a finer filter and 0,79 for a coarser filter. In addition, microstraining, in which the mechanism is purely mechanical straining, resulted in the same ratio being in the range 0,43 to 0,6.

Suspended solids, together with colloidal and dissolved impurities, which are not removed by the general transport mechanisms are removed by adsorption either on a sticky gelatinous coating formed around the filter bed grains or through physical mass attraction and electrostatic attraction [Huisman and Wood, 1974]. The electrostatic attraction is the most effective but it occurs only between particles having opposite electrical charges. Clean quartz sand has a negative charge and is, therefore, unable to adsorb negative-charged particles such as bacteria, colloidal matter of organic origin, anions of nitrate, phosphate and others - this explains why a clean filter bed is not able to produce a high quality filtrate. Thus, during the *ripening* process of a SSF, only positive-charged particles are adsorbed e.g. floc of carbonates, iron- and aluminium hydroxide, and cations of iron and manganese. However, the adsorption of positive-charged particles will continue to a stage when over-saturation occurs. The overall charge of the sand grain coatings then reverses and becomes positive, after which negative-charged particles will be attracted and retained. This reversal of charge is characteristic of the life of a SSF and leads to the adsorption of most impurities from the passing water. Stenkamp and Benjamin (1994) used positively charged iron-oxide coated sand particles to treat an influent of latex and ferrihydrite particles. They concluded that factors other than electrostatic interactions also influence particle removal since the difference between the performance of coated and uncoated sand was not significant.

Collins *et al* (1992) mention that adsorption and biodegradation are considered to be the primary natural organic matter (NOM) removal mechanisms in a SSF, with the larger hydrophobic-humic organic molecules being predominately removed by adsorption. Bonnet *et al* (1992) indicates that removal of refractory dissolved organic carbon (RDOC) in a SSF is due to adsorption on the biofilm or bioflocculation. Montiel and Welte (1992), in their study of alternative options for the pesticide atrazine, discovered that the mechanism of removal for one of its possible replacements, terbuthylazine, seemed to be reversible adsorption in a SSF.

Schmidt (1978) indicated that although absorption occurs mainly on organic material in the topmost layer of the filter bed, persistent loading of harmful materials results in their displacement to greater depths. When layers with little or no biological growth have been reached, for many materials the absorption capacity of the solid phase decreases and the passage through the filter bed is considerably accelerated.

#### 3.1.1.2 PURIFICATION MECHANISMS

The various purification processes, whereby the trapped impurities on and within the filter-bed are broken down and rendered harmless, are interdependent. The two principal agencies contributing to the overall effect are chemical and microbiological oxidation [Huisman and Wood, 1974], but other microbiological processes involving various forms of animal and vegetable life may play a significant part.

Poynter and Slade (1977) have concluded that the reduction in efficiency at low temperatures, the adverse effects of drainage and the phenomenon of maturation are all consistent with the view that the removal of bacteria and viruses by SSF is essentially a biological process. They also cited Taylor (1970) who demonstrated that viruses were not removed by clean *sterile* sand and thus physical mechanisms were not the only removal process in a SSF. Ellis (1987) also showed that the higher ratios of $BOD_5$ removed to suspended solids removed obtained from the operation of a SSF to those obtained from the operation of microstrainers must be the result of appreciable biological activity within the sand bed. Experiments performed by Bellamy *et al* (1985a, 1985b) have also confirmed the presence of biological activity in a SSF.

Bacteria derived from the raw water multiply selectively within the *schmutzedecke*, the deposited organic matter being used as food. The bacteria oxidise part of the food to provide the energy they need for their metabolism (dissimilation), and they convert part of it into cell material for their growth (assimilation) [Schmidt, 1978; Huisman and Wood, 1974]. Thus dead organic matter is converted into living matter. The dissimilation products are carried away by the water, to be used again at greater depth by other organisms.

These original organic compounds are usually polluting and thus their removal is beneficial. The most abundant of these are humic compounds which impart a yellow or brown colour to the water and are derived from vegetation and soil drainage and sewage effluents [Burman, 1978]. They can also include, however, many man-made compounds of industrial origin, including detergents, pesticides, oils, phenols, etc. Pesticide removal, in particular, has been investigated by Montiel and Welte (1992).

Eighmy *et al* (1992) suggest that smaller molecular weight assimilable organic matter (AOM) supports growth in the filters. Collins *et al* (1992) mention that smaller hydrophilic material, e.g. carbohydrates, aldehydes and simple organic acids, is considered to be more amenable to biodegradation than is humic material. They also concluded that the removal of organic matter was a function of filter biomass; more biomass resulted in greater organic carbon removals.

Inorganic matter is also removed by the bacteria. Eighmy *et al* (1988) have found that extractable iron and manganese is complexed to the bacterial biomass. The removal of selenium [Carlo *et al*, 1992] is also linked to the bacteria of the *schmutzedecke.*

Bacterial activity is most pronounced in the upper part of the filter-bed and gradually decreases with depth as food becomes scarcer [Huisman and Wood, 1974]. In practice it has been found that full bacterial activity extends over a depth of about 600 mm [Huisman and Deazevedonetti, 1981]. In fact, Datta and Chaudhuri (1991) have observed that a matured filter bed was well populated throughout with active micro-organisms, with its maximum in the top 100 to 250 mm layer. Other authors like Eighmy *et al* (1988, 1992) and Seelaus *et al* (1986) have confirmed this decline in microbial activity with the depth of the SSF. A detail description of the change in the ecology of a SSF with depth is also given by Duncan (1988).

Enough oxygen must be available for satisfactory biochemical oxidation of organic matter. If the oxygen content falls to zero during filtration then anaerobic decomposition occurs, with consequent production of hydrogen sulphide, ammonia, and other taste and odour-producing substances together with dissolved iron and manganese, which makes the treated water unsuitable for washing clothes and other purposes. Sudden loading of readily degradable substances can cause an intensified oxygen consumption which can give rise to anaerobic conditions in a SSF [Schmidt, 1978]. Huisman and Wood (1974) recommends a minimum oxygen consumption of 3 mg/$\ell$ to avoid anaerobic conditions. Vaillant (1981), on the other hand, recommends a minimum oxygen consumption of 2 mg/$\ell$.

All micro-organisms have their optimum temperature for growth and activity. Mixed communities in an aquatic environment have optimum activity at temperatures around 30 to 35 $^{o}$C [Burman, 1978]. The efficiency of SSF may be reduced by low temperatures, owing to the influence of temperature both on speed at which chemical reactions take place and on the rate of metabolism of bacteria and other micro-organisms [Huisman and Wood, 1974]. This implies that SSF is less effective in countries with prolonged winters with extremely cold conditions.

Conditions within the filter are unsuitable for the multiplication of intestinal bacteria. These intestinal bacteria may be destroyed by the many types of predatory organisms that exist in the SSF [Huisman and Wood, 1974 ]. These will include the microbial viruses, bacteriophages, actinophages and mycophages, the very small bacterial predator *Bdellovibrio bacteriovorus* and the bacterial predators of the genus *Myxobacterium*, the antibiotic-producing bacteria, *actinomycetes* and fungi and the predatory unicellular animals, the protozoa, including amoebae, flagellates and ciliates, as well as rotifera and larger animals such as oligochaetes [Burman, 1978].

It is believed that the protozoa play a major role in predation on other organisms in SSFs and have a significant effect on bacterial numbers and activity [Burman, 1978]. Datta and Chaudhuri (1991) characterised the effectiveness of a SSF to inactivate enteric micro-organisms, using *E.Coli* as a model. According to their findings, the SSF bed harbours a microbial population that is capable of inactivating enteric micro-organisms throughout the filter bed, with the top 100 or 250 mm of the bed being the most active layer.

### 3.1.2 EFFECTS OF ALGAE ON FILTERS

Algae do not take part in the mechanism of filtration but certain types of algae can have significant effects on the working of a biological filter [Huisman and Wood, 1974]. These effects may be beneficial or harmful, depending on a variety of conditions.

Two groups of algae, filter *passers* and filter *blockers* can be distinguished [Phillips *et al*, 1985]. Filter *blockers* consist of the larger non-motile organisms such as *Melosira granulata* and *passers* are a variable group, which, by virtue of size, shape or motility are able to penetrate between the sand grains. On the other hand, Bellinger (1979) has divided algal populations into three main groups:

i) Those living in the supernatant water.
ii) Those living on the sand surface.
iii) Those living below the sand surface.

The ability of algae to penetrate the fine sand filters could be partly predicted, by the size of the mean minimum dimension of the species [Phillips *et al*, 1985]. Results show that the thinnest organisms penetrate the furthest into the SSF, the largest organisms remain on the surface, and motile phototactic genera such as *Navicula* are active in the upper 20 mm of sand. These results can thus be related to Bellinger's (1979) classification of the algal population.

Algae are beneficial to the treatment process if they are in moderate numbers [Pearson, 1989b]. These algae can filter out certain nutrients and even some metals. They are also able to build up cell material from simple minerals such as water, carbon dioxide, nitrates and phosphates, thereby producing oxygen which is beneficial to other bio-chemical processes [Vaillant, 1981]. In addition, algae can consume organic matter and convert part of it to more biodegradable cell material.

Huisman *et al*, 1981, mention that the algae forms a thin slimy matting on top of the filter bed which achieves a large removal of organic matter and bacteria. However, the species of predominating algae is important in this situation. Filamentous algae are buoyed up into the water by excess photosynthetic oxygen which is trapped as bubbles in amongst the matted filaments [Bellinger, 1979; Huisman and Wood, 1974]. This minimises the chances of large increases in headloss.

On the other hand, when small algae such as diatoms predominate, the matting is poorly formed and the resistance of the filter skin is increased in addition to the lower effluent quality that results [Huisman and Wood, 1974]. Clarke (1988), however, pointed out that mature SSFs can cope with those diatoms that possess chitin fibrils.

Finally, the effectiveness of SSF in coping with sudden changes in algal blooms is dependent upon whether the criteria judged is the finished water quality or the ability to operate and maintain an effective treatment [Lambert and Graham, 1995]. For example, an algal bloom observed by Cleasby *et al* (1984) reduced SSF run lengths to only 9 d, but an efficient removal (98 %) of the influent turbidity was maintained. Esen *et al* (1991) also made similar observations.

### 3.1.3 HYDRAULICS OF FILTRATION

Several authors have attempted to model the hydraulic behaviour of SSFs. Darcy's law [Woodward and Ta, 1988; Barrett and Silverstein, 1988; Huisman and Wood, 1974] is often used as a basis for a hydraulic model. This is justified by the low filtration velocity in a SSF, which makes it possible to assume the laminar flow conditions necessary for Darcy's law. One form of this law is as follows:

$$H = \frac{v_f\ h}{k}$$

where $H$ = resistance of clean bed

$v_f$ = filtration rate

$k$ = coefficient of permeability

$h$ = thickness of bed

Toms and Bayley (1988), however, have used a model which assumes that the normalised headloss varies exponentially with filtration velocity. The normalised headloss includes headloss values which have been corrected to a standard flow. This is done by dividing headloss by a standardised flow rate of 0,2 m/h.

The model used by Woodward and Ta (1988) predicts the flow rates for given headloss data within 15 % of the observed values. Toms and Bayley (1988) have managed to discern three main classes of headloss behaviour from their analysis. These classes are called *standard* (S-type), *jacked-up* (J-type) and *jacked-up-recovered* (R-type). The term S-type arises because of the pattern formed by the data. A *jacked-up* headloss is characterised by a sudden increase in headloss over a period of time.

The coefficient of permeability, $k$, can be determined empirically or theoretically from formulae available in, amongst others, Woodward and Ta (1988), Huisman and Wood (1974) and Vanvuuren (1981). Factors which affect the coefficient of permeability are discussed in detail by Huisman and Wood (1974) viz. shape factor of sand particles, coefficient of uniformity, porosity, effective sand particle diameter and specific sand particle diameter. The effective particle size and uniformity coefficient can be determined from a sieve analysis which is described by Visscher *et al* (1987).

With the aid of the theoretical hydraulic formulae, which can be justified practically as well, it can be shown that the coefficient of permeability for a sand bed consisting of large effective sand particle sizes e.g. 0,35 mm is very large e.g. 6 m/h for a porosity of 0,38. Thus, the headloss is very low e.g. 0,1 m even for a thick bed of 1,2 m [Huisman and Wood, 1974]. Alternatively, for very small effective particle sizes of 0,15 mm the bed thickness must be limited to about 0,5 m and the filtration rate must be restricted to about 0,2 m/h since the permeability is only 1,1 m/h.

Clogging of a filter is essentially a surface phenomenon [Fraser *et al*, 1988]. This phenomenon has a marked influence on the pressure distribution in the bed. Pressure increases hydrostatically with depth when there is no flow of water. Under conditions of water flow, however, the pressure at a given depth is lowered. The large pressure drop across the *schmutzedecke* can result in a condition known as air binding described by Seelaus *et al* (1986), Huisman and Wood (1974), Huisman *et al* (1981) and Bowles *et al* (1983). A partial vacuum can form immediately below the *schmutzedecke* thus causing air bubbles to form. This can occur particularly in algae laden water with an increased content of dissolved oxygen. Fissures in the sand bed result when the air bubbles burst. These fissures allow water to pass through part of the bed without adequate purification. The problem of air binding is prevented by a simple design in which the filtrate is passed through an outlet weir located at a height of about 100 mm above the *schmutzedecke.* Seelaus *et al* (1986) also mention that filling of the SSF from the top can cause air binding. The solution is thus to fill the SSF with water from the bottom after filter cleaning or commissioning.

### 3.1.4 EFFECTS OF FILTRATION ON DELIVERED WATER QUALITY

Ultimately the success of a SSF will be judged on the quality of water that it produces. Therefore the aim of the designer of a SSF must be the maintenance of a high standard of quality of the treated water. He must also try to economise on operating costs by ensuring that the filtration cycles are as long as possible. Besides the design and operation, the performance of a SSF also depends on raw water quality [Cullen and Letterman, 1985]. In general, Huisman and Wood (1974) mention that both of the abovementioned aims depend on four factors:

i) The quality of the raw water.
ii) The climatic conditions.
iii) The filtration rate.
iv) The composition of the filter medium.

The designer has control of the latter two conditions. The first two must therefore be accepted as they exist.

Increase in filtration rates cause more of an operational problem rather than that of water quality. For example, Ellis (1987) recorded no significant decrease in filtrate quality when the filtration rate was doubled from 0,146 m/h to 0,292 m/h. However the filtration cycle time was halved. Fraser *et al* (1988) also discovered that SSF effluent turbidity was not sensitive to filtration rates. Filtration rates were found to have a greater effect on filter operating times.

Experimental work was also performed by Ellis and Aydin (1993) at various flowrates ranging from 0,1 m/h to 0,5 m/h. They used SSFs containing sands of different effective sizes viz. 0,17 mm, 0,36 mm and 0,45 mm. They noted a correlation between increasing sand particle size and improved removal of suspended solids. There was also some indication of a reduction in the removal of total coliforms with increasing flow rates. This is possibly because biological activity is time-dependent. Higher filtration rates lower the contact time between water and the purifying bacteria of the sand media. Nevertheless, the authors have noted that an adequate removal of total coliform and faecal coliform was achieved at all flow rates. This varied for the faecal coliforms from a mean of 1,41 log (0,17 mm sand size, 0,1 m/h) to 3,3 log (0,45 mm sand size, 0,2 m/h) and for the coliforms from a mean of 1,74 log (0,36 mm sand size, 0,5 m/h) to 3,4 log (0,45 mm sand size, 0,2 m/h). The data given by Ellis and Aydin (1993) also show that a decrease in the filtration rate, when sand particle size increases, helps to improve filtered water quality. Bellamy *et al* (1985a) have also noted a decrease in the removal of *Giardia* cysts, coliform bacteria, standard plate count and turbidity when the filtration rate increases. However, this decrease was not significant. Even at 0,4 m/h, they noted that the removal of *Giardia* cysts and coliform bacteria was high e.g. 99,98 % and 99,01 % respectively.

The effect of the sand media is noted when comparing the work performed by Schuler *et al* (1991) and Fogel *et al* (1993). The former experienced a 100 % *Cryptosporidium* removal during SSF experiments whilst the latter experienced a 48 % removal. The filter medium of Schuler *et al* had a uniformity coefficient of 1,67. The SSFs of Fogel *et al* had an average uniformity coefficient of 3,5 and ranged up to a uniformity coefficient of 3,8. This high uniformity coefficient indicates an increased particle size and thus the large pore spaces existing within the SSF.

The large pore spaces inhibit the biological removal capacity of the SSF. The organic material, necessary for an active population of bacteria and other micro-organisms to exist, passes easily between the bed's sand grains. The retarding of the microbiological population in turn retards the creation of the zooglea , a sticky film formed on the sand grain surfaces. The organic materials are assimilated into this zooglea as discussed in Section 3.1.1.

Tanner and Ongerth (1990), after examining three SSFs with very similar raw water feeds and sharing many design similarities concluded that the results were still distinctly individual. In one instance, turbidity removal differed between filters because of fines loss in one of the filters. Tanner and Ongerth, however, as opposed to Fogel *et al* (1993), have concluded that a high uniformity coefficient represents widely graded sand with smaller pore spaces. They claim that this has led to a more effective removal of particles in the *Giardia* cyst range. However, there was also rapid headloss accumulation and increased cleaning frequency.

The experience of Fogel *et al* and Tanner and Ongerth indicate that none of the variables (raw water quality, filtration rates, media characteristics, temperatures etc.) affecting SSF performance can be viewed in isolation. Coincidentally, the plant referred to by Tanner and Ongerth had a higher filter loading rate which could possibly explain the rapid headloss accumulation. Fogel *et al* (1993) also point out that the lower efficiency of removal of *Cryptosporidium* in the SSFs that they observed compared to those of Schuler *et al* (1991) may be due to the decreased biological activity within the SSF associated with operation at lower temperatures (about 1 C°) than those of Schuler *et al*. This was confirmed by Bellamy *et al* (1985b) when comparing removals of total coliforms and standard plate count bacteria at temperatures of 5 °C and 17 °C. Williams (1987) also confirmed these findings. In addition, Cullen and Letterman (1985) mention that in their observations the factor that seemed to have the most significant effect on the quality of the filtrate was the amount and nature of the particulate matter present in the raw water. This was confirmed by Fraser *et al* (1988) who observed that a spike in the raw water turbidity would cause a deterioration in treated water quality. It was suspected that higher than normal levels of colloidal material were present in the raw water turbidity when this occurred.

The trend nowadays is to model the performance of technology using computers. This saves time when compared to lengthy experimental work. It is noted that attempts were made to model the performance of SSF [Ojha and Graham, 1994 ; Matsui and Tambo, 1995; Woodward and Ta, 1988]. These models, supported by empirical work, gave a reasonably close fit to the actual operation of a SSF. For example, Woodward and Ta (1988) predicted flowrates for a given headloss within 15 % of the observed values.

## 3.2 DESIGN CRITERIA

Plain sedimentation has been chosen as a pre-treatment because of its simplicity. An upflow plain sedimentation tank (cylindroconical tank) was chosen because of its compact nature which makes it attractive for package plants or modular-type designs. It is suitable especially where land is not available to build larger horizontal-flow basins [Schulz and Okun, 1984].

The motivation for choosing SSF has already been discussed in Section 1.1.1.2. Tanner and Ongerth (1990), after evaluating the performance of SSFs in Northern Idaho which have in some instances differed from conventional SSF design practice, have recommended that SSFs should conform closely to the recommendations of the WHO [Huisman and Wood, 1974] and the International Reference Centre (IRC) for Community Water Supply and Sanitation [Visscher *et al*, 1987]. After the discussion on the effect of filtration on water quality in Section 3.1.4, one can only agree with Tanner and Ongerth in this regard.

### 3.2.1 Pre-treatment: Cylindroconical tank

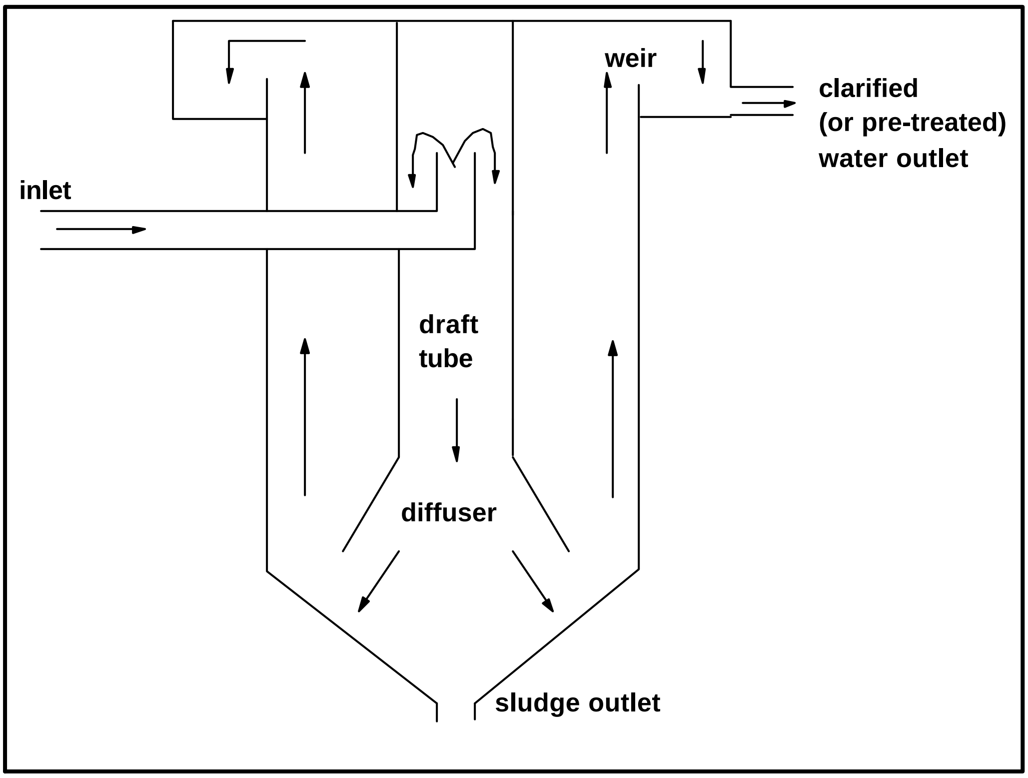


**Figure 3.1: Cylindroconical plain sedimentation tank**

#### 3.2.1.1 Settling velocity and upflow rate

In the case of a vertical upflow clarifier, the upflow velocity should not exceed half of the settling velocity [Denysschen, 1985a]. The settling velocity can be calculated by an iterative procedure using the following equations.

$$v_s = \sqrt{\frac{4\,g}{3\,C_D}\left(\frac{\rho_p - \rho}{\rho}\right) D_p}$$

$$C_D = 24\,\frac{\Phi}{R_e}$$

$$R_e = \frac{\upsilon_s D_p}{\nu}$$

| | | | |
|---|---|---|---|
| where | $v_s$ | = | settling velocity (m/s) |
| | $\rho_p$ | = | particle density (kg/m$^3$) |
| | $\rho$ | = | fluid density (kg/m$^3$) |
| | $\nu$ | = | kinematic viscosity (m$^2$/s) |
| | $\Phi$ | = | spericity (-) |
| | $g$ | = | gravitational constant (m/s$^2$) |
| | $R_e$ | = | Reynolds number (-) |
| | $D_p$ | = | particle diameter (m) |
| | $C_D$ | = | dimensionless drag coefficient (-) |

Heber (1985) gives the above equations for calculating the settling velocity. However the popular *Stokes law* equations can be found in most books on the design of water treatment plants or in books on fluid mechanics e.g. [Massey, 1984]. In general, the average upflow rate for a cylindroconical plain sedimentation tank should be from 0,5 to 1 m/h for the clarification of drinking water [Degremont, 1991].

#### 3.2.1.2 Design of inlet system

The design of the inlet system is important to reduce disturbances created by the flow of the raw water entering the plain sedimentation tank. In a centre-feed system, especially, the relatively small feed well region (draft tube) is overloaded and thus the energy must be carefully dissipated. If a simple circular draft tube, extending a short distance into the water, is used, then the flow from this draft tube is apt to be a jet stream [Denysschen, 1985a].

Degremont (1991) has illustrated a conical diffuser system, shown in Fig. 3.1, which would gradually reduce the inlet velocity to a value close to the calculated upflow velocity. This entire inlet system, draft tube and diffuser, should extend at least to mid-depth [Denysschen, 1985a]. The angle of the conical diffuser will depend on the designer's chosen velocity reduction from the draft tube to the diffuser outlet. This angle can be easily calculated using geometrical principles.

#### 3.2.1.3 Design of outlet

Similarly, the design of the clarified water outlet system is important to reduce flow disturbances at the outlet of the plain sedimentation tank. Schulz and Okun (1984) and several other water treatment experts e.g. Degremont (1991) recommend a system of weirs to withdraw the clarified water from the plain sedimentation tank. In addition, a V-notch weir is recommended to ensure uniform flow, especially when low overflow rates are used.

The V-notches can be arranged at a distance of 150 to 300 mm apart [Schulz and Okun, 1984]. Thus the number of weirs that can fit around the circumference of a plain sedimentation tank and their respective flowrates can be calculated. *Perry's Chemical Engineer's Handbook* (1984) gives the following equation for designing a V-notch weir.

$$q = \frac{0{,}31\ h_o^{2{,}5}\ \sqrt{2\,g}}{\tan\ \Phi}$$

where $q$ = volumetric flow ($m^3/s$)

$\Phi$ = angle of slope with respect to horizontal (deg.)

$h_o$ = weir head (m)

$g$ = gravitational acceleration ($m/s^2$)

With respect to the sludge outlet, Degremont (1991) recommends an angle of 45 to 60$^o$ for the slope of the conical bottom.

### 3.2.2 Slow sand filtration

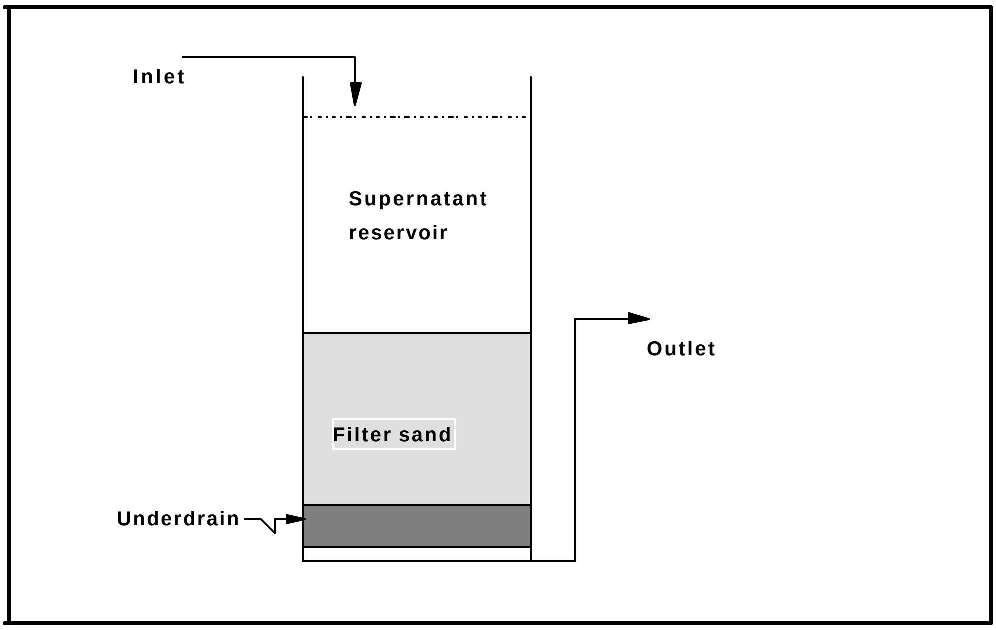


**Figure 3.2: Schematic of slow sand filter**

#### 3.2.2.1 System capacity

It is important to consider the capacity of the plant or the daily water demand when designing a SSF. This depends on the design period, the number of users the system is to serve and the quantity of water to be provided per person per day.

The design period is the length of time for which the SSF is expected to provide a community with good quality water in sufficient quantities. This period should be neither too short, not less than 10 years, nor too long because of economic reasons and the difficulty of predicting future water demand. Visscher *et al* (1987) therefore recommends a design period of 10 to 15 years. The USA Agency for International Development [USAAID, 1982a], however, states that a SSF should be designed to meet a community's needs for about 7 to 10 years. At the same time it also states that some systems can be designed for up to 20 years. In South Africa, the design period limit of 15 [Korte, 1985] agrees with the recommendation of Visscher *et al* (1987).

After the design period has been selected, the design population must be determined. The following equation [Visscher *et al*, 1987] can be used to estimate the population:

$$P_d = P_p\,(1 + 0{,}01\,a)^{Y}$$

where $P_d$ = design population

$P_p$ = present population

$a$ = annual growth rate (%)

$Y$ = design period (years)

The term $(1 + 0{,}01a)^Y$ can be used to generate a table of growth factors. A typical example of growth factors is shown in Table 3.1.

**Table 3.1: Population growth factors [USAAID, 1982a]**

| Design period (years) | Yearly growth rate (%) | | | | | |
|---|---|---|---|---|---|---|
| | 1.50 | 2.00 | 2.50 | 3.00 | 3.50 | 4.00 |
| 7.00 | 1.10 | 1.15 | 1.19 | 1.23 | 1.27 | 1.32 |
| 10.00 | 1.16 | 1.22 | 1.28 | 1.34 | 1.41 | 1.48 |
| 15.00 | 1.25 | 1.35 | 1.45 | 1.56 | 1.68 | 1.80 |
| 20.00 | 1.35 | 1.49 | 1.64 | 1.81 | 1.99 | 2.19 |

The average amount of water fetched from water supply systems in developing countries ranges from 20 to 150 ℓ/d per person. In a first world country like the USA the demand per person is much higher e.g. 946 ℓ/d [Seelaus *et al*, 1986]. In South Africa, the minimum consumption is set at 25 ℓ/d per person [DWA, 1994]. It is not considered to be adequate for a full, healthy and productive life which is why it is considered as a minimum.

The design capacity, that is, the total quantity of water that the SSF has to provide per day, can be calculated by multiplying the design population by the water demand per person per day. However, if water losses and wastage are not included in the water demand figures, the design daily water demand should be increased by 20 to 30 % [Visscher *et al*, 1987].

### 3.2.2.2 Filtration rate

The filtration rate should be decided upon at the outset of the design stage so that the filter bed area and number of filter beds can be determined. Section 3.1.4 has already discussed the effects and choice of filtration rate on the treated water quality.

In general, the quality of the influent and choice of sand size influence the selection of the optimum filtration rate. In addition, Bellamy *et al* (1985a, 1985b) and Williams (1987) have reported no deterioration in filtrate quality with increasing flowrate, although the run length was reduced at higher rates. Even though there is a decrease in run length at higher rates, the cumulative volume filtered per run is essentially the same for high-rate and conventional-rate filters [Rachwal *et al*, 1988]

For surface water, a rate between 0,1 and 0,2 m/h [USAAID, 1982a] is usually satisfactory, because the filter clogs within a shorter period of time using higher rates . However, the rate may be increased to 0,3 m/h for short periods of one or two days without undue harm e.g. when a filter is being cleaned [Visscher, 1990]. Huisman and Wood (1974) recommend an upper limit of 0,4 m/h.

### 3.2.2.3 Filter bed area and number of filter beds

As a rule the minimum size of a filter bed is 5 $m^2$, but filters of less than 1 $m^2$ are equally efficient, provided raw water does not flow directly along the inside of the walls to the filter drains without being filtered [Visscher *et al*, 1987]. In another paper, Visscher (1990) recommends that it is advisable to restrict the area per filter unit to 200 $m^2$ in rural areas to facilitate manual cleaning.

The total filter bed area is determined from the SSF design capacity and the chosen filtration rate. The following equation can be used to calculate the filter bed area:

$$A = Q / v_f$$

where $Q$ = design capacity ($m^3 / h$)

$v_f$ = filtration rate ($m / h$)

$A$ = bed cross-sectional area ($m^2$)

Both Huisman and Wood (1974) and Visscher *et al* (1987) recommend a minimum number of 2 SSFs. This would ensure a continuous supply of water if one of the filter beds is being cleaned. Williams (1986) of South Africa recommends at least 3 SSFs.

An indication of a suitable number of rectangular SSF units may be obtained with:

$$n = 0,5\,(A)^{\frac{1}{3}} \qquad \text{[Visscher } et\ al\text{, 1987]}$$

where $n$ = total number of rectangular units

$A$ = total surface area ($m^2$)

On the other hand, Huisman and Wood (1974) use the design capacity to estimate the number of SSF units as follows:

$$n = \tfrac{1}{4}\sqrt{Q}$$

where $Q$ = design capacity ($m^3/h$)

#### 3.2.2.4 Supernatant water reservoir

The supernatant water reservoir consists of an upward extension of the walls of the filter box from the *schmutzedecke* surface.. The static head created by the supernatant water provides the driving force to maintain gravity flow through the sand-bed. It also provides a waiting period of some hours for the raw water, during which sedimentation, particle agglomeration and oxidation occur.

It is mainly the static head of the water which determines the vertical dimension of the supernatant reservoir. The static head depends on the filter bed resistance (*H*) and is preferable to maintain it at a value equal to or greater than the maximum resistance $H_{\max}$ [Huisman and Wood, 1974]. The static head can be calculated from the equations detailed in Section 3.1.3.

Huisman and Wood (1974) recommend a static head between 1 and 1,5 m. They also comment that the head may, exceptionally, be as high as 2 m but rarely more than this. Schuler *et al* (1991) have discovered that *Giardia* and *Cryptosporidium* removal were unsatisfactory when the headloss exceeded 1,5 m, especially in a biologically immature filter bed. They do, however, imply that this removal may be improved when the bed is completely biologically mature. The design specifications of the filter bed used by Schuler *et al* were within those recommended by Huisman and Wood. Therefore it may be good practice to maintain a maximum static head value of 1,5 m.

One may also argue that the static head can be increased above 1,5 m if the sand bed-depth is also increased proportionally. Ellis and Aydin (1993) used a sand bed-depth of 1,2 m and a static head of 1,5 m. They reported that an excellent quality of filtrate was achieved in their experiments. In addition, the headloss across the SSF outlet valve also affects the choice of a static head value.

The motivation in designing for a high static head would be to ensure longer filter runs. However, there is no merit in increasing the static head above 1,5 m if the sand bed-depth has to be increased or if the filtrate quality deteriorates. Seelaus *et al* (1986), in realising that a limit in permissible headloss has not been defined, have commented that it is likely to be determined by economic considerations rather than technical ones.

Finally, once the static head has been determined, the walls of the supernatant reservoir must be increased by 200 to 300 mm above the water surface to form a freeboard [Huisman and Wood, 1974].

#### 3.2.2.5 Filter bed

Although any inert, granular material can be used as the filter medium, sand is usually selected because it is cheap, inert, durable and widely available. When placed in the filter, the sand should be free from clay, soil and organic matter.

The filter medium is described in terms of its effective size and uniformity coefficient. The International Reference Centre for Community Water Supply and Sanitation [Visscher *et al*, 1987] recommends an effective sand size in the range of 0,15 to 0,30 mm and a uniformity coefficient lower than 5 but preferably below 3. The WHO [Huisman and Wood, 1974] recommends an effective sand size in the range 0,15 to 0,35 mm and a uniformity coefficient below 3. The WHO goes on to mention that a uniformity coefficient of less than 2 is preferable, but there is little advantage, in terms of porosity and permeability, in the sand having a uniformity coefficient below 1,5 if additional cost is thereby incurred. In fact, Vaillant (1981) specifically recommends a uniformity coefficient in the range of 1,8 to 2,5. A profile of South African silica sand, investigated by Ceronio and Haarhof (1994), indicates that the above specifications for SSF media can easily be maintained in South Africa.

The zone in which purifying bacteria exist is usually 300 to 400 mm thick. Below this depth is the mineral oxidation zone, within which the organic materials liberated by the bacterial life-cycle in the upper sand layer are chemically degraded. The thickness of this zone may be between 400 and 500 mm. One should also consider the filter cleanings by the removal of 20 mm of sand at an average of every 2 months. An allowance of an additional 500 mm of thickness will therefore allow for 4 years of operation before resanding becomes necessary. After taking all these considerations into account, Huisman and Wood (1974) recommend a total filter-bed thickness of 1 200 to 1 400 mm.

Huisman and Wood (1974) also note that the minimum thickness of the filter-bed should be 700 mm. Visscher *et al* (1987), however, recommend a minimum thickness of 500 mm. Use of a shallower filter-bed, for example a depth of 380 mm [Tanner and Ongerth, 1990] and 480 mm [Ellis and Aydin, 1993], produces relatively poorer water quality than deeper filter-beds. In London, however, SSFs have been operated to a minimum bed-depth of 300 mm [Toms and Bayley, 1988].

Farooq and Al -Yousef (1993) have shown that removal of turbidity and coliform decreased by decreasing the sand depth and/or increasing the sand size. Based on this, they suggest that a sand of coarser size with a deep bed can be used in contrast to finer sand of shallow bed in order to get desired efficiency. Although coarse and fine sand give fairly similar rates of removal, the coarser sand results in longer filter run times. In addition, Tanner and Ongerth (1990) have shown that a sand with a high uniformity coefficient i.e. 6,8 leads to low porosity and thus an increase in the frequency of filter cleanings (38 filter cleanings were required in 1 year).

#### 3.2.2.6 Under-drainage system

The under-drainage system serves the dual purpose of supporting the filter medium and of providing an unobstructed passageway for the treated water. This system is therefore made up of a filter bottom or drain and a gravel support system. For example, in a piped system, the lateral drains consist of porous or perforated unglazed drainage tiles, glazed pipes laid with open joints, or perforated pipes of asbestos cement or polyvinylchloride, covered with layers of gravel of successfully diminishing grain size to prevent the intrusion of the filtering medium [Huisman and Wood, 1974]. In small systems the main drain may also be constructed of pipes, but in large filters it is commonly made of concrete. Figure 3.3 [USAAID, 1982b] illustrates two examples of filter bottoms made up of bricks and concrete respectively and Figure 3.4 [USAAID, 1982a] illustrates a schematic diagram of a typical 4 layered filter support system.

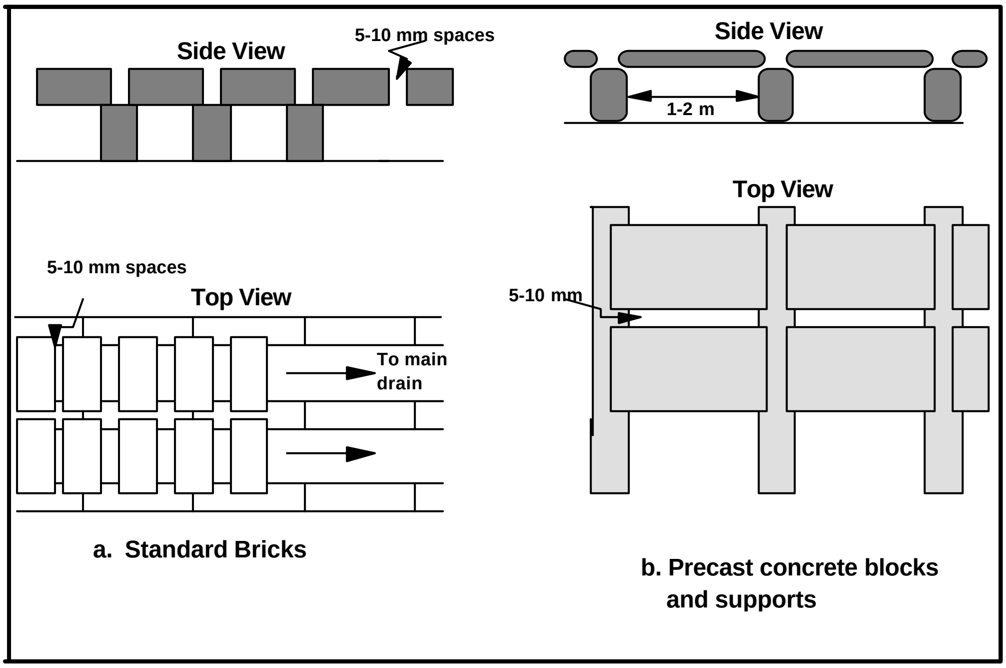


**Figure 3.3: Filter bottoms made up of bricks and concrete**

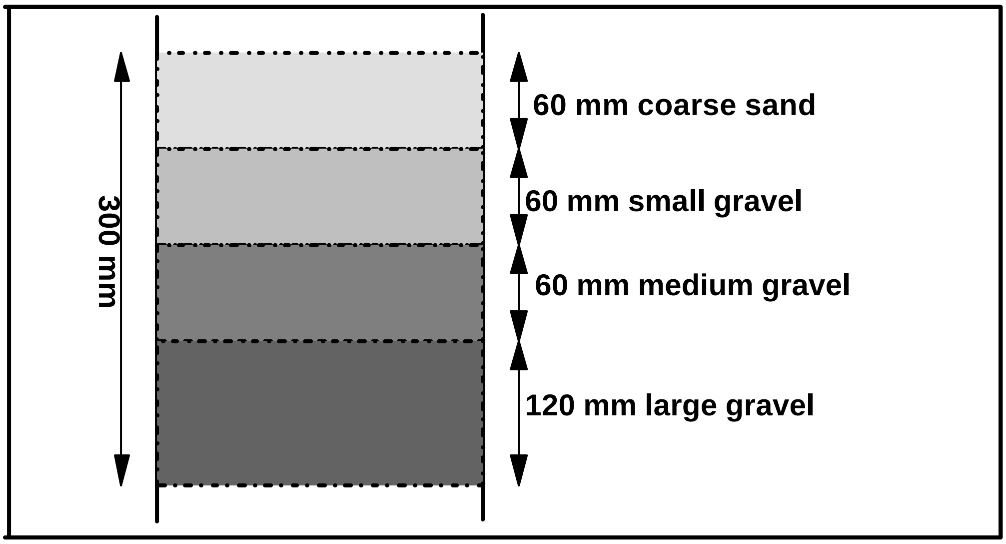


**Figure 3.4: Filter support system made up of four gravel layers**

Huisman and Wood discuss the design of an under-drainage system in more detail than other authors. They recommend that, after a sieve analysis of each supporting gravel layer, the 10 % ($d_{10}$) and 90 % ($d_{90}$) passing diameters should differ by a factor of not more than the square root of 2 i.e. 1,41. The gravel of the bottom layer should have an effective diameter of at least twice the openings into the filter bottom e.g. the spacings between the bricks in Figure 3.3. Each successive layer should be graded so that its smaller particle diameters ($d_{10}$) are not more than 4 times smaller than those of the layer immediately below. The uppermost layer of gravel must be selected with a $d_{10}$ value more than 4 times greater than the $d_{15}$ value of the coarsest filtration sand and less than 4 times greater than the $d_{85}$ value of the finest filtration sand.

One should, however, note that if a porous concrete bottom (Figure 3.3) is used, then only one layer of gravel support, 1,2 to 2,4 mm particle size [Huisman and Wood, 1974], is required. Williams (1986) also mentions a single layer of gravel, but, with a layer of commercial drainage fabric (e.g., Bidim) between the gravel and filter sand. This option still needs to be tested in practice. Ellis (1989) mentions that it is possible to use 3 layers of gravel instead of 4 layers. Visscher (1990) makes mention of an underdrain system in Columbia, where corrugated polyvinyl chloride pipes of 60 mm diameter are placed 1 000 mm apart and covered with a 100 mm layer of fine gravel. Here too, the need for graded gravel is reduced and the total height of the filter box is some 300 mm lower.

Traditionally, the thickness of each layer should be at least 3 times the diameter of its largest stones, however for practical purposes the minimum thickness of the layers is usually increased to 50 to 70 mm for the finer material and to 80 to 120 mm for the coarser gravel [Huisman and Wood, 1974]. Visscher *et al* (1987) mention that the thickness of the entire underdrain system may range from 300 to 500 mm, although its depth will be smaller if corrugated pipes are used.

Although one of the purposes of the underdrain system is to allow unobstructed passage of filtered water, a severely clogged filter can take days to drain through the system. Therefore Tanner and Ongerth (1990) recommend that drains should also be installed above the filter sand bed to facilitate draining of the bed for cleaning.

#### 3.2.2.7 Filter box

The total dimensions of the filter box can be obtained by considering the dimensions of the filter bed, supernatant reservoir and under-drainage system. The USA Agency for International Development [USAAID, 1982b] and the International Reference Centre for Community Water Supply and Sanitation [Visscher *et al*, 1987] have given numerous practical tips on the construction of a SSF. Table 3.2 below is a summary of a SSF design.

**Table 3.2: Slow Sand Filter Design [USAAID, 1982b]**

| Description | Units | Design Limits | Technical Note Example |
|---|---|---|---|
| Area per filter bed | $m^2$ | 10 - 100 | 26 |
| Number of filter beds | m | Minimum 2 | 2.00 |
| Water level height in filter | m | 1 - 1,5 | 1,2 |
| Depth of filter bed | m | 1 - 1,4 | 1,2 |
| Depth of underdrain system | m | 0,3 - 0,5 | 0,46 |
| Spacing of laterals in drain | m | 1 - 2 | 1,5 |
| Size of spaces in laterals | mm | 2 - 4 | 3.00 |
| Distance between spaces in laterals | m | 0,1 - 0,3 | 0.15 |
| Filtration rate | m/h | 0,1 - 0,2 | 0,1 |
| Filter box height | m | 2,5 - 4 | 3.11 |

SSFs consist of either a stiff box made from reinforced concrete, mass concrete, masonry, brickwork or ferrocement, or an excavated structure with protected sloping walls [Visscher *et al*, 1987]. Earth berms with elastomeric liners was used successfully in Oregon to minimise capital costs [Leland and Damewood III, 1990]. Most small to medium-sized SSFs can be constructed using local labour and materials as long as good supervision is available [USAAID, 1982b]. Larger filters should only be built if an engineer or a person experienced with filter construction is available for technical support.

Visscher *et al* (1987) mention that filters with vertical walls may be circular or rectangular in shape, but those with protected sloping walls are usually rectangular. Circular filters can be used in smaller plants and can be constructed of masonry (natural stone, quarry stones or bricks), ferrocement or reinforced concrete. Reinforced concrete has the disadvantage of requiring complicated formwork. Circular filters have structural advantages, such as uniform compressive or tensile stresses and limited bending moments in the wall, and these can result in the economic use of materials.

The piping and valves in rectangular filters are easily accessible and future extensions can be incorporated easily [Visscher *et al*, 1987]. Provided the necessary skills are available, rectangular filters are usually constructed of reinforced concrete, but smaller units may also be built in mass concrete or masonry. Smaller rectangular units have the advantage of ensuring watertight construction. In addition, shrinkage of concrete and masonry, differential settlements, and temperature stresses which depend on the span of the walls, are less in smaller units.

Short circuiting of the water along the inner wall face, especially in small units with vertical walls, without passing through the filter-bed endangers the purity of the effluent. In order to eliminate wall effects it is necessary either to roughen the walls at the sand level or to ensure that the drainage system is at least 600 mm from the walls [Ellis, 1989]. However, the latter method decreases the filtration area and is rarely used. The most effective precaution is to give the walls a slight outward batter, so as to obtain the advantages of sloping walls, and to use grooved and roughened surfaces [Huisman and Wood, 1974]. Roughening the surface of the walls, for example, can be carried out by painting the walls with cement milk and covering it with a film of coarse sand [Visscher *et al*, 1987].

In India, the filter box, in the form of a packaged SSF, has been used successfully [World Water, 1986]. The need for gravel has been eliminated through the use of disc-type strainers. Wall effects or short circuiting is also a common disadvantage of package plants and pilot plants. The walls effects of the filtration process in a pilot plant will have to be small to ensure reliable scale-up. Lang *et al* (1993) have suggested that the most common means of achieving this objective is to make the diameter of the pilot SSF column large relative to the diameter of the filter media. They recommend a ratio, between filter column and media diameter, of 50 or greater. Collins *et al* (1992), in their pilot filter constructed from a 300 mm diameter PVC pipe, used a 6,4 mm PVC collar which was glued on the interior wall 76 mm below the media surface, to deter sidewall channelling.

#### 3.2.2.8 Filter controls

The function of the outlet control system (see Fig. 3.5) is to regulate the flow of water to the design rate [Ellis, 1989]. Daily or every two days the outlet valve has to be opened a little farther to compensate for the increase in resistance in the filter skin.

Thus, the operator is forced to visit the plant at least every day, otherwise the output will fall [Visscher, 1990].

In an inlet control system the rate of filtration is set by the inlet valve and no further manipulation is required. At first the water level above the sand will be low, but it will gradually rise to compensate for the increasing resistance of the filter skin. Once the level has reached the scum (or overflow) outlet, the filter is taken out for cleaning.

Leland and Damewood III (1990) recommend the use of inlet flow control rather than outlet flow control schemes, especially for small systems. Huisman and Wood (1974), however, recommend an outlet control system. Inlet control simplifies operational procedures since no daily flow adjustments are required. In addition, the build-up of resistance in the filter skin is directly visible. The operator is able to monitor the headloss across the filter by observing the increasing depth of water over the top of the filter surface. On the other hand, the water is retained for a shorter period of time at the beginning of the filter run because of the shallow depth of the supernatant water level [Visscher, 1990]. Also, the low level complicates the removal of scum and algae [Visscher *et al*, 1987] which would normally be removed through the overflow outlet. Huisman and Wood (1974) offers the argument that even under the most careful working conditions it is possible for sudden changes in supernatant level to cause changes in filtration rate. For example, in rapid filtration, with the filtration rate in the region of 5 to 10 m/h, a change in water level at a rate of 0,1 m/h would change the filtration rate by a mere 1 to 2 % which is negligible, but in SSF, with the filtration rate as low as 0,1 to 0,2 m/h, it would alter the filtration rate by 50 to 100 %. If this change was in the form of a consequent filtration rate increase then a deterioration in filtrate quality will result.

A more accurate control valve in a pipeline is a butterfly valve because it is quick acting and allows for better control of the flow rate [USAAID, 1982b; Visscher *et al*, 1987]. In fact, Huisman and Wood (1974) mentions the use of a float-controlled butterfly valve to maintain raw water level. Visscher *et al* (1987) recommend the use of a gate valve for rural areas in developing countries because of their simplicity. With the gradual changes in the filtration rate of a SSF, a manually controlled gate valve, in an outlet control system, will suffice [Huisman and Wood, 1974]. On the other hand, the outlet weir and control valve may be combined with a single and very simple unit consisting of a pair of telescopic tubes, the inner of which can be raised and lowered to adjust the rate of filtration. Tanner and Ongerth (1990) reported on an outlet control system using a solenoid valve actuated by a mercury float switch located in the clean water reservoir. This system caused the filters to operate intermittently, turning the filters on and off according to demand. Although the filtration rate could be adjusted manually by means of a butterfly valve, the use of solenoid valves was not recommended by the authors because the sudden changes in filtration rate, due to the on-off control, caused a deterioration in filtered water quality.

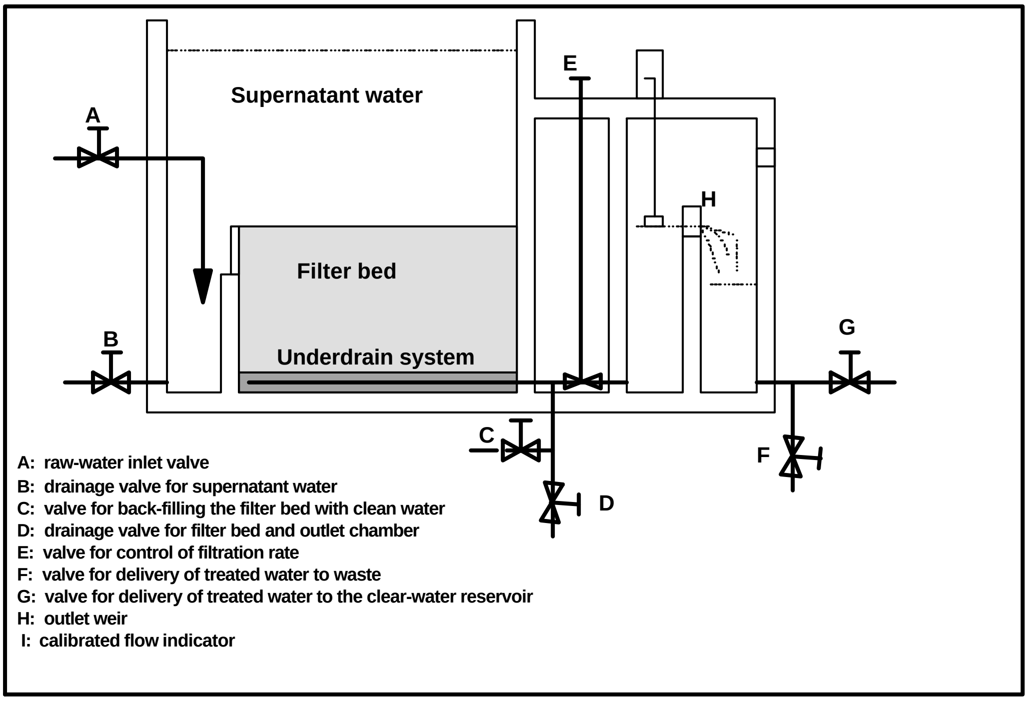


**Figure 3.5: Basic components of an outlet controlled slow sand filter**

### 3.2.2.9 Covering

Covering of SSFs is necessary, especially for filters constructed in areas of temperate or cold climates and subtropical climates. Filters that are vulnerable to windborne contamination, bird droppings [Schellart, 1988] and flying insects [Phillips *et al*, 1985] should also be covered.

An insulated covering is generally recommended for SSFs that are constructed in cold climates [Huisman and Wood, 1974]. Huisman and Wood (1974) mention the use of concrete roofs covered with soil. Soil, when heavy, requires an expensive load bearing roof. In addition, wet soil has poor insulation properties. Therefore concrete roofs covered with soil are not used anymore. Seelaus *et al* (1986) and Tanner and Ongerth (1990) have both reported on filter designs that use an insulated covering to prevent ice damage or freezing of filters.

In tropical or subtropical climates the exclusion of sunlight only may be needed [Huisman and Wood, 1974]. Therefore a less solid structure will suffice. Huisman and Wood (1974) have mentioned the use of grass matting, placed on bearers immediately above the water level and having small sections easily lifted for inspection. The major reason for covering in these type of climates is to prevent the growth of algae caused by sunlight penetration. Both Seelaus *et al* (1986) and Schellart (1988) have reported that coverings can successfully prevent algae growth. However covering will not alone be sufficient if algal blooms have already developed in raw waters [Visscher *et al*, 1987].

Additional benefits of SSF covering have been reported by Schellart (1988), who has investigated the use of filter covering in more detail. Some of these additional findings are as follows:

i) No faecal contamination of birds and therefore no introduction of coliforms, pathogenic micro-organisms, fertilising nitrogen and phosphorous compounds.
ii) Much lower cleaning frequency (longer filter runs) and thus much higher capacity all year round.
iii) Higher filtration rates possible and thus lower filtration area and building expenses.
iv) Rather constant and high oxygen concentration in the filtrate.

Visscher *et al* (1987) also mention that the use of covering to increase filter run length. Vaillant (1981), too, reported on work performed on a SSF that indicates that the filtration rate could be increased considerably. Phillips *et al* (1985), in addition to confirming the decrease in algal growth in the filter and the subsequent longer filter runs, have estimated that filter covering could decrease annual labour costs by 25 %.

# 4 THE PILOT PLANT

## 4.1 GENERAL DESCRIPTION OF PILOT PLANT

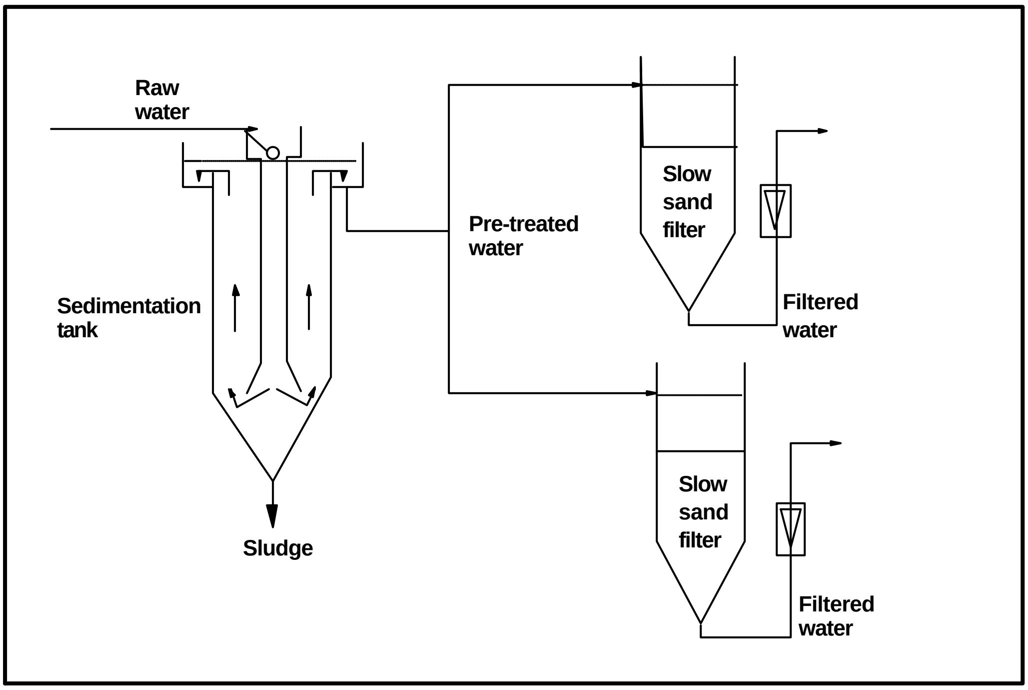


**Figure 4.1: Schematic of plain sedimentation-slow sand filtration pilot plant**

The plain sedimentation-SSF pilot plant comprises a plain sedimentation tank followed by two SSFs (see Fig. 4.1). The design and operating parameters of the SSF are similar to previous pilot plant studies e.g. Collins *et al* (1992). Table 4.1 shows the design and operating parameters of the plain sedimentation-SSF pilot plant used in the present study.

The raw water is pre-treated by means of a cylindroconical plain sedimentation tank, which separates silt and suspended matter from the water. The sludge is drained from the bottom of the plain sedimentation tank on a regular basis. The overflow, referred to as pre-treated water, from the plain sedimentation tank is fed to two SSFs where one is operated as a control filter and the other as an experimental filter. The flowrate through each SSF is adjusted by a manual diaphragm valve on the outlet of each filter and measured on a variable area flowmeter (rotameter).

**Table 4.1: Plain sedimentation and slow sand filter design / operating parameters of present study**

| Parameter | Units | Specification (per filter) |
|---|---|---|
| **Plain sedimentation step:** | | |
| Upflow rate | m/h | 0.30 |
| Annulus area | ($m^2$) | 0.15 |
| Detention time | (h) | 6.67 |
| **Filtration step:** | | |
| Filtration area | ($m^2$) | 0.12 |
| Filtration rate range | (m/h) | 0.1 to 0.3 |
| Nominal capacity | ($\ell$ /h) | 10 to 30 |
| Recommended terminal head loss | (m) | 1.90 |

## 4.2 DESCRIPTION OF CYLINDROCONICAL TANK

A cylindroconical plain sedimentation tank, made of PVC, was designed for the pre-treatment stage since this type of plain sedimentation tank can handle small flows [Degremont, 1991]. The inlet energy is dissipated by means of a draft tube. A diffuser was incorporated into the draft tube to decrease the velocity of raw water from 15 m/h to 0,5 m/h, when it enters the annulus. The annulus was designed to ensure an upflow velocity of 0,3 m/h which is less than half of the expected settling velocity (assuming a density of soil particles to be 1121,4 kg/$m^3$) of 0,8 m/h [CSIR, 1981]. V-notch weirs were installed around the circumference of the tank since they accommodate variations in flow. To ensure easy sludge removal a 40$^o$ conical bottom was fitted into the tank [Degremont, 1991]. The plain sedimentation process was not aided by coagulants or flocculants.

## 4.3 DESCRIPTION OF SLOW SAND FILTER

Two SSFs were installed in parallel to ensure continuous operation and to test different operating variables. Both SSFs were each 2 850 mm high and 400 mm in diameter. Collins *et al* (1992) and various papers in Graham (1988) have similar designs of a SSF. For example, Collins *et al* (1992) used a SSF constructed from a 300 mm diameter schedule-40 grey PVC pipe. A 6,4 mm PVC collar was glued onto the interior wall 76 mm below the media surface to deter sidewall channelling. In the design used at Umgeni Water's Process Evaluation Facility, a 20 mm wide, 10 mm thick PVC collar was fixed to the interior wall about 100 mm below the sand surface.

The various components of the SSF were as follows:

i) A 1 400 mm deep supernatant reservoir, the principal function of which was to maintain a constant head of water above the filter medium, provided the driving force that carried water through the filter. Settling also took place here.

ii) A bed of filter medium containing 0,3 mm sand particles which was a 1 000 mm in depth.

iii) An under-drainage system with the specifications listed in Table 4.2.

iv) A float control in the sedimentation tank maintained a constant reservoir level.

**Table 4.2: Slow sand filter under-drainage system**

| | **Depth (mm)** | **Gravel size (mm)** |
|---|---:|---:|
| Layer 1 (Top) | 60.00 | 0,8 - 1,5 |
| Layer 2 | 60.00 | 2,0 - 4,0 |
| Layer 3 | 60.00 | 5,0 - 12,0 |
| Layer 4 (Bottom) | 60.00 | 15,0 - 30,0 |

No calibrations were required for the operation of the SSFs. The rotameters had to be adjusted to their respective flowrates which decreased as the pressure drop in the SSF increased.

# 5 ORGANISATION AND ANALYSIS OF DATA

## 5.1 TESTING PROTOCOL

Turbidity, microbiology, filtration rates, cycle times, iron, manganese and colour were monitored. Turbidity and microbiological sampling were given priority. Iron, manganese, colour and algae were monitored randomly.

Turbidity and microbiology were monitored daily (weekdays only) and weekly respectively. Turbidity was chosen as an overall performance parameter because it covers all suspended solids (including biological and microbiological solids). More practically, turbidity measurements were easily performed since the facilities were available on site, at the Umgeni Water Process Evaluation Facility in Durban, unlike equipment for the measurement of the other parameters which were located 80 km away in Pietermaritzburg. The time lag between sampling and analysis for turbidity measurement was therefore minimal. The time lag between sampling and analysis for the other parameters such as microbiology was as much as 24 hours. All analyses were carried out in accordance with Standard Methods for the Examination of Water and Wastewater [American Public Health Association, 1985].

The raw water quality was an uncontrolled parameter in the SSF pilot plant. However, since there were 2 SSFs, the effect of filtration rate was monitored by using one filter as the control filter and the other as an experimental filter.

## 5.2 CRITERIA USED FOR ANALYSIS

The criteria used for analysis is divided broadly into aesthetic, health and operating criteria. The potable water quality guidelines of the DOH (1994) were used to measure the performance of the plain sedimentation -SSF pilot plant with respect to the aesthetic and health criteria. It was decided to analyse the performance of the plain sedimentation tank and SSF with respect to the respective NHR and IHR ranges (see Tables 2.1 and 2.2) only. Thus this study represents a conservative analysis of the performance of plain sedimentation and SSF. Although the LHR of the pre-treated and filtered waters is not discussed, it is nevertheless indicated in this study.

Filtration rate was the main parameter used to determine the effect of operating criteria.

### 5.2.1 Aesthetic criteria

The aesthetic criteria can be used as a tool to get a first impression of the water quality. A very poor aesthetic water quality is often an indication that the water may also not be very healthy. The aesthetic criteria was listed in Table 2.2 in Section 2.2.3. Turbidity monitoring was used as a general measure of the performance of plain sedimentation and SSF with respect to the aesthetic criteria.

#### 5.2.1.1 High raw water and pre-treated water turbidity

The high raw and pre-treated water turbidity is generally a function of the type of raw water source. In this study high raw and pre-treated water turbidity was mainly represented by Umgeni river water.

The grouping of the turbidity data according to high raw and pre-treated water turbidity was done to:

i) investigate the performance of both the plain sedimentation tank and the SSF under high turbidity conditions.
ii) enable one to find the SSF feed water turbidity cut-off point that produces a filtered water of potable quality.
iii) investigate the effect on plain sedimentation and SSF of selecting a river water source.

#### 5.2.1.2 Low raw water and pre-treated water turbidity

The low raw and pre-treated water turbidity is also generally a function of the type of raw water source. In this study low raw and pre-treated water turbidity was the characteristic of Inanda impoundment water.

There was a need to group the data into a separate low raw and pre-treated water turbidity so that:

i) one could confirm all past experimental work discussed in the literature. This was necessary to justify the use of SSF since it is claimed in the literature that SSFs only perform well under conditions of low raw water turbidity (more especially less than 10 NTU) [Wolters and Visscher, 1989; Wegelin, 1988a].

ii) one could investigate the effect on plain sedimentation and SSF of selecting an impounded water source.

#### 5.2.1.3 Other contaminants

The true colour, an indication of the dissolved matter present in the water, was randomly monitored. A high colour in the water is often an indication of a high iron and manganese content. Some of the samples taken for inorganic analysis, viz. iron and manganese, can be used to confirm this.

### 5.2.2 Health criteria

The health criteria was listed in Table 2.1 in Section 2.2.2. Total coliforms, *E. Coli*, *F. Strep*. and SPC at 37 °C and 22 °C were monitored during this study. The microbiological monitoring was performed mainly on the raw and pre-treated waters. Thus only the entire plain sedimentation-SSF train could be evaluated and not the SSF alone. The evaluation of the plain sedimentation-SSF train concentrated mainly on the removal of total coliforms and SPC at 37 °C.

#### 5.2.2.1 Effect of turbidity on microbiological removal

Turbidity, compared to microbiology, is a simple and inexpensive water quality monitoring determinand. On-site turbidity measurements are easily performed. Therefore it will be useful to relate turbidity to microbiology. The following were investigated:

i) Raw, pre-treated and filtered water turbidities that result in a filtered water conforming to the DOH's microbiological guidelines, especially total coliforms and SPC at 37 °C.

ii) The effect of raw water source and filter cleaning on the relationship between turbidity and microbiology.

Turbidity was monitored more frequently than microbiologically. Therefore a statistical analysis, of the entire turbidity data set and the turbidity data set that corresponded only to microbiological sampling, was performed. This had to be done to check the validity of relationships between turbidity and microbiology investigated in this study.

#### 5.2.2.2 Microbiological concentration and removal

An attempt was made to find the effect of the microbiological concentration, of the raw water, on the filtered water. This grouping of data was also useful in

i) finding the cut-off point that produces a filtered water of potable quality.

ii) observing the effect of bacterial maturation on the filtered water quality. In effect this was done to investigate the microbiological removal with an increase in filter operating time (or the age of the filter bed).

iii) observing the effect, of raw water source and filter cleaning, on the filtered water microbiology.

#### 5.2.2.3 Biological removal

The biological removal of a SSF was tested by monitoring the algae content of the inlet and outlet water of the SSF pilot plant. The sedimentation tank was uncovered during random periods of the experimental work. This helped to stimulate the growth of algae. This data is therefore useful in testing the effect of an uncovered sedimentation tank or SSF on the performance of the SSF process in terms of biological removal.

### 5.2.3 Filtration rates

Out of the 2 SSFs used during the experiments, one was used as a control filter and the other was used as an experimental filter. The control filter consistently operated at a filtration rate of 0,1 m/h. Filtration rates on the experimental filter were varied from 0,1 to 0,5 m/h. The effect of filtration rates on water quality and SSF operation was studied.

### 5.2.4 Filter cleaning

The effect of the *schmutzedecke* removal, or the filter cleaning process, on the quality of filtered water produced by the SSF was analysed.. The effect of raw water source on filter cleaning was also observed. This was done by comparing turbidity and microbiological results of the filtered water for the following cases:

i) The *Umgeni* and *Inanda filtered water* microbiological and turbidity results during *filter recovery* i.e. the period of *schmutzedecke* regrowth after filter cleaning.

ii) The *Umgeni* and *Inanda filtered water* microbiological and turbidity results after *filter recovery* i.e. during *normal filtration*.

The effect of filtration rate on the frequency of filter cleaning was also studied.

### 5.2.5 Time lag

The sampling procedure did not take into account the time lag created by the residence times of the plain sedimentation tank and SSF. The average residence times of the plain sedimentation tank was 10 h. The average residence time of the SSFs ranged from 6 to 12 h. Sampling of the raw, pre-treated and filtered water was only performed within 10 minutes apart. Therefore the effect of time lag on sampling was also investigated.

# 6 EXPERIMENTAL RESULTS AND DISCUSSION

An attempt, similar in concept to the disturbance variables often mentioned in control theory (Stepanopoulos, 1984), is made to analyse the performance of SSF by eliminating those factors that can disturb its performance. The three factors that affect the performance of SSF are:

i) the effect of the raw water turbidity.
ii) the effect of filter cleanings or *schmutzedecke* removal.
iii) the effect of filtration rate.

The effect of raw water turbidity, although dampened by the plain sedimentation pre-treatment step, cannot be eliminated totally.

The effect of filtration rate was eliminated by maintaining it reasonably constant in the control filter, SSF2, operated at 0,1 m/h. The experimental filter, SSF1, operated from 0,1 to 0,5 m/h, was used to test the effect of higher filtration rates on filtered water quality and SSF operation.

It was difficult to relate all the variables into a single discussion. The discussion in this chapter therefore first combines raw water quality, raw water source and filtered water quality. The latter part of the discussion is about the effect of filtration rates on filtered water quality and SSF operation. Thus the approach to the overall discussion is somewhat linear in format.

The sampling of the raw, pre-treated and filtered water was performed within a period of 10 minutes apart. Therefore the effect of the time lag, due to the residence time of the SSFs and sedimentation tank, on sampling is first discussed in Section 6.1.

The aesthetic water quality aspects are discussed in Section 6.2. This section, concentrates mainly on turbidity removal with a brief discussion on iron (Fe), manganese (Mn) and colour removal in the SSF pilot plant. The length of the *filter recovery* period for SSF2 with respect to turbidity removal and raw water source is also investigated in Section 6.2. *Filter recovery* is the period taken for the redevelopment of the *schmutzedecke.* The redevelopment of the *schmutzedecke* is necessary after filter cleaning which involves removal of the upper 20 to 30 mm of sand. The effect of filter cleaning and raw water source on filtered water quality is then addressed in all other sections of this chapter.

The performance of the SSF pilot plant with respect to the health criteria is discussed in Section 6.3. Tests for total coliform bacteria and SPC should always be undertaken since they are practical and sensitive indicators of unforeseen treatment failure or pollution [DOH, 1994]. Therefore this section concentrates mainly on standard plate count (SPC) at 37 °C and total coliform removal by the SSF pilot plant. In addition, the removal of SPC at 22 °C, *E. Coli, F. Strep.* and algae are discussed briefly. The length of the *filter recovery* period with respect to microbiological removal and raw water source is also discussed in this section. Turbidity sampling was performed more frequently than microbiological sampling. This section therefore includes a statistical comparison between turbidity and microbiogical sampling.

Lastly, the effect of filtration rate and upflow rate on the performance of the SSF and sedimentation tank respectively is discussed in Section 6.4.

## 6.1 THE EFFECT OF TIME LAG, DUE TO RESIDENCE TIME, ON SAMPLING

The sampling schedule did not give any consideration to the effect of the time lags created by the residence times of both the sedimentation tank and the SSFs on the passage of raw water through the system. The raw, pre-treated and filtered waters were sampled within a period of 10 minutes apart. This was not deliberate but can be attributed to an oversight during the early part of the experimentation. Therefore it is appropriate, before going into the detail analysis of the data, to determine the effect of the time lags due to the residence time in the sedimentation tank and SSFs on sampling. Figure 6.1 shows a schematic diagram of the plain sedimentation-SSF pilot plant.

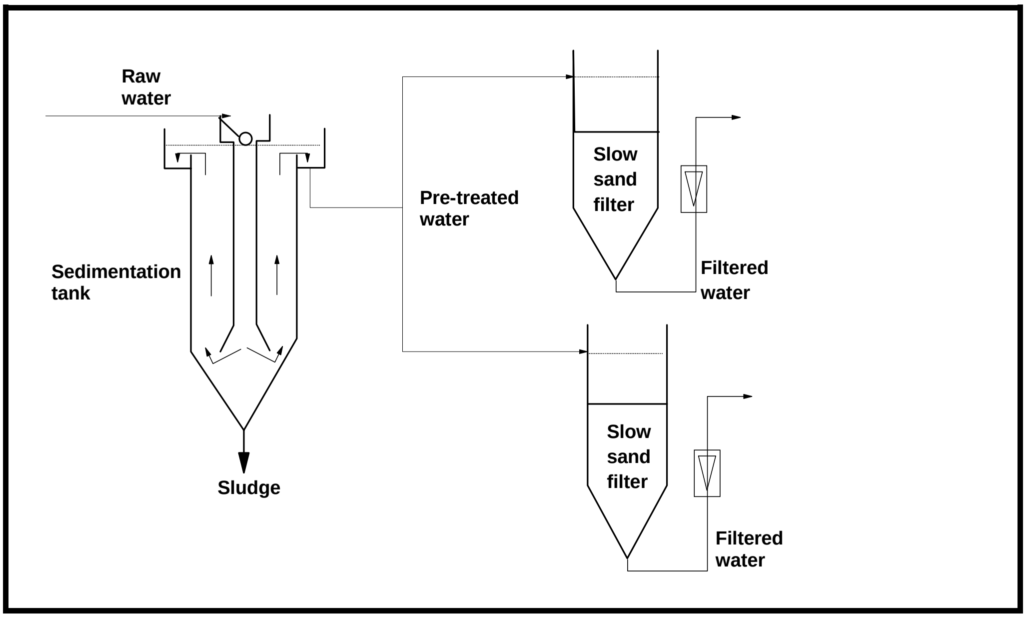


**Figure 6.1: Schematic of plain sedimentation-slow sand filter pilot plant**

The average residence time, assuming plug flow, of the sedimentation tank was 10 h. The average residence time of SSF1 was 6 h whilst that of SSF2 was 12 h. The total residence time from the point of entry of the raw water to the exit of the filtered water therefore ranged from 16 to 22 h. The residence times indicate that it would have been practical to account for the time lags of the sedimentation tank and SSF2 within an accuracy of +/- 2 h if one had taken the raw water sample at 8h00. The pre-treated water would have then been sampled at 16h00 on the same day and the filtered water at 8h00 the following morning. For SSF1, this type of sampling schedule would have been impractical since the filtered water would then have been sampled between 20h00 to 22h00 the same evening.

Turbidity sampling of the *Umgeni raw water* was performed daily. The *Inanda raw water* was initially sampled daily and thereafter sampling was performed almost weekly. Appendix A, besides showing the sampling frequency, also shows that the *Inanda raw water* turbidity did not vary significantly from day to day. Section 6.3.1.1 also discusses the raw water sampling frequency. Microbiological sampling, although inconsistent, was performed weekly.

In Figs. 6.2 and 6.3 the filtered water turbidity data of SSF2 is used as an example to indicate the effect of neglecting the vessel time lags on the analysis of the results. The filtered water turbidity data, indicated as *without time lag* with respect to *Umgeni raw water,* was rearranged to correspond to the raw and pre-treated water turbidity data of the previous day. This compensates for the effect of the time lag of both the plain sedimentation tank and SSF2 on the filtered water turbidity. However, there is about a 10 h discrepancy when compensating for the effect of the time lag of SSF2 only on the filtered water turbidity. This discrepancy results from the daily sampling of pre-treated water. If SSF1 were considered then this discrepancy would have been approximately 16 h. The turbidity data, indicated as *with time lag*, was not rearranged thus neglecting the effect of time lag.

The effect of the time lag of the SSF would have been neglected if the pre-treated and filtered water results taken on the same day were considered. Alternatively, the effect of time lag of the plain sedimentation tank would have been neglected if the pre-treated water and raw water results taken on the same day were considered. It was decided to opt for the latter case since the focus of this thesis is on SSF.

The data with respect to *Inanda raw water* was not arranged to overcome the effects of time lag since the sampling of this water was not performed daily. However, Figure 6.2 shows that the *Inanda raw water* was treated by SSF2 to almost consistently produce filtered water within the NHRt range. Therefore ignoring the effects of time lag with respect to *Inanda raw water* will not affect the analysis of the SSF results significantly.

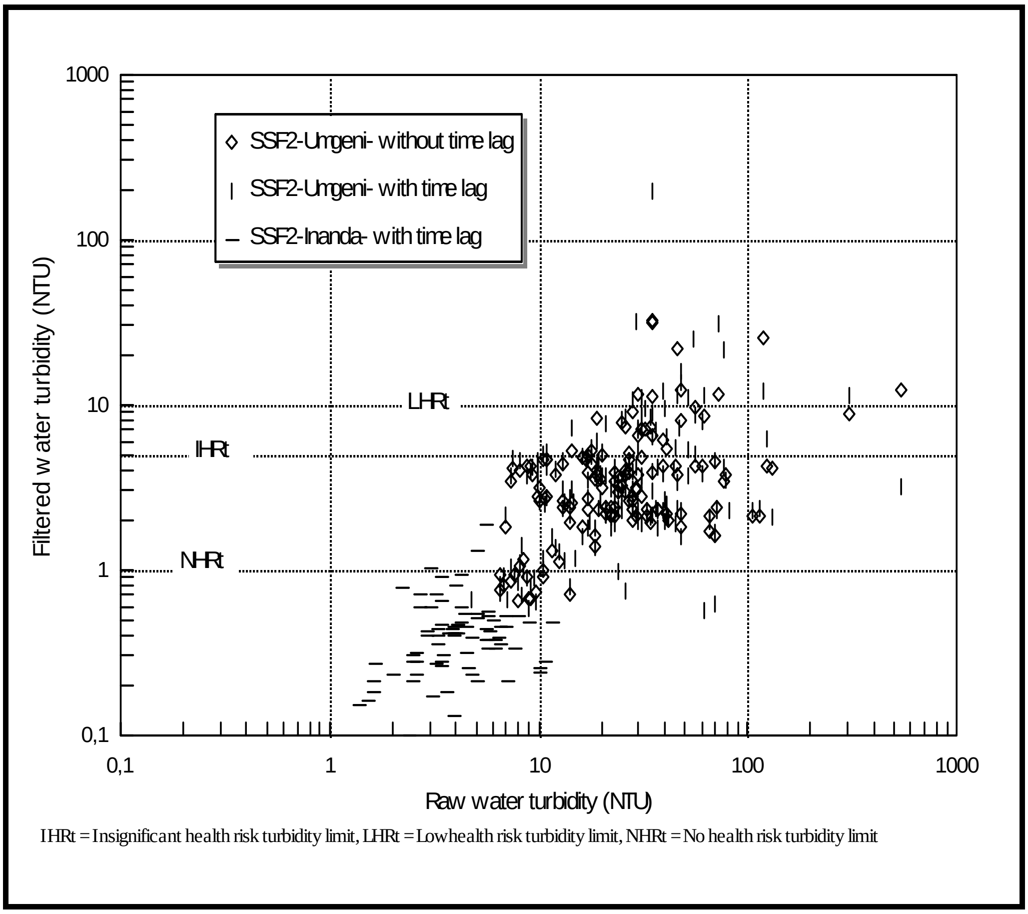


**Figure 6.2: The overlap of filtered water turbidity data showing that total time lag (22 h) of both the sedimentation tank and SSF2 did not affect the analysis significantly.**

The overlap of the filtered water turbidity results of *Umgeni raw water*, in Figs. 6.2 and 6.3, indicate that the analysis of the filtered water turbidity results was not affected significantly by neglecting the time lag caused by the residence times in the sedimentation tank and SSF2. However, neglecting the time lag after treatment of shock loads of raw water turbidity, after heavy rainfall, will affect filtered water results. Note that the Umgeni filtered water turbidity of 200 NTU, occurring after a day of heavy rainfall, does not overlap with other data.

Rearranging the sample data, on every consecutive weekday, to compensate for the vessel time lags will result in the discarding of some data. Therefore all future sections will analyse all the data, thus disregarding the effect of vessel time lag.

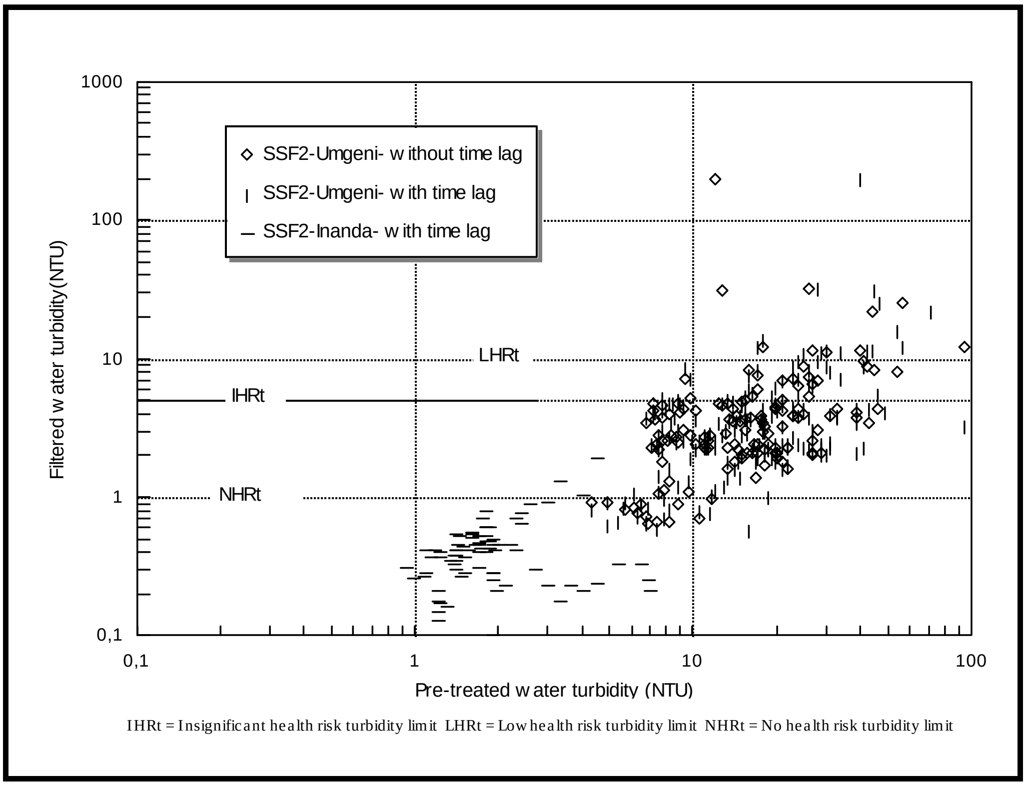


**Figure 6.3: The overlap of filtered water turbidity data showing that the time lag (12 h) of SSF2 did not affect the analysis significantly.**

Figure 6.4, taking SSF2 as the conservative case, indicates that 82 % of the filtered water turbidity differences between two consecutive days are less than 1 NTU. The respective pre-treated and raw water differences are 3,1 and 15 NTU. This possibly explains the overlap of data within the narrow band in Figs. 6.2 and 6.3.

Now it is difficult to confirm the effects of time lag on microbiological sampling since these were, on average, sampled weekly. However, since it was shown in Figs. 6.2 and 6.3 that the vessel time lag did not affect the turbidity results, it is assumed that it did not affect the microbiological results also. The reason being that turbidity is a measure of all suspended solids including microbiological solids.

Section 6.3 which discusses the microbiological content of water, however, looks mainly at the relationship between the microbiological and turbidity content of water. This is because it is easier to relate water quality to a surrogate determinand such as turbidity, which is a simple and more economical method of monitoring water quality, than to microbiological determinands. This is especially valid in a rural area. The statistical fit of the microbiological sample population to the turbidity sample population will also be discussed in Section 6.3.

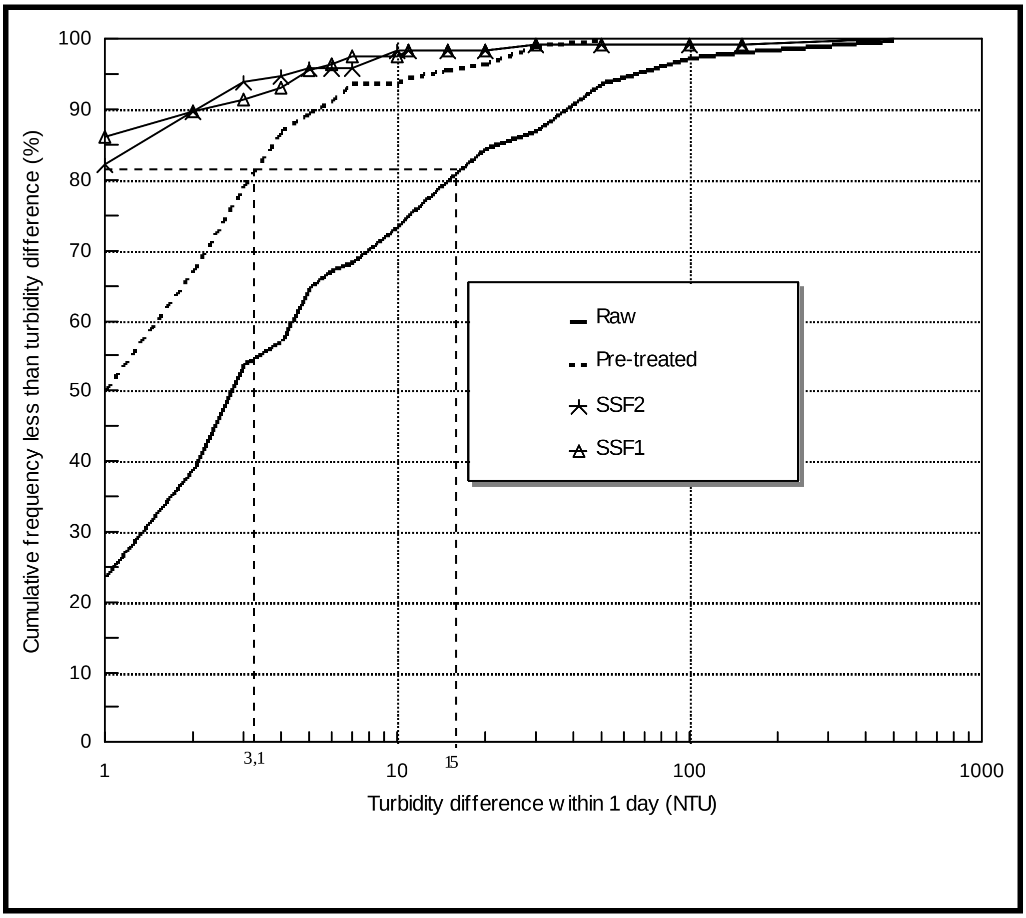


**Figure 6.4: The cumulative frequency distributions, of the turbidity differences of raw, pre-treated and filtered water, between two consecutive days.**

## 6.2 AESTHETIC WATER QUALITY

Most literature sources use the turbidity removed by SSF as a measure of its performance. However, since this study concentrates on the production of potable water, it was decided to assess the performance of SSF with respect to its ability to produce a filtered water quality within the guidelines for potable water set by the Department of Health (see Table 2.1). The raw data is tabulated in Appendix A, Table A1.

### 6.2.1 Turbidity removal

Figure 6.5 summarises all the data regarding turbidity removal. The following general observations were made:

- The turbidity of the *Inanda raw water* was generally lower than *Umgeni raw water*. The SSFs performed well in producing a filtered water of potable water quality after the changeover from *Umgeni raw water* to *Inanda raw water.*
- The pre-treated water turbidity was consistently lower than the low values of raw water turbidity. The *Umgeni raw water* turbidity peaks were significantly reduced by the plain sedimentation tank.
- There is a continual improvement in the filtered water turbidity as time progesses.
- The turbidity of *Umgeni raw water* peaked during spring and summer and then decreased in winter. During the spring of 1993 *Umgeni raw water* peaked at a turbidity 4 000 NTU (see Table A1 or Figs. 6.9 and 6.10 - the raw and pre-treated water turbidities indicated in Figure 6.6 were smoothed). The turbidity of the *Inanda raw water* was not affected significantly by seasonal changes.
- Except for the seasonal influences, some of the turbidity peaks of filtered water corresponded to the period immediately after filter cleaning.
- SSF2 was consistently operated at 0,1 m/h except when it was operated at 0,2 m/h to speed up the filter *ripening* process during commissioning.
- SSF1 was resanded down to 400 mm after 356 d. Both SSF1 and SSF2 were thereafter operated at 0,1 m/h so that the effects of resanding could be noted. Resanding resulted in the *Inanda filtered water* turbidity exceeding the NHRt of 1 NTU. However the *Inanda filtered water* still conformed to the IHRt of 5 NTU.
- After 456 d the filtration rate of SSF1 was increased to within the range of 0,2 to 0,5 m/h to note the effects of high filtration rates on filtered water turbidity. The *Inanda filtered water* turbidity conformed to the NHRt of 1 NTU.

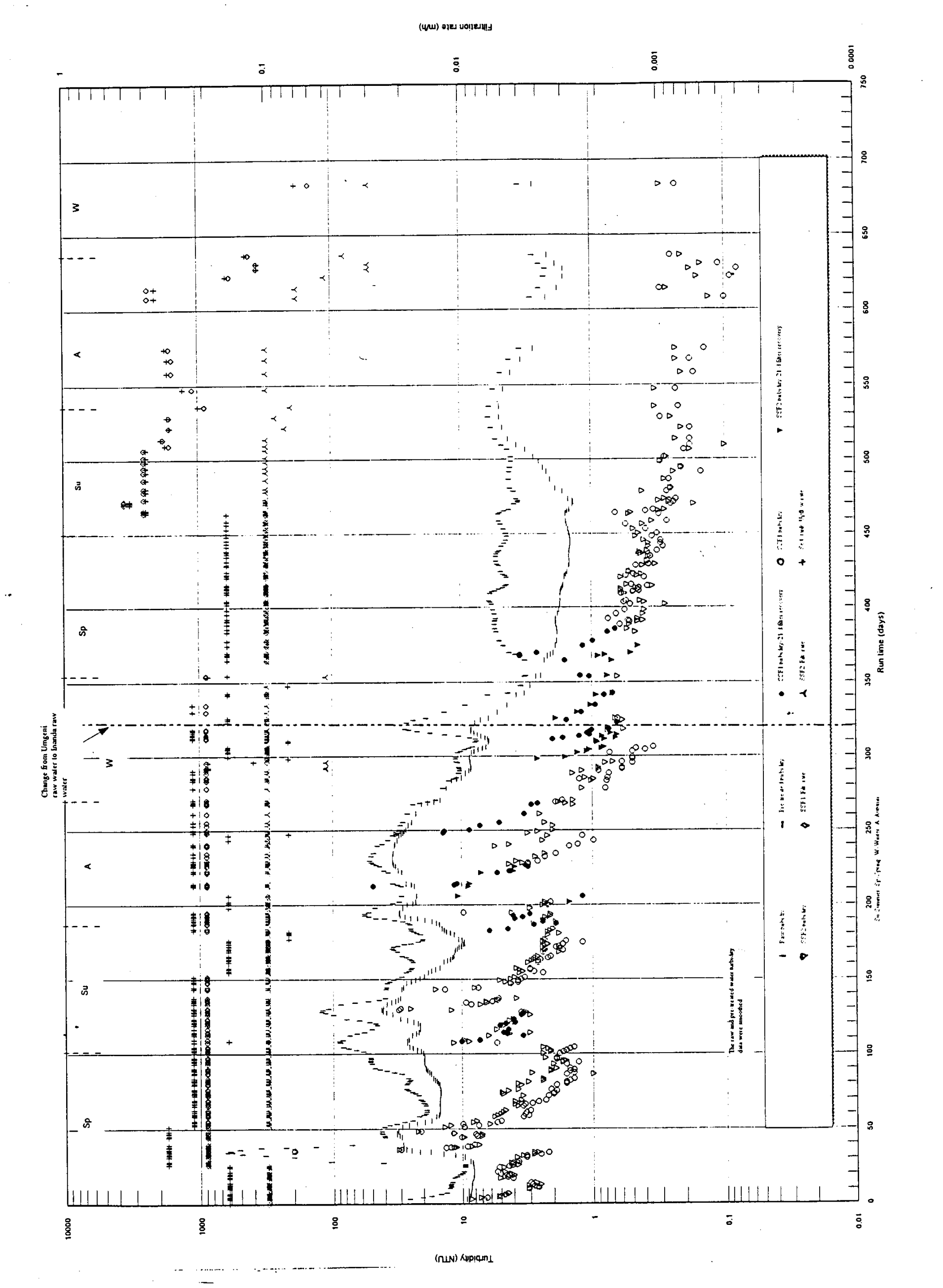

**Figure 6.5: Summary of turbidity removal results also showing the SSF filtration rates and the sedimentation tank upflow rates.**

Figure 6.6 indicates that turbidity removal percentages of over 80 % do not necessarily result in a filtered water turbidity less than the NHRt of 1 NTU. Therefore it was decided, rather than to use turbidity removal percentages, instead to assess the performance of SSF with respect to its ability to produce a filtered water quality within the guidelines for potable water set by the DOH.

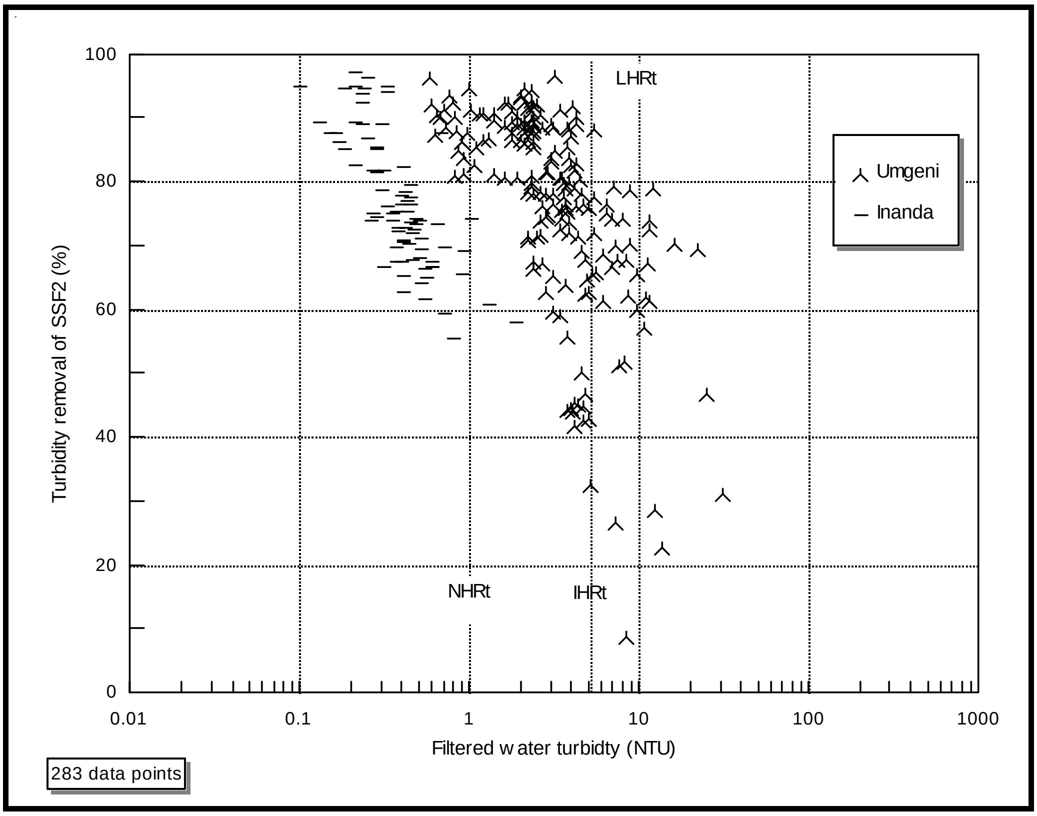


**Figure 6.6: Turbidity removal in SSF2 operated at 0,1 m/h and showing that turbidity removal did not measure the performance of SSF sufficiently with respect to the NHRt range.**

The general trend in turbidity removal indicated decreasing turbidity removal with increasing filtered water turbidity. Of all the raw water turbidity samples, 61 % exceeded a turbidity of 10 NTU during the entire period of experimentation. Section 1.1.1.2 mentioned that the USEPA guide, *Technologies for upgrading existing or designing new water treatment facilities*, recommends that the feed water turbidity to the SSF should not exceed 10 NTU.

#### 6.2.1.1 An investigation into the time taken for *filter recovery* in slow sand filtration with respect to turbidity removal

Now, an attempt is made to analyse the length of *filter recovery* or filter downtime with respect raw water source. Figure 6.7 shows the filtered water turbidity of SSF2 during a 23 d period after filter cleaning. This period was chosen to confirm observations of *filter recovery*, of approximately 21 d, in the literature [Huisman and Wood, 1974]. Filter cleaning involved the removal of the *schmutzedecke.* The *schmutzedecke* usually consisted of 20 to 30 mm of the upper sand media.

The following observations were made:

- The *Inanda filtered water* conformed to the NHRt limit at 9 d after filter cleaning. Note that the turbidity is actually slightly above the NHRt limit and therefore 9 d is a fair approximation.
- The *Inanda filtered water* conformed to the IHRt limit 4 d after filter cleaning. Note, however, that no samples were taken prior to the 4$^{th}$ day. Therefore there is no proof that the *Inanda filtered water* conformed to the IHRt limit before the 4$^{th}$ day.
- The *Umgeni filtered water* conformed to the IHRt limit at 19 d after filter cleaning.

Therefore the following observations on *filter recovery* can be made:

- The *filter recovery* period was 9 d for *Inanda filtered water* to conform to the NHRt limit.
- The *filter recovery* period was 4 d for *Inanda filtered water* to conform to the IHRt limit. However, it is possible that this *filter recovery* period can be less than 4 d.
- The *filter recovery* period was 19 d for *Umgeni filtered water* to conform to the IHRt limit.
- The unacceptably high *filter recovery* period exceeded 21 d for *Umgeni filtered water* to conform to the NHRt limit.

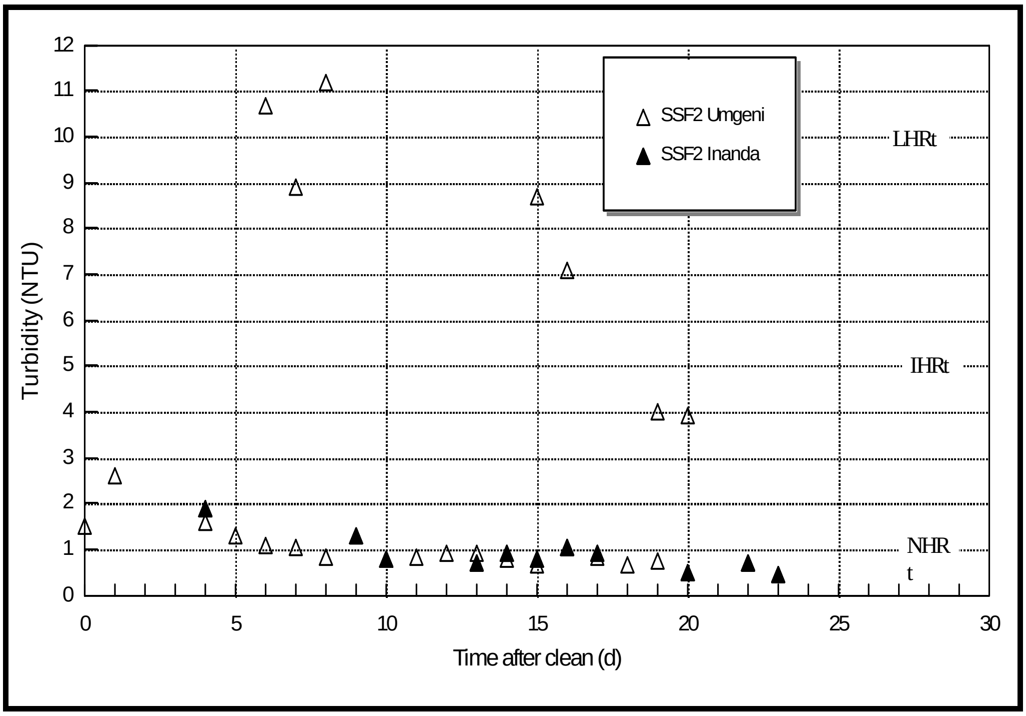


**Fig 6.7: Filtered water turbidity of SSF2, operated at 0,1 m/h, during 21 d after filter cleaning showing the time taken for *filter recovery* and the effect of raw water source**

An estimate of 19 d was used, in the rest of Section 6.2, to simulate the *filter recovery* period with respect to *Umgeni raw water*. Note, however, that the *filter recovery* period, with respect to *Umgeni raw water* and the NHRt limit, exceeded 21 d. Nevertheless, the *filter recovery* period was 19 d with respect to *Umgeni raw water* and the IHRt limit. The discussion on the treatment of *Umgeni raw water* is therefore expected to lead into the acceptability of the respective IHR limits.

#### 6.2.1.2 Overall turbidity removal of plain sedimentation-slow sand filtration train

The plain sedimentation step can be used to simulate a buffer storage tank of raw water.

The following observations were made from Fig. 6.8:

- A raw water turbidity about 4 NTU was consistently treated by the plain sedimentation-SSF2 train to produce a filtered water turbidity conforming to the NHRt limit of 1 NTU.
- A raw water turbidity about 10 NTU was consistently treated by the plain sedimentation-SSF2 train to produce a filtered water turbidity conforming to the IHRt limit of 5 NTU.
- The plain sedimentation-SSF2 train treated raw water turbidities of approximately 8 and 30 NTU to produce filtered water turbidities conforming to the NHRt and IHRt limits respectively, within a 95 % probability.

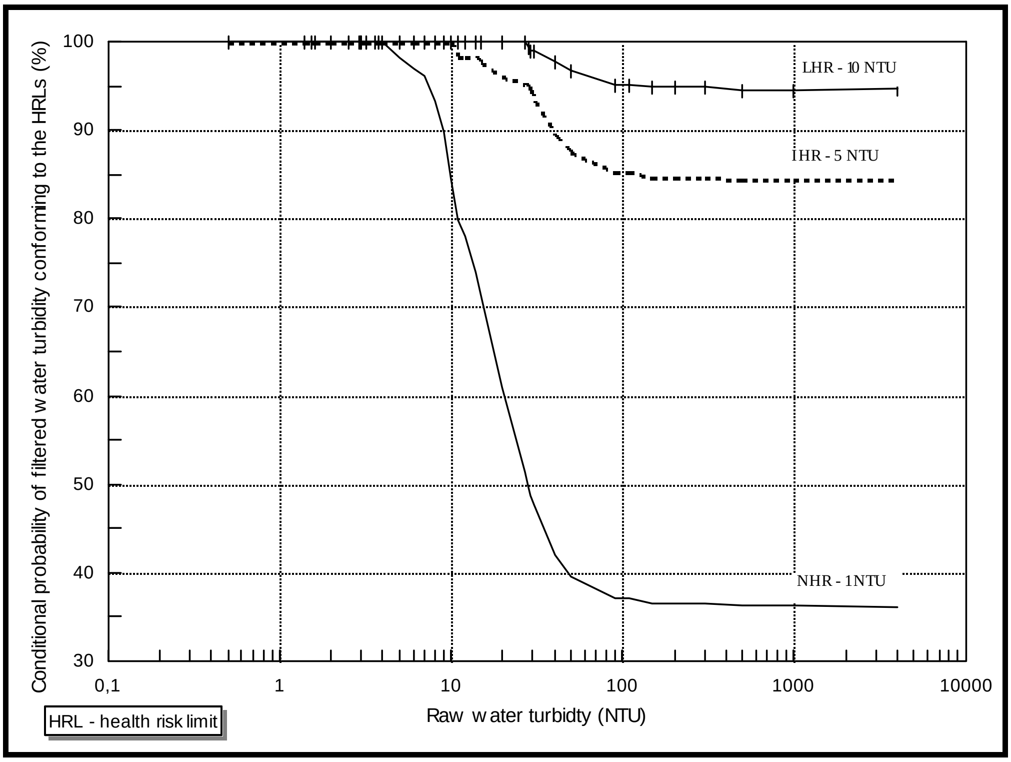


**Figure 6.8: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) turbidity conforming to the HRLs as a function of raw water turbidity**

Figure 6.9 shows the normal probability density function (PDF) distributions of *Inanda raw water* and *Umgeni raw water.* The *Umgeni* and *Inanda raw water* turbidity data did not extend below 6 and 1,5 NTU respectively. Note that the raw water turbidity data spread around three standard deviations from the mean raw water turbidity represent 99,7 % of the total distribution of data in a normal PDF graph. Thus 99,7 % of the raw water turbidity distribution can be used to approximate the total raw water turbidity distribution if the *tails* (low probability tapered ends of a normal PDF graph) cannot be seen clearly from the graphs.

The effect of the skewness can be neglected in approximating the raw water turbidity distribution since the fraction of data in the *tails* is minimal. Note that a positive skewness value indicates a generally higher turbidity than the mean turbidity value i.e. a *heavy turbidity tail*. In addition, a negative skewness indicates a generally lower turbidity than the mean turbidity value i.e. a *light turbidity tail*.

In Fig. 6.9 the *tails* can be seen fairly clearly. One observes that:

- the positive skewness of *Umgeni raw water turbidity* indicates a *heavy turbidity tail.*
- *Inanda raw water* turbidity ranged from 1,5 to 12 NTU with a mean of 4,5 NTU.
- *Umgeni raw water* turbidity ranged from 6 to 4 000 NTU with a mean of 53,7 NTU.

A comparison of the observations from Figs. 6.8 and 6.9 indicates that:

- *Inanda raw water* was more likely to be treated by the plain sedimentation-SSF train to produce a filtered water turbidity conforming to the NHRt and IHRt limits.

The possible reasons why *Inanda filtered water,* compared to *Umgeni filtered water,* conformed to the NHRt and IHRt limits are:

- *Inanda raw water* was lower in turbidity than *Umgeni raw water*. Thus the SSF could handle the solids loading of *Inanda raw water*.
- *Inanda raw water* came on line about 300 d after commissioning of the SSFs. Thus the filter bed maturity could have also contributed to turbidity

removal during the treatment of *Inanda raw water*. The higher bacterial content of a mature SSF bed makes microbiological purification, discussed in Section 3.1.1.2, a plausible mechanism of turbidity removal.

- Absorption onto the sticky gelatinous coating found around the filter bed grains throughout a mature SSF bed is also a plausible mechanism of turbidity removal.

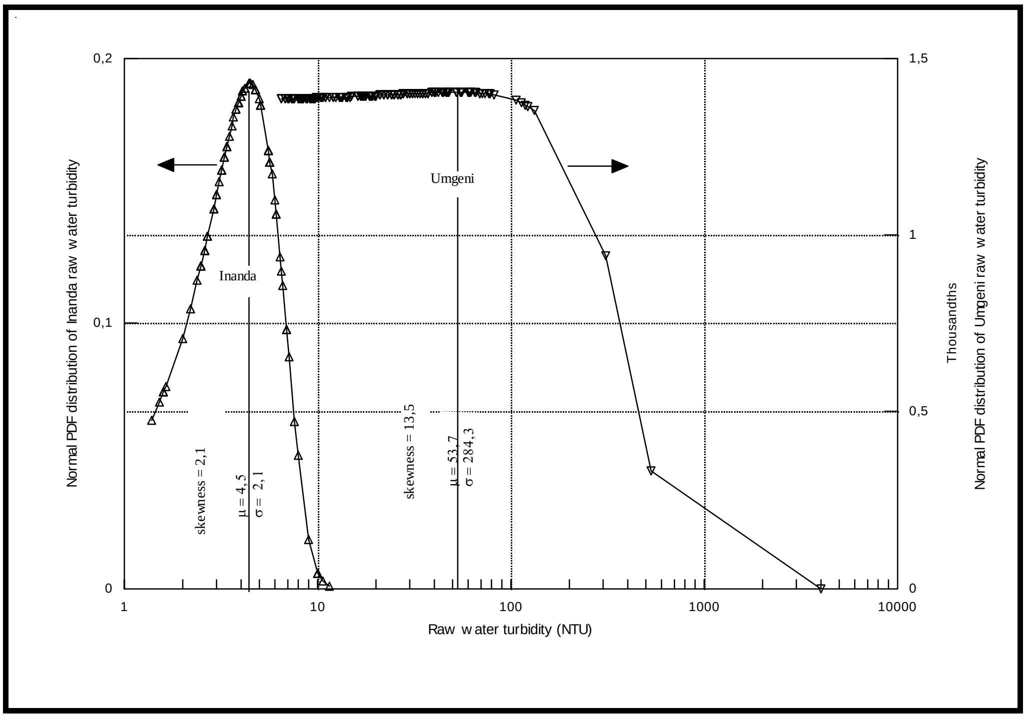


**Figure 6.9: Normal PDF distribution of *Umgeni* and *Inanda raw water* turbidity.**

The observations made from Fig. 6.8 were conservative because the results of turbidity breakthrough during *filter recovery* was included. There was a risk of the SSF not producing potable quality water during *filter recovery*. Therefore

Fig. 6.10 shows the effect of filter cleaning and raw water source on filtered water turbidity.

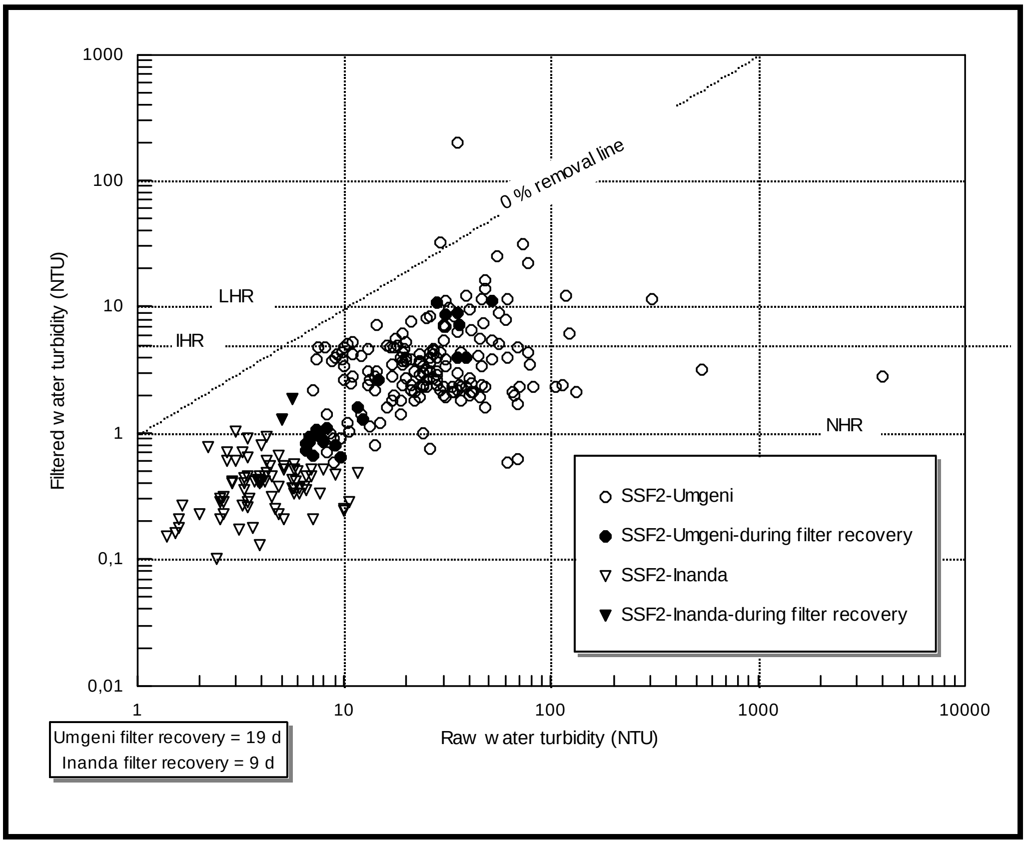


**Figure 6.10: Turbidity removal performance of the plain sedimentation-SSF2 train showing the effect of raw water source and filter cleaning**

In addition to confirming the observations made from Figs. 6.8 and 6.9, the following observations were made from Fig. 6.10:

- *Umgeni raw water* was treated by the plain sedimentation-SSF2 train to produce a filtered water turbidity mainly conforming to the LHRt limit. Figure 6.8 has indicated a 95 % probability of *Umgeni filtered water* turbidity conforming to the LHRt limit for the full range of *Umgeni raw water* turbidity.
- There was an increasing trend of filtered water turbidity with raw water turbidity.
- The *Umgeni filtered water* mainly exceeded the NHRt limit during *normal filtration*. It exceeded the IHRt and LHRt limits to a lesser extent during *normal filtration*. Therefore turbidity breakthrough during *filter recovery*

did not significantly affect the overall *Umgeni filtered water* with respect to all the HRLs.

- *Inanda filtered water* mainly conformed to the NHRt limit. However, turbidity breakthrough during *filter recovery*, caused the *Inanda filtered water* to exceed the NHRt limit. Therefore filter cleaning significantly affected the production of *Inanda filtered water*, with respect to the NHRt limit, by the plain sedimentation-SSF2 train.
- The *Inanda raw water* turbidity, treated by the plain sedimentation-SSF train to produce filtered water conforming to the NHRt limit, would have increased from 4 to approximately 12 NTU if turbidity breakthrough during *filter recovery* had not occurred.

The possible reasons why *Umgeni raw water*, with a turbidity less than 12 NTU, did not produce a filtered water within the NHRt range were as follows:

- There was a significant amount of turbidity breakthrough at *Umgeni raw water* turbidities less than 12 NTU.
- *Umgeni raw water* consists of colloidal material, generally existing in river water. This colloidal material passed through the SSF.
- The sand media of SSF2 during the period that *Umgeni raw water* was on line to the filter was not as mature, throughout its depth, as when the *Inanda raw water* came on line. Bellamy *et al* (1985a) have shown that the maturity of a SSF assists it in producing potable quality filtered water.

The decrease in turbidity removal after filter cleaning indicates that the purification mechanism contributes towards turbidity removal. The bacteria that occupy a mature *schmutzedecke* are also necessary to purify water.

Electrostatic absorption is another plausible mechanism. The relatively clean quartz sand, after filter cleaning, has a negative charge. Therefore this clean sand is unable to absorb matter of organic origin, anions of metals, phosphate and others (Huisman and Wood, 1974).

#### 6.2.1.3 Turbidity removal by plain sedimentation

The observations made from Fig. 6.11 were as follows:

- There was a general increasing trend of pre-treated water turbidity with respect to raw water turbidity.
- There were occasional increases in the pre-treated water turbidity to above that of the raw water turbidity.
- The *Umgeni raw water* peak turbidity of 4 000 NTU was significantly reduced to a pre-treated water turbidity below a 100 NTU. The effect of time lag on sampling was neglected in Fig. 6.11. Thus the pre-treated water turbidity of 13 NTU corresponding to a raw water turbidity of 4 000 NTU was not representative. Section 6.1 indicated that time lag does affect sampling for shock increases in raw water turbidity. Appendix A shows a more representative pre-treated water turbidity of 40 NTU occurring a day after the raw water turbidity peaked at 4 000 NTU.

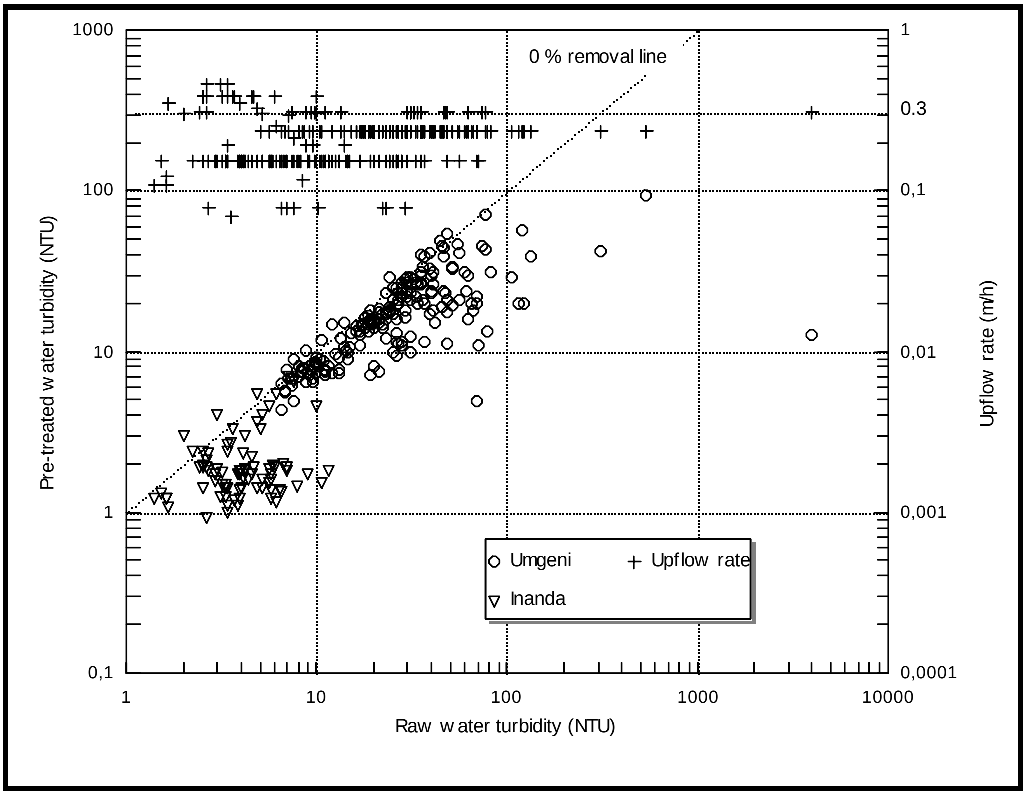


**Figure 6.11: Turbidity removal performance of the plain sedimentation pre-treatment step showing the upflow rates and the effect of raw water source.**

The possible reasons for the increases in pre-treated water turbidity above the raw water turbidity were as follows:

- ○ The upflow rate of the sedimentation tank exceeded its design value of 0,3 m/h with respect to *Inanda raw water*. This occurred when the filtration rate of SSF1 exceeded 0,3 m/h, as already shown in Fig. 6.5 of Section 6.2.1.
- ○ There was colloidal material in the *Umgeni raw water*.

Figure 6.12 shows the following:

- ♦ A general trend of increasing turbidity removal with respect to both *Umgeni* and *Inanda raw water* turbidity. Ahmad *et al* (1984) also observed that the turbidity removal, in a plain sedimentation tank, follows an increasing trend with raw water turbidity.
- ♦ A scatter of data below a raw water turbidity of 100 NTU.

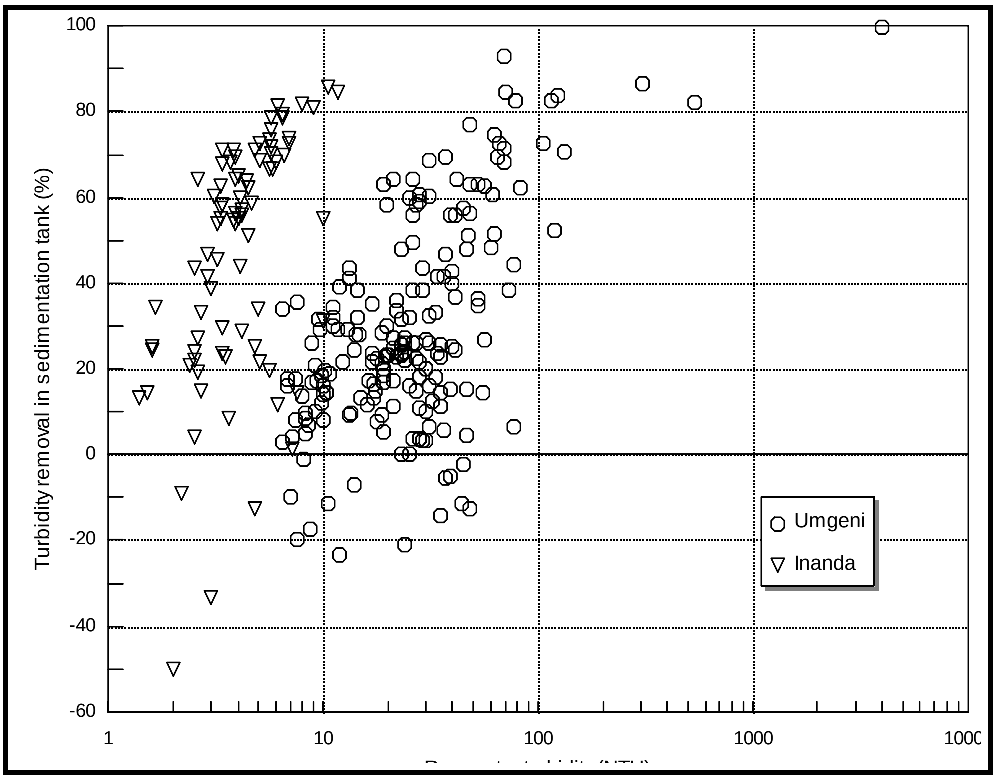


**Figure 6.12: Turbidity removal of plain sedimentation step on a percent basis showing differences in the treatment of *Umgeni* and *Inanda raw water***

Since the plain sedimentation tank was not covered, this scatter could be due to:

- ♦ wind effects.
- ♦ algae growth.

The scatter, especially for a covered plain sedimentation tank, could also be due to the:

- bacterial content and other colloidal matter in the raw water.
- bacterial growth in the plain sedimentation tank.

#### 6.2.1.4 Performance of the slow sand filters with respect to turbidity removal

The pre-treated water, from the plain sedimentation tank, formed the feed water to the SSFs. For consistency this feed water is also referred to as pre-treated water when reference is made to the SSF.

Figure 6.13 shows the probability of the filtered water turbidity conforming to the respective HRLs for a given pre-treated water turbidity. Turbidity data for *filter recovery* was included. The pre-treated water was filtered by SSF2 which was operated mainly at 0,1 m/h. The following observations were made:

- The filtration of a pre-treated water turbidity up to 3 NTU consistently ensured a filtered water turbidity conforming to the NHRt limit of 1 NTU.

- The filtration of a pre-treated water turbidity up to 7,5 NTU consistently ensured a filtered water turbidity conforming to the IHRt limit of 5 NTU.

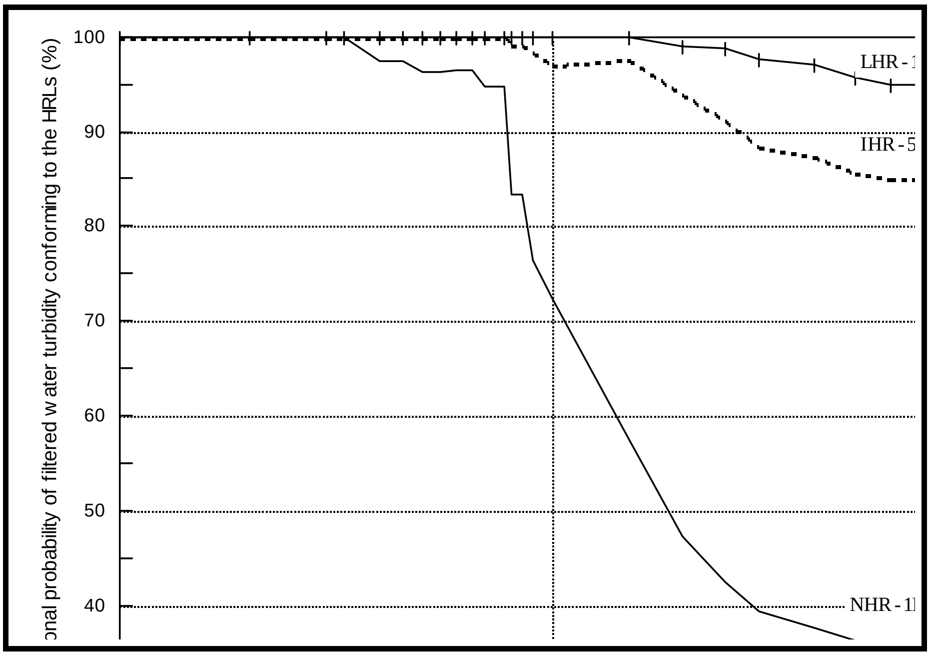


**Figure 6.13: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) turbidity conforming to the HRLs as a function of pre-treated water turbidity.**

When comparing the observations of Figs. 6.8 and 6.13 one notes the following:

- The plain sedimentation tank increased by 25 %, from a pre-treated water turbidity of 3 NTU to a raw water turbidity of 4 NTU, the turbidity range that was treated to produce a filtered water conforming to the NHRt limit.
- The plain sedimentation tank increased by 33 %, from a pre-treated water turbidity of 7,5 NTU to a raw water turbidity of 10 NTU, the turbidity range that was treated to produce a filtered water conforming to the IHRt limit.

Figure 6.14 shows the normal PDF distribution of *Inanda* and *Umgeni pre-treated waters*. The minimum *Umgeni* and *Inanda pre-treated water* turbidities were 4 and 0,9 NTU respectively.

One observes the following:

- The positive skewness values of the PDFs indicate that both *Inanda* and *Umgeni pre-treated water* have a *heavy turbidity tail.*
- *Inanda pre-treated water* was within the low turbidity range of 0,9 to 7 NTU.
- *Umgeni pre-treated water* was within the high turbidity range of 4 to 100 NTU.

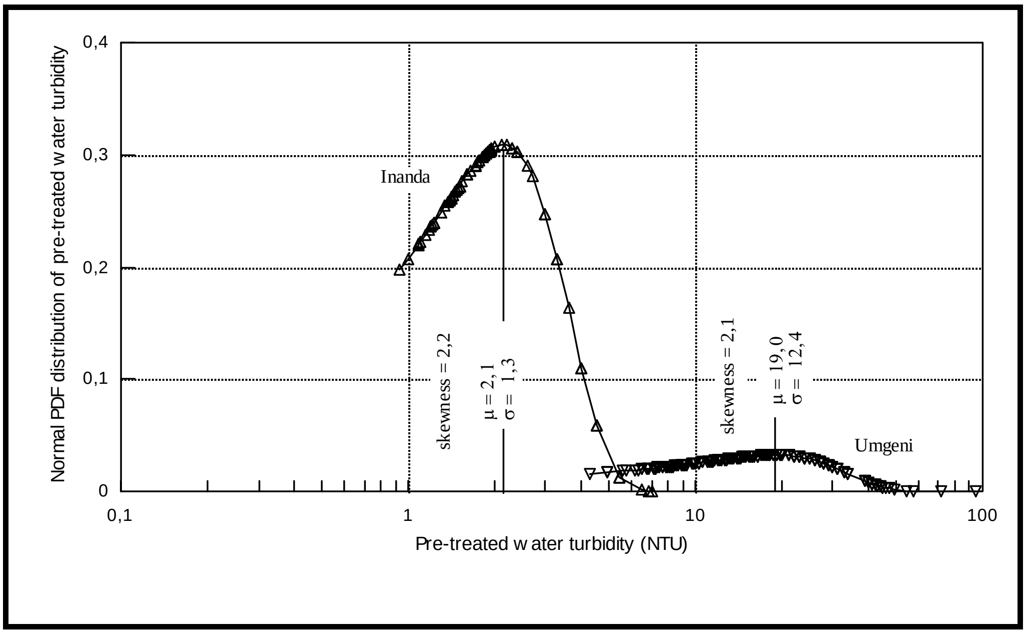


**Figure 6.14: Normal PDF distribution of *Umgeni* and *Inanda pre-treated water* turbidity.**

Therefore, considering observations from Figs. 6.13 and 6.14, *Inanda filtered water* was most likely to conform to the NHRt limit and occasionally to the IHRt limit. There was a 85 and 95 % chance of filtering high turbidity *Umgeni pre-treated water* so that the filtered water turbidity conformed to the IHRt and LHRt turbidity limits respectively.

Observations that were made from Fig. 6.15 were as follows:

- *Inanda filtered water* conformed to the NHRt limit except for the occasional turbidity breakthrough during *filter recovery*.
- The observations made from Fig. 6.13, for the production of a filtered water within the NHRt range are confirmed in Fig. 6.15.
- The observations, from Figs. 6.13 and 6.14, that *Umgeni filtered water* conformed mainly to the IHRt and LHRt limits are also confirmed in Fig. 6.15.
- The outlier, above the 0 % removal line, represents an *Umgeni filtered water* filtered water sample with a turbidity of 200 NTU. This occurred a day after the *Umgeni raw water* peaked at 4 000 NTU (see Table A1 in Appendix A). Thereafter, the *Umgeni filtered water* turbidity exceeded 10 NTU for approximately 14 d. The two possible causes of the high *Umgeni filtered water* turbidity were that:
    - the entire filter was saturated with fine material from the raw water.
    - the raw water could also have been composed of fine colloidal material which was carried through the filter by the incoming pre-treated water.

The turbidity reduction from 4 000 NTU to 200 NTU represents a 95 % removal of turbidity. The settling or straining mechanism, amongst other mechanisms, seems to contribute towards removal with respect to high raw water turbidity loads. The large sand surface area combined with the low rate of filtration gives a very low surface loading. The settling efficiency will therefore be so high that even small particles can be completely removed.

Figure 6.15 also indicates the following:

- The *Umgeni pre-treated water* was high in turbidity, mainly above 10 NTU.
- The turbidity of the *Umgeni filtered water* frequently exceeded the NHRt limit during *normal filtration* i.e. after *filter recovery*. The IHRt and LHRt limits were exceeded to a lesser extent by *Umgeni filtered water* during *normal filtration.* Therefore *filter recovery* did not significantly impact on the overall production of *Umgeni filtered water* with respect to the HRLs.
- The *Inanda filtered water* consistently conformed to the NHRt limit, except during *filter recovery*. The *Inanda filtered water* was therefore significantly affected by the filter cleaning.
- There would have been a 100 % probability of the *Inanda filtered water* turbidity conforming to the NHRt limit for *Inanda pre-treated water* turbidities up to 7 NTU, if *filter recovery* was not considered. An *Inanda pre-treated water* turbidity of 7 NTU represents a 133 % improvement from that of 3 NTU observed from Fig. 6.13.

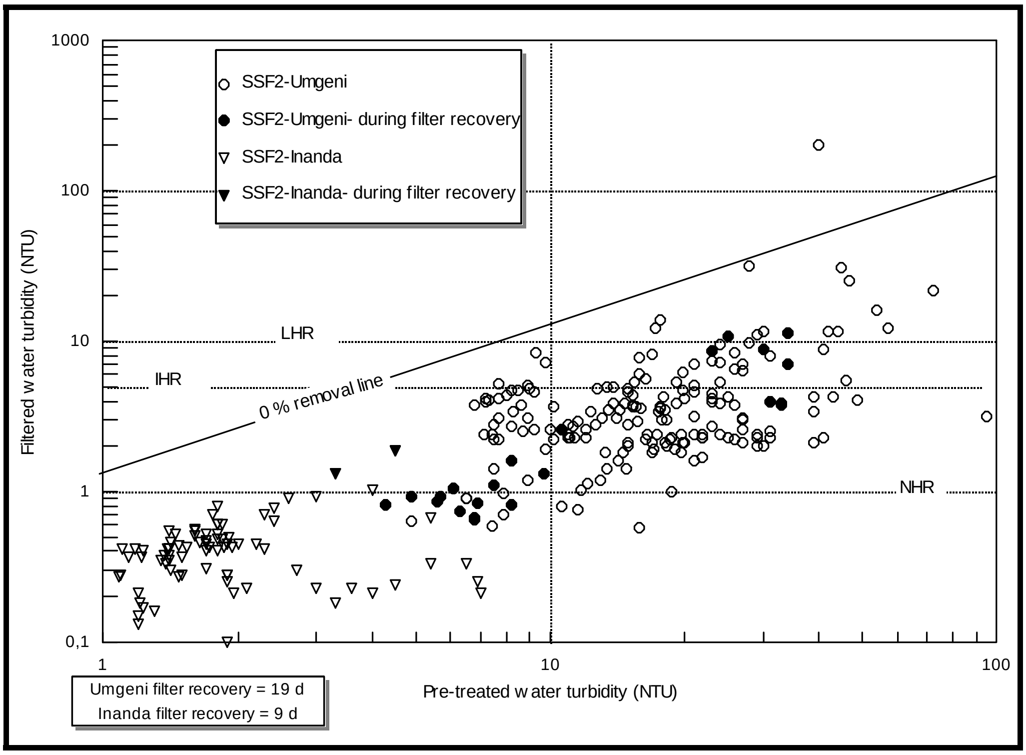


**Figure 6.15: Turbidity removal performance of SSF2, operated at 0,1 m/h, showing the effect of raw water source and filter cleaning**

Increasing the *Inanda pre-treated water* turbidity limit that can be treated by SSF is practical if:

- the filtered water is diverted to waste during *filter recovery* or
- the filtered water is secondary filtered in a polishing filter during *filter recovery* or
- the filtered water conforming to the IHRt limit is acceptable to the local authority or the community.

### 6.2.2 Removal of colour, iron and manganese

A limited amount of data was gathered on colour, Fe and Mn. Colour was measured in the units of Hazens (°H). These were taken around the treatment train as a whole.

From Table 6.1 one can note the following:

- The change from a running water source (Umgeni) to an impounded water source (Inanda) resulted in a decrease in raw water colour. The most abundant of the organic matter are humic compounds which impart a yellow or brown colour to the water. Humic compounds are derived from vegetation, soil drainage and sewage effluents (Burman, 1978). Running water has a greater chance of contacting humic compounds from sewage effluents and as it moves through vegetation and silt matter present on the river banks.
- The exception to the generally good performance of the plain sedimentation-SSF train occurred 3 d into *filter recovery* when the filtered water colour exceeded 5 ºH.
- The colour removal of the plain sedimentation-SSF train was generally less than 60 %. Although the colour removal for *Inanda raw water* was low, the colour of this raw water was already below the drinking water limit of 5 ºH. The plain sedimentation-SSF train reduced the *Umgeni raw water* colour to mainly below the 5 ºH limit.

**Table 6.1: Colour removal in plain sedimentation-SSF2 treatment train**

| Date | Raw water | | SSF2 (0,1 m/h) | | |
|---|---|---|---|---|---|
| | Colour (ºH) | Source | Removal (%) | Colour (ºH) | Time since clean (d) |
| 03/03/94 | 7.4 | Umgeni | 55.0 | 3.3 | 188.0 |
| 31/03/94 | 11.7 | Umgeni | 28.0 | 8.5 | 3.0 |
| 25/05/94 | 8.3 | Umgeni | 43.0 | 4.8 | 57.0 |
| 22/06/94 | 5.1 | Umgeni | 48.0 | 2.6 | 86.0 |
| 08/11/94 | 2.9 | Inanda | 32.0 | 2.0 | 74.0 |
| 10/11/94 | 3.3 | Inanda | 14.0 | 2.8 | 77.0 |
| 15/03/95 | 3.3 | Inanda | 19.0 | 2.7 | 204.0 |

Colour generally indicates the amount of dissolved organic matter present in the water. The incident of the filtered water colour exceeding 5 ºH, 3 d into *filter recovery,* confirms the significance of the microbiological *schmutzedecke* layer in removing dissolved organics, as discussed by Eighmy *et al* (1988) and Collins *et al* (1992). They observed that dissolved organic matter as well as Fe and Mn are removed through biodegradation and adsorption in the *schmutzedecke* layer. The bacteria, present within the sand media, oxidise the organic matter to provide the energy they need for the metabolism, and they convert part of it into cell material for their growth (Schmidt, 1978; Huisman and Wood, 1974).

Observations made from Table 6.2 were as follows:

- There was an improvement in raw water quality, especially regarding the Fe content, when *Inanda raw water* came on line. The Fe content of the *Inanda filtered water* consistently conformed to the NHRfe limit of 0,1 mg/ℓ.
- The *Umgeni filtered water* Fe content exceeded the NHRfe limit at 3 d and at 28 d after filter cleaning.
- The change in the Mn content of the raw water did not affect both *Umgeni* and *Inanda filtered water* quality. The Mn content was consistently below 0,01 mg/ℓ, thus conforming to the NHRmn limit of 0,05 mg/ℓ.

**Table 6.2: Fe and Mn removal in the plain sedimentation-SSF train also showing the raw water source.**

| Date | Raw | | | Sedimentation tank | | SSF2 | | |
|---|---|---|---|---|---|---|---|---|
| | Source | Fe (mg/ℓ) | Mn (mg/ℓ) | Fe (mg/ℓ) | Mn (mg/ℓ) | Fe (mg/ℓ) | Mn (mg/ℓ) | time after clean (d) |
| 31/03/94 | Umgeni | 1.3 | 0.2 | - | - | 0.2 | <0.01 | 3.0 |
| 26/04/94 | Umgeni | 1.6 | 0.2 | - | - | 0.2 | <0.01 | 28.0 |
| 17/05/94 | Umgeni | 1.4 | <0.01 | - | - | <0.02 | <0.01 | 49.0 |
| 25/05/94 | Umgeni | 0.9 | 0.0 | - | - | <0.02 | <0.01 | 57.0 |
| 08/11/94 | Inanda | 0.2 | 0.1 | - | - | 0.1 | <0.01 | 74.0 |
| 10/11/94 | Inanda | 0.2 | 0.1 | - | - | <0.02 | <0.01 | 76.0 |
| 18/12/94 | Inanda | 0.4 | 0.2 | - | - | <0.02 | <0.01 | 116.0 |
| 14/03/95 | Inanda | 0.3 | 0.1 | 0.2 | <0.01 | <0.02 | <0.01 | 204.0 |
| 23/05/95 | Inanda | 0.1 | 0.1 | 0.1 | <0.01 | <0.02 | <0.01 | 273.0 |
| 06/06/95 | Inanda | 0.1 | <0.01 | 0.1 | <0.01 | <0.02 | <0.01 | 288.0 |

- no data available

The Fe removal in the plain sedimentation pre-treatment step ranged from 0 to 33 % whilst the Mn removal was greater than 90 %. Plain sedimentation had already reduced the Fe and Mn content to within the respective NHR ranges. It is suspected that the open water surface of the plain sedimentation tank enables oxidation to take place thus precipitating the dissolved Fe and Mn to an extent.

The removal of Fe in SSF2 was greater than 80 %. In all cases the Fe and Mn content were within the respective NHR ranges. This is accordance with the findings of Eighmy *et al* (1988) that SSFs perform well in removing Fe and Mn. They found that extractable Fe and Mn is compexed to the bacterial biomass. Thus the purification mechanism contributes to the removal of Fe and Mn.

The removal of Fe and Mn across the whole treatment train was greater than 59 and 90 % respectively.

## 6.3 PERFORMANCE WITH RESPECT TO HEALTH CRITERIA

Here too, attention is drawn to the ability of SSF to produce drinking water within the guidelines set by the Department of Health (DOH). Therefore there is less emphasis on the percentage of microbiological removal by SSF. Focus is made on the final water quality conforming to the health risk limits (HRLs) defined by the DOH (1994), especially the NHR and IHR limits .

As discussed in Section 2.2.2, the DOH recommends that tests for total coliform bacteria and standard plate count (SPC) should always be done. Therefore the discussion is centred around total coliform removal and in some cases both total coliform and SPC removal. Although results are sometimes reported for both SSF1 and SSF2, discussion in this section is on the constant rate filter viz. SSF2.

Microbiological sampling was performed mainly on the raw and filtered water. The raw data is located in Appendix C. A limited number of pre-treated water microbiological samples were taken when the *Inanda raw water* came on line. Discussion is, therefore, centred mainly around the microbiological removal of the entire sedimentation-SSF train.

### 6.3.1 Microbiological removal

Figure 6.16 summarises the raw water microbiology. The following observations were made:

- The levels of total coliforms, *E.coli* and *F. strep.* in the raw water decreased when the Inanda impoundment came on line.
- The levels of standard plate counts (SPC) were similar for both *Umgeni* and *Inanda raw water.*
- There was a general increase in *Umgeni raw water* microbiology during the summer season.
- There was no noticeable seasonal effect on the *Inanda raw water* microbiology.

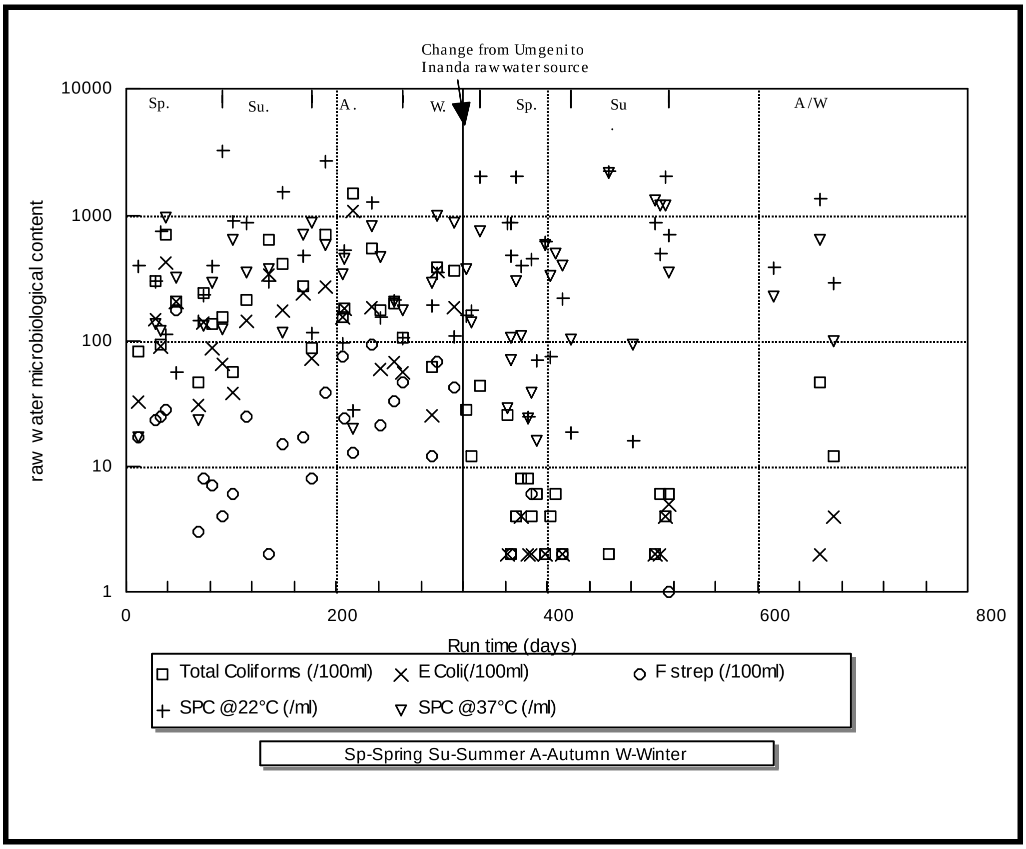


**Figure 6.16: Summary of the raw water microbiology over the entire period of experimentation**

Figure 6.17 summarises the filtered water total coliform content as a representation of the general filtered water microbiology. The observations were as follows:

- The exceeding of all the filtered water total coliform HRLs were due either to filter cleaning or the *Umgeni raw water* in general.
- There seemed to be no significant difference in filtered water microbiology with respect to filtration rates of 0,1 and 0,2 m/h.
- Although the filtration rate of SSF1 was increased to 0,5 m/h after approximately 450 d, this also did not affect the filtered water microbiology significantly.
- The possible reason for these high filtration rates not having an effect on the filtered water microbiology was that they occurred when the low microbiological *Inanda raw water* was being treated by SSF1.

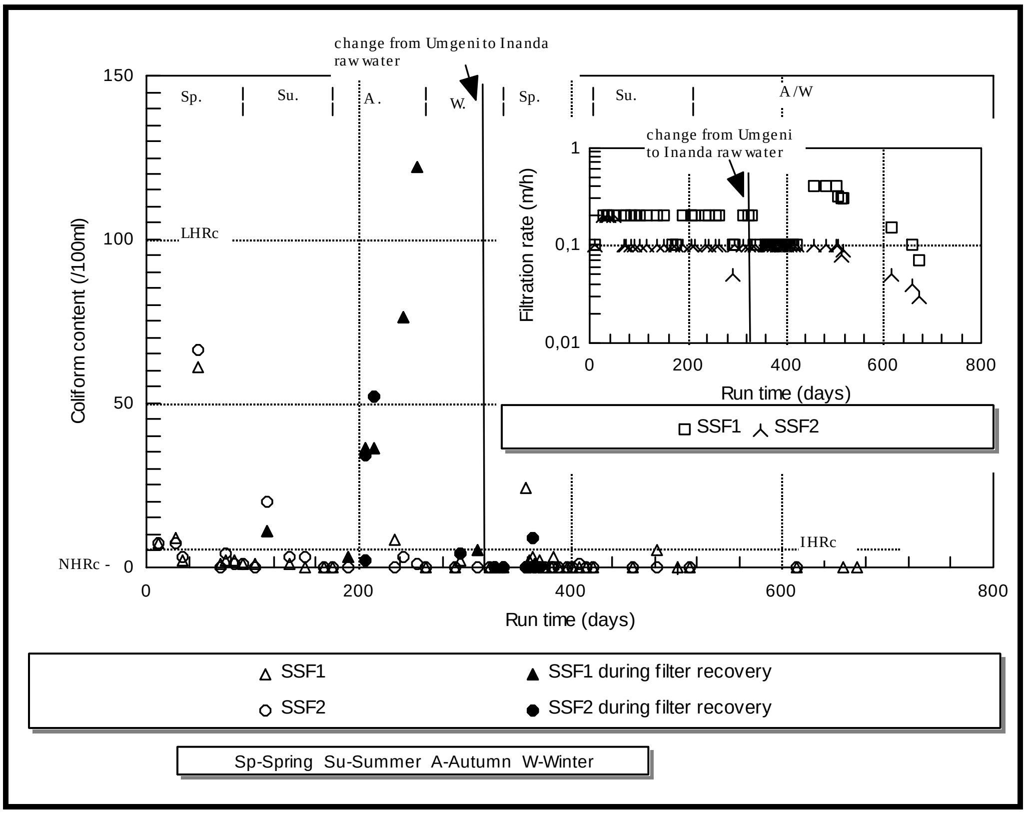


**Figure 6.17: Summary of the filtered water microbiology of SSF1 and SSF2, represented by total coliform content, during the entire period of experimentation. The inset summarises the filtration rates of SSF1 and SSF2.**

#### 6.3.1.1 Statistical comparison of turbidity and microbiological sampling

Turbidity is a simple and convenient water quality monitoring parameter. The turbidity meter is easy to operate and it can be used on site. It is for this reason that turbidity sampling was performed more frequently than microbiological sampling.

Figure 6.18 shows the relative frequency of all turbidity samples. It also shows the relative frequency of the turbidity samples that were taken about the same time as the microbiological samples. This latter set of turbidity samples is therefore used to represent the relative frequency of microbiological sampling. In general, the turbidity sampling was performed more frequently than the microbiological sampling. However, there were periods during the latter part of the experimentation, after 300 d, when the frequency of microbiological sampling was increased to observe the *filter recovery*.

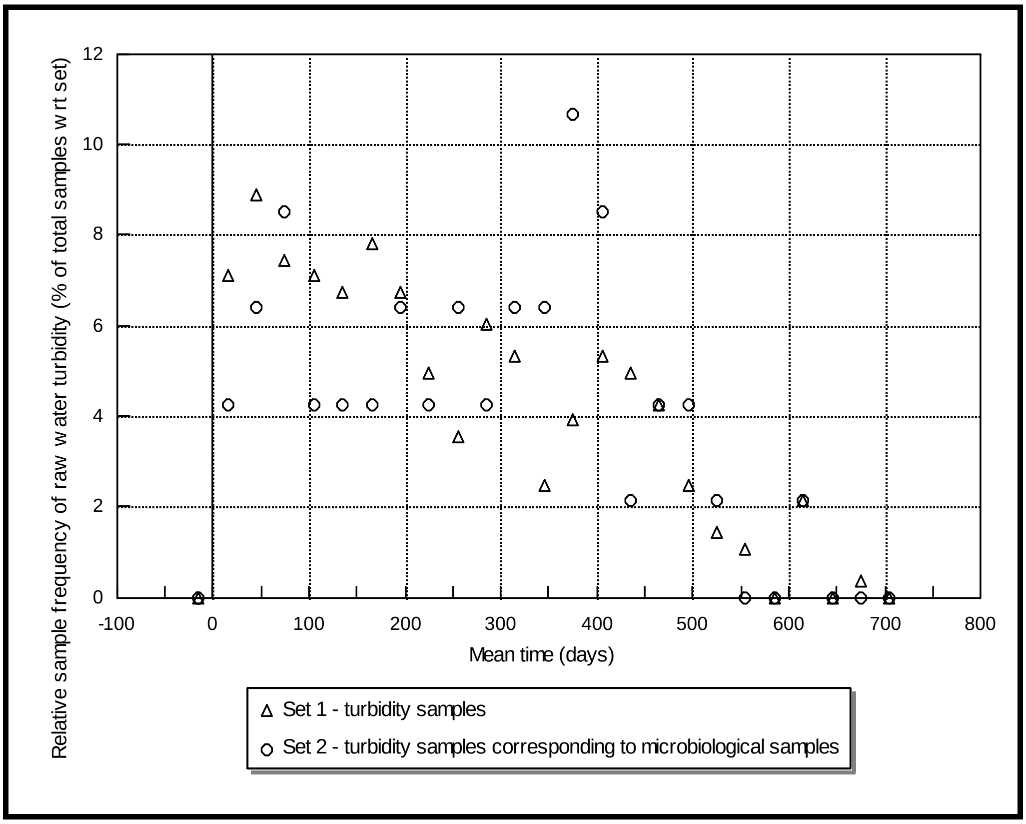


**Figure 6.18: Relative frequency of turbidity and microbiological sampling where set 1 is composed of all turbidity samples and set 2 is composed of only turbidity samples that corresponded to microbiological sampling.**

It is useful to relate the microbiological water quality to turbidity. In a rural area it may be only possible to monitor turbidity frequently. Turbidity can then be used as a warning indicator to determine if filtered water is microbiologically safe or not. Alternatively it can be used to determine if the raw water can be treated to produce microbiologically safe water.

Now, the microbiological samples form a smaller set when compared to the turbidity samples. There were 47 microbiological samples and about 282 turbidity samples taken over the entire period of experimentation. To correctly relate the microbiological results to raw water turbidity one has to determine whether the smaller raw water turbidity set, sampled at approximately the same time as the raw water microbiologically, is the same, qualitatively and quantitatively, as the larger turbidity set .

Firstly, the larger raw water turbidity set will be analysed. Then a statistical comparison of a smaller turbidity set will be performed against the former larger raw water turbidity set.

Appendix B shows the results of a randomness test for the larger turbidity set. This test showed that raw water turbidity formed patterns of high and low turbidity periods. The seasonal and raw water source influences, observed in Section 6.2, were possible causes of this high and low turbidity pattern. The randomness test, however, also indicates that there were random fluctuations of raw water turbidity within the high and low turbidity periods. The *Umgeni raw water* turbidity confirms these fluctuations.

Figure 6.19 shows the patterns of high and low raw water turbidity that occurred over the period of experimentation. Note that an increasing slope indicates a period of high raw water turbidity and vice versa. In relation to Section 6.2, one notes that the period:

- up to 28 d, low in raw water turbidity, occurred during the winter and spring season with respect to *Umgeni raw water*.
- from 28 to 249 d, high in turbidity, generally represents the late spring to late autumn season with respect to *Umgeni raw water*.

- from 249 to 317 d, low in turbidity, occurred during the Winter season with respect to *Umgeni raw water*.
- after 317 d, also low in raw water turbidity, occurred after *Inanda raw water* came on line.

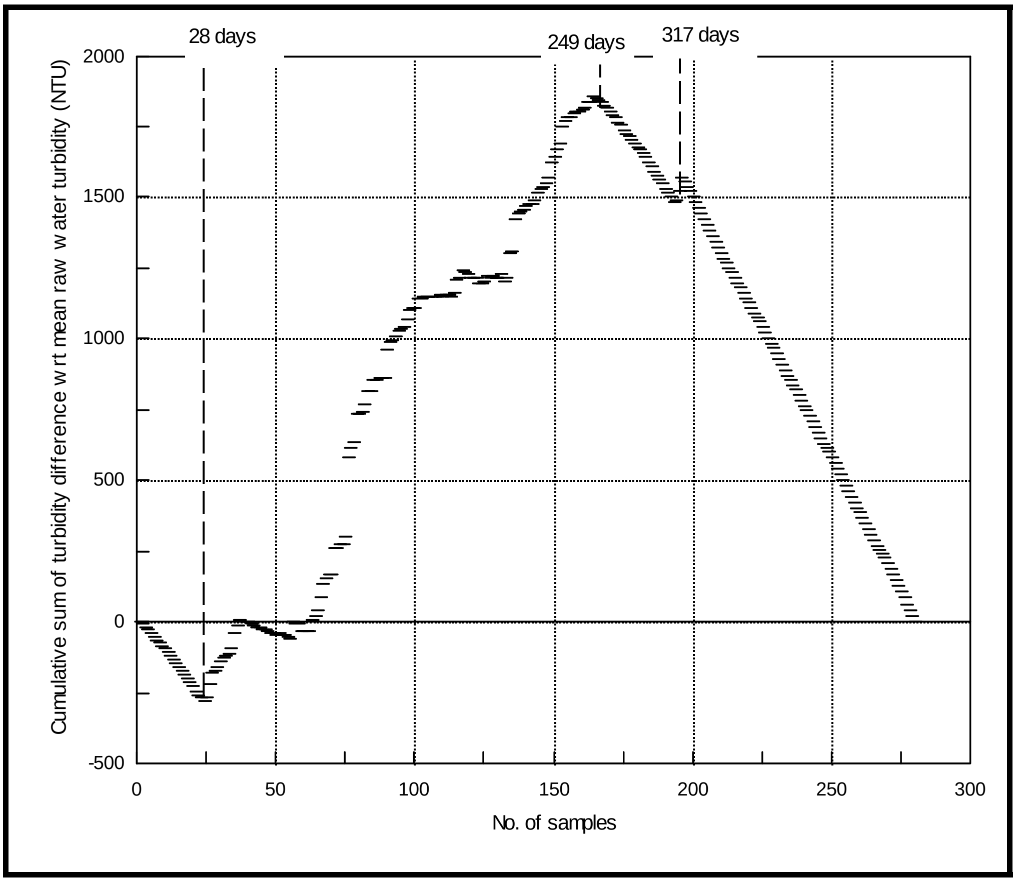


**Figure 6.19: Cumulative raw water turbidity differences with respect to the mean raw water turbidity, showing patterns of high and low turbidity over the sampling period**

The raw water turbidity sampled a day before the microbiological sample was used to represent the turbidity of the raw water microbiological sample. This was done to minimise the effects of the time lag caused by the residence time of the sedimentation tank-SSF train when relating the filtered water microbiology to the raw water turbidity. As pointed out in Section 6.1 sampling of the raw and filtered water was performed within 10 minutes apart, thus neglecting the residence time of the plain sedimentation-SSF train.

Table 6.3 shows the comparison between the two raw water turbidity sets regarding each of the periods identified in Fig. 6.19. The observations that were made were as follows:

- The sampling frequency of the raw water turbidity set, representative of microbiological sampling, was less that of the general raw water turbidity during all four periods.
- The median raw water turbidities, of set 1 compared to set 2, were similar during all periods.

**Table 6.3: Summary statistics of the large turbidity sample set 1 and the smaller turbidity sample set 2 representing microbiological sampling.**

♦

| Period (days) | Set 1 (wrt turbidity) | | | Set 2 (wrt microbiology) | | | | |
|---|---|---|---|---|---|---|---|---|
| | Sample frequency | Average turbidity (NTU) | Median turbidity (NTU) | Sample frequency | Average turbidity (NTU) | Median turbidity (NTU) | Sample frequency proportion wrt set1 sample frequency (%) | Sample frequency proportion wrt to set2 total sample frequency (%) |
| 0 to 28 | 21.0 | 11.7 | 10.4 | 2.0 | 11.2 | 11.2 | 9.5 | 3.8 |
| 32 to 249 | 143.0 | 38.0 | 30.0 | 19.0 | 29.5 | 28.0 | 13.3 | 36.6 |
| 249 to 317 | 33.0 | 14.3 | 9.6 | 5.0 | 16.7 | 11.6 | 15.2 | 9.6 |
| 317 + | 83.0 | 4.5 | 4.0 | 26.0 | 4.6 | 4.0 | 31.3 | 50.0 |

wrt - with respect to

Figure 6.20 indicates the following observations:

- The maximum raw water turbidity of that representing the microbiological sample set was 73 NTU.
- Approximately 4 % of the highest raw water turbidity values of the larger turbidity set did not have corresponding microbiological samples.
- The turbidity distributions of both raw water turbidity sets are similar enough up to a raw water turbidity up to 73 NTU to make useful conclusions.

Therefore relationships of microbiologically and turbidity, in this particular study, can only be made for those samples corresponding to a raw water turbidity below 73 NTU. This does not imply that relationships between microbiology and turbidity cannot be drawn, in other studies, if the raw water turbidity corresponding to microbiological sampling exceeded 73 NTU.

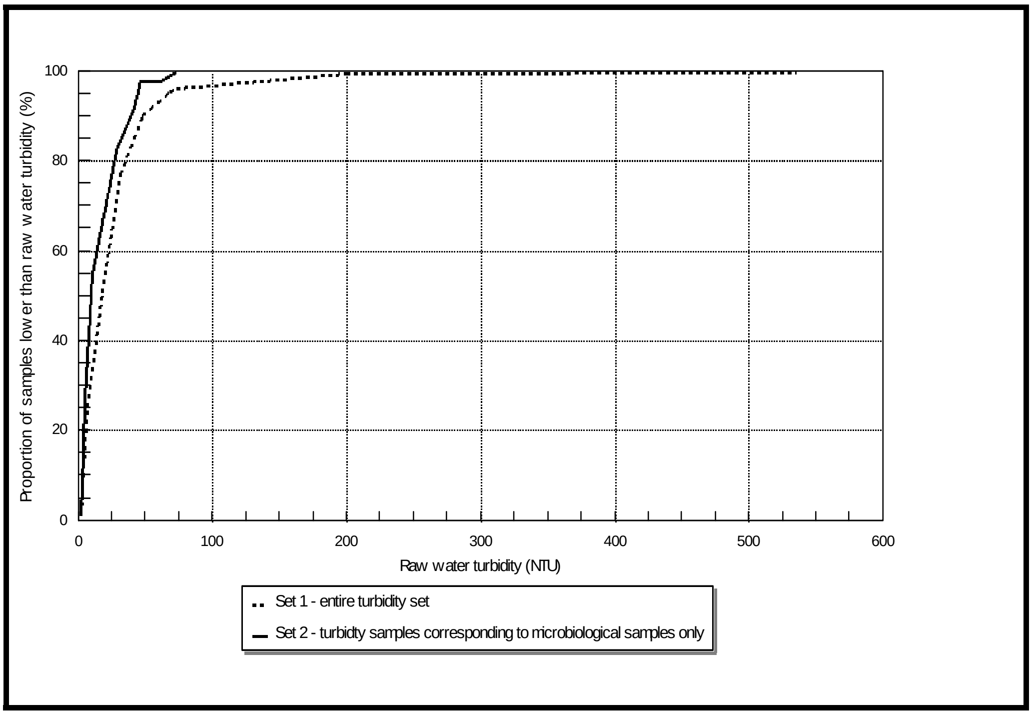


**Figure 6.20: Cumulative distributions of raw water turbidity where set 1 is composed of all turbidity samples and set 2 is composed of only turbidity samples that corresponded to microbiological sampling.**

#### 6.3.1.2 An investigation into the length of *filter recovery* with respect to microbiology

The total coliform content will be used to simulate general filtered water microbiology. Figure 6.21 shows the total coliform content of the filtered water of SSF2 during a period of about 21 d after filter cleaning. The time taken, after filter cleaning, to conform to the NHRc limit will be used to conservatively estimate the length of *filter recovery*. The observations were as follows:

- The *Inanda filtered water* took 8 d after filter cleaning to conform to the *no health risk* coliform (NHRc) limit.
  - Note that filtered water total coliforms was not sampled prior to the 8 d after filter cleaning thus this is a conservative estimate. There is a possibility that the *Inanda filtered water* total coliforms conformed to the NHRc limit prior to the 8$^{th}$ day.
  - Note that the filtered water total coliform *outlier* of 9 cells/100mℓ was not considered. The three filtered water total coliform results, after the same filter clean, prior to this were all at 0 cells/100 mℓ. Figure 6.22 shows that that this result occurred for a raw water total coliform count of 0 cells/100 mℓ. It also shows that the filtered water total coliforms generally conformed to the NHRc limit on several occasions when the raw water total coliforms exceeded 0 cells/100 mℓ.
  - Note the other filtered water total coliform *outlier*, from Fig. 6.22, of 1 cell/100 mℓ corresponding to a raw water total coliform count of 6 cells/100 mℓ. This result occurred about 2 months after filter cleaning (see Appendix C).
- Some of the possible reasons for the filtered water total coliform *outlier*s are as follows:
  - Part of the sampling procedure includes flushing the sample pipe with the sampled water for 5 minutes. Heating the edge of the sample pipe with a gentle flame is also recommended but this was not done since the sample pipe was made of PVC. This procedure ensures that total

coliforms arising from the regrowth in the sample pipe are not sampled. Therefore an increase in total coliforms in the filtered water relative to the raw water would result if the sampling procedure was not performed consistently.

- ○ The raw and filtered water samples were switched in the laboratory. This is a unlikely reason for the filtered water total coliform result of 1 cell/100 mℓ corresponding to a raw water total coliform count of 6 cells/100 mℓ.
- ○ The effect of vessel time lag on sampling was not considered during sampling procedure. Therefore the filtered water sample was not representative of the actual filtered water resulting from treatment of the raw water by the sedimentation-SSF2 train. This implies that the actual raw water total coliforms was above 9 cells/100 mℓ. However, Fig. 6.22 indicates that Inanda raw water total coliforms up to 44 cells/100 mℓ was reduced to 0 cells/100 mℓ. Therefore ignoring the effect of vessel time lag on sampling is an unlikely reason for the occurrence of these *outliers*.

♦ The Umgeni filtered water took 21 d after filter cleaning to conform to the NHRc limit.

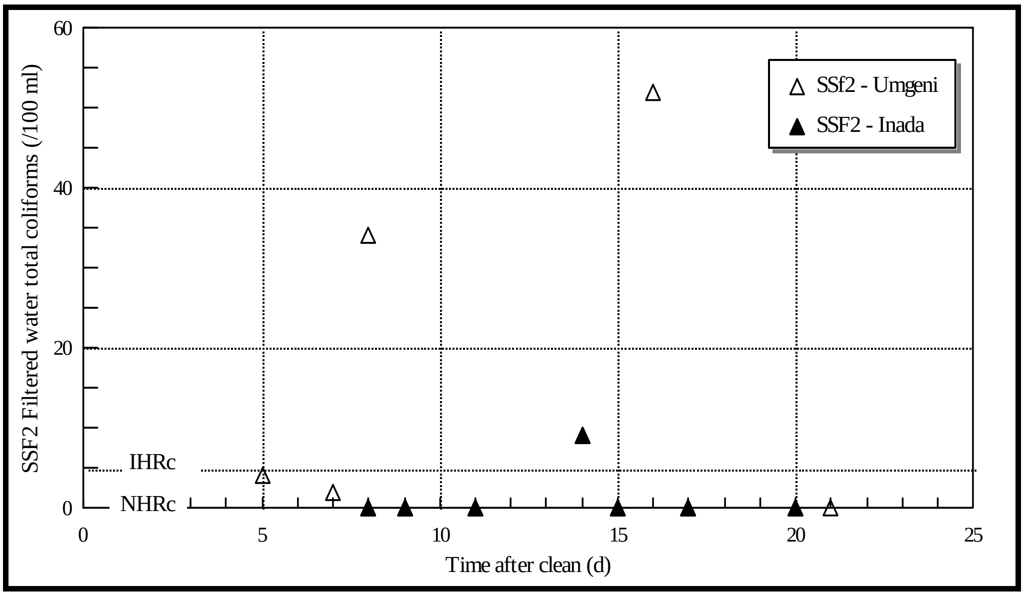


**Figure 6.21: Total coliforms of filtered water of SSF2, operated at 0,1 m/h, during 21 d after filter cleaning showing the time taken for *filter recovery* and the effect of raw water source**

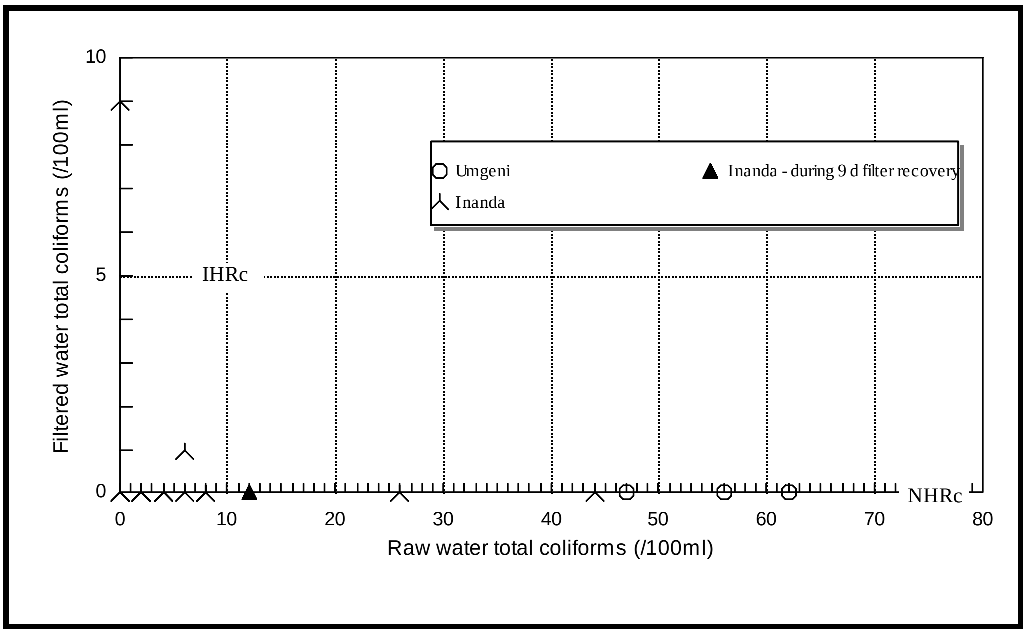


**Figure 6.22: Total coliforms of filtered water of SSF2, operated at 0,1 m/h, showing the *outliers* that occurred despite the low raw water total coliform content**

Therefore the length of the microbiological *filter recovery* periods were 8 d and 21 d for *Inanda* and *Umgeni filtered waters* respectively. The length of the microbiological *filter recovery* period, with respect to *Inanda filtered water*, corresponds well to that of the turbidity *filter recovery* period. Section 6.2.1.1 showed that the length of the turbidity *filter recovery* periods was 9 d for *Inanda filtered water* with respect to the NHRt limit. The length of the turbidity *filter recovery* period exceeded 21 d for *Umgeni filtered water* with respect to the NHRt limit. A conservative overall estimate of the length of the *filter recovery* periods will thus be 9 d and over 21 d for *Inanda* and *Umgeni filtered waters* respectively. Note that the *filter recovery* period with respect to *Umgeni filtered water* is still simulated by a 21 d duration in the future sections of this study.

Note that further discussion, on the *Inanda filtered water* total coliforms *outlier* of 9 cells/100 mℓ, will not be necessary. Therefore all graphs in the remaining discussion have ignored this result.

### 6.3.1.3 The effect of turbidity and filter cleaning on microbiological removal

The total coliform content and SPC at 37°C were used as a representation of the general microbiology of the raw water. Fig. 6.23 indicates an exponential increase of total coliforms up to a raw water turbidity of 10 NTU. The total coliform counts above 10 NTU were reasonably constant. There was no general trend regarding the SPC at 37 °C of the raw water.

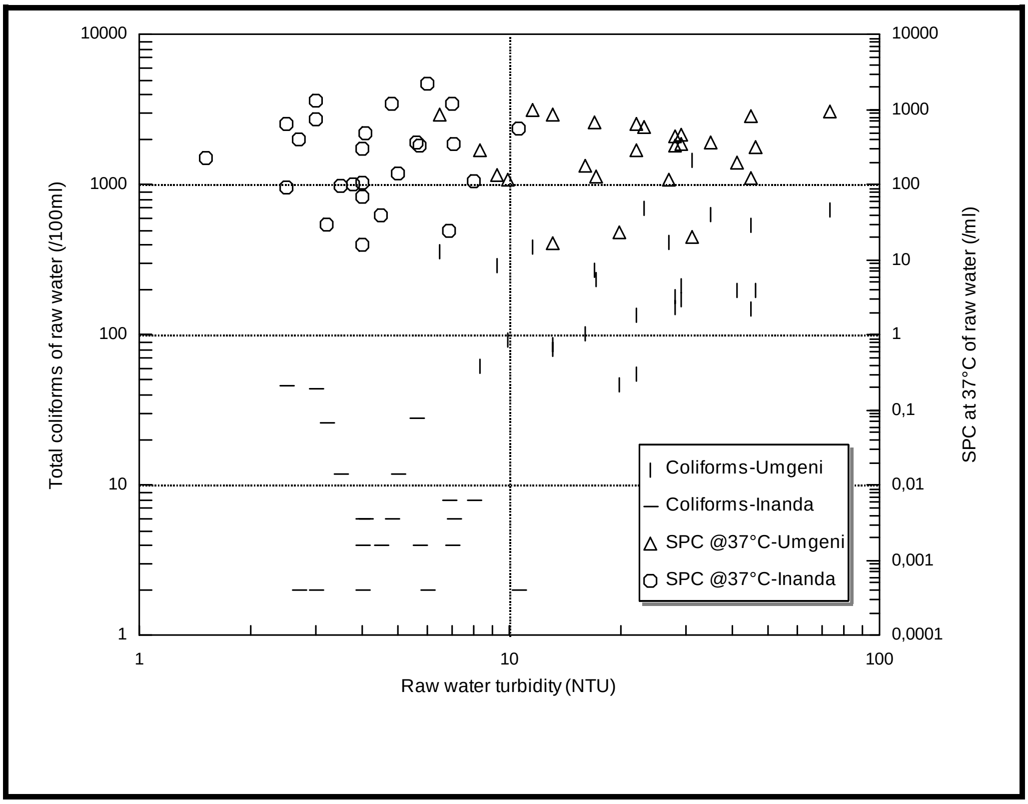


**Figure 6.23: Relationship between raw water turbidity and raw water microbiology for SSF2 operated at 0,1 m/h**

In the following discussion, information on the actual number of samples on which probability calculations are based is located in Appendix C. Figure 6.24 shows the following:

- ♦ There was just over a 95 % probability of the filtered water conforming to the no health risk total coliform (NHRc) limit of 0 cells/100 mℓ when the filtered water conformed to the no health risk turbidity (NHRt) limit of 1 NTU.
- ♦ There was approximately a 100 % probability of the filtered water conforming to the IHRc limit of 5 cells/100 mℓ for a filtered water turbidity up to 2,5 NTU.
- ♦ There was a 100 % probability of the filtered water conforming to the LHRc limit of 100 cells/100 mℓ when the filtered water conformed to the LHRt limit of 10 NTU.

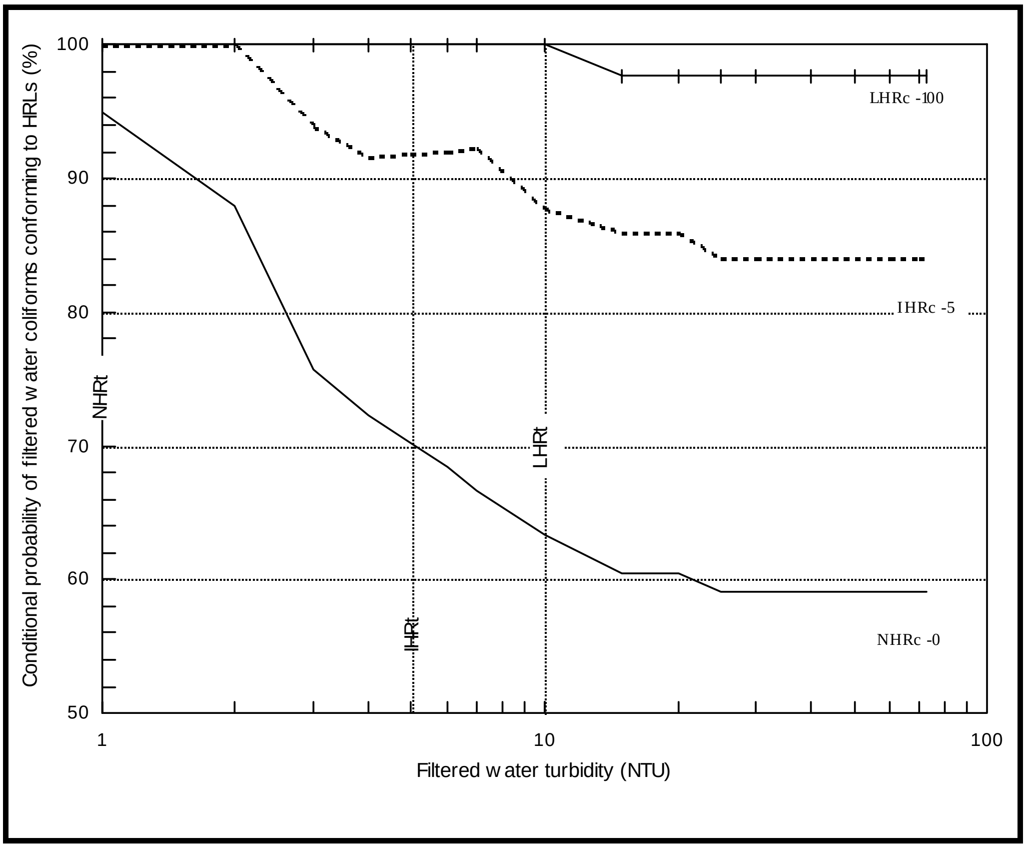


**Figure 6.24: Conditional probability of SSF2 filtered water (operated at 0,1 m/h) total coliforms conforming to the HRLs as a function of filtered water turbidity**

The observations from Figure 6.25 were as follows:

- The lower than 100 % probability of the filtered water conforming to the NHRc and IHRc limits occurred during:
    - *filter recovery.*
    - the treatment of *Umgeni raw water* that was generally high in total coliforms.
- The occasional breakthrough of total coliforms shown by *troughs*, in Fig. 6.24, was due to *filter recovery* and/or *Umgeni raw water*. The *troughs* are indicated by a decrease and subsequent increase in the probability of filtered water total coliforms conforming to the HRLs.
- If the effects of filter cleaning were eliminated, e.g. by post-chlorinating both *Umgeni* and *Inanda filtered waters* during *filter recovery*, then there would have been a 100 % probability of producing filtered water conforming to the NHRc limit for a filtered water turbidity up to 2 NTU.

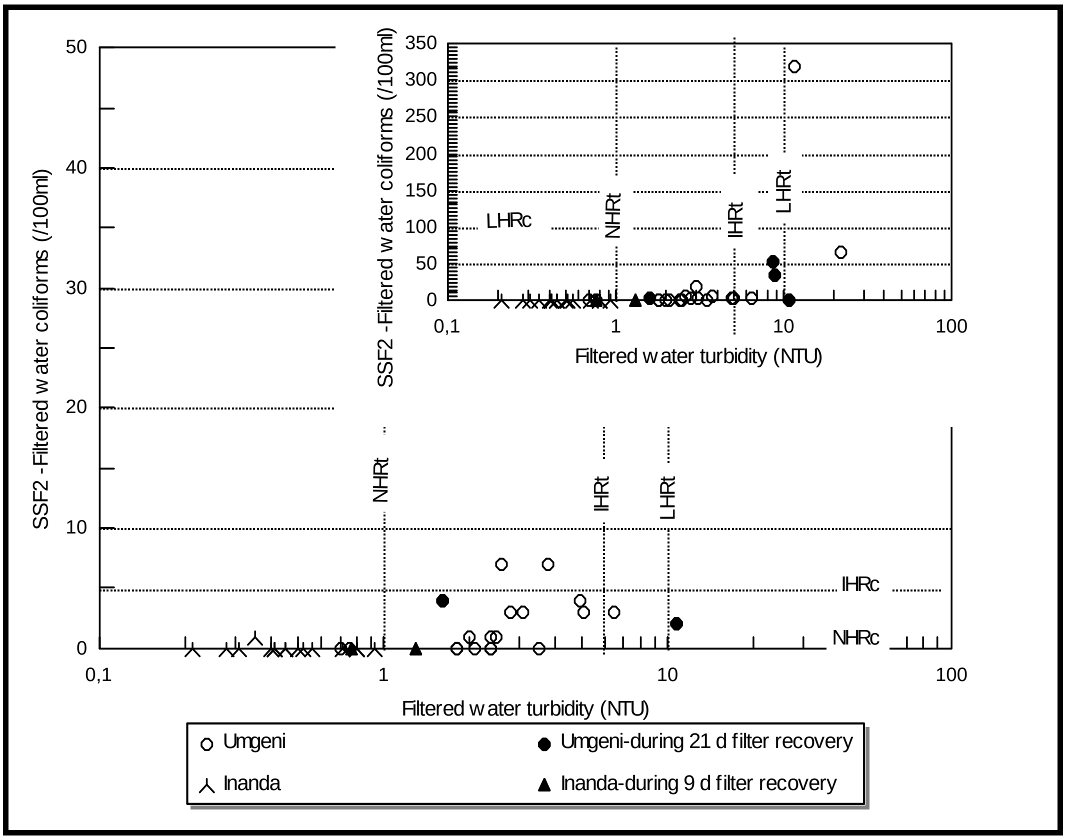


**Figure 6.25: Relationship between filtered water turbidity and filtered water total coliform content for SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source. The inset includes the outlying data.**

The decrease in total coliform removal during *filter recovery* indicates that the primary bacteria removal processes of screening and absorption of suspended particles and bacteria in the *schmutzedecke* are not the only removal mechanisms. The bacteria that occupy a mature *schmutzedecke* are also necessary to purify the water (Williams, 1987).

Sections 6.2.1.2. and 6.2.1.4. have shown that the *Inanda filtered water* exceeded the NHRt limit during *filter recovery*. Thus secondary filtration, in addition to post-chlorination, would ensure conformance to both the NHRt and NHRc limits. If the IHRt limit is acceptable to the local authority or community then secondary filtration will not be necessary. In addition, the *filter recovery* period of 9 d for *Inanda raw water* results in a 57 % saving in filter downtime when compared to that of 21 d for *Umgeni raw water*. Thus there would have been a consistent 100 % probability of obtaining filtered water conforming to both NHRc and NHRt limits if:

- *Inanda raw water* was fed to the pilot plant instead of *Umgeni raw water* and
- the *Inanda filtered water* was secondary filtered during *filter recovery* and post-chlorinated during the entire filtration cycle.

The evaluation of SSF is a conservative one since the *Inanda filtered water* total coliform *outlier* of 1 cell/100 mℓ at a raw water total coliform count of 6 cells/100 mℓ, discussed in Section 6.3.1.2, was considered here. If this *outlier* were not considered then post-chlorination of *Inanda filtered water* would only be required during *filter recovery*. It will be beneficial to post-chlorinate during *filter recovery* only to save on operating costs.

Note that *Inanda filtered water* consistently conforms to the IHRt and IHRc limits without the need for any form of secondary treatment.

Figure 6.26 shows that the filtered water, with a probability of 100 %, conformed to:

- the no health risk SPC at 37 °C (NHRs) limit up to a filtered water turbidity of 1,5 NTU.
- both IHRs and LHRs limits up to filtered water turbidity of 30 NTU.

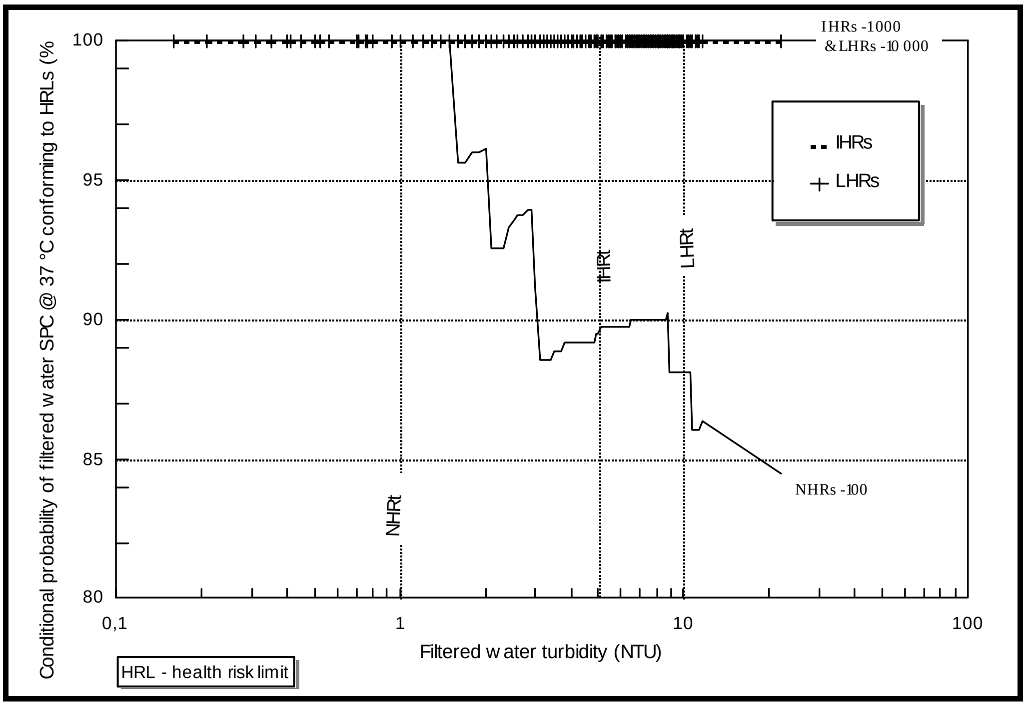


**Figure 6.26: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) SPC at 37°C conforming to the HRLs as a function of filtered water turbidity**

The observations made from Fig. 6.27 were as follows:

- *Umgeni filtered water*, conforming to the NHRs limit, would have been produced at a *Umgeni filtered water* turbidity up to 2,5 NTU if the effects of filter cleaning were eliminated.
- *Inanda filtered water* consistently conformed to the NHRs limit.
- The *troughs*, forming an irregular pattern in Fig. 6.26, were due to the increase in the proportion of filtered water exceeding the NHRs limit relative to the filtered water conforming to the NHRs limit.

Thus the *Umgeni filtered water* turbidity can be extended from 1 NTU to 2,5 NTU, ensuring conformance to the NHRs limit, if this water was post-chlorinated during *filter recovery* or throughout the entire filtration cycle.

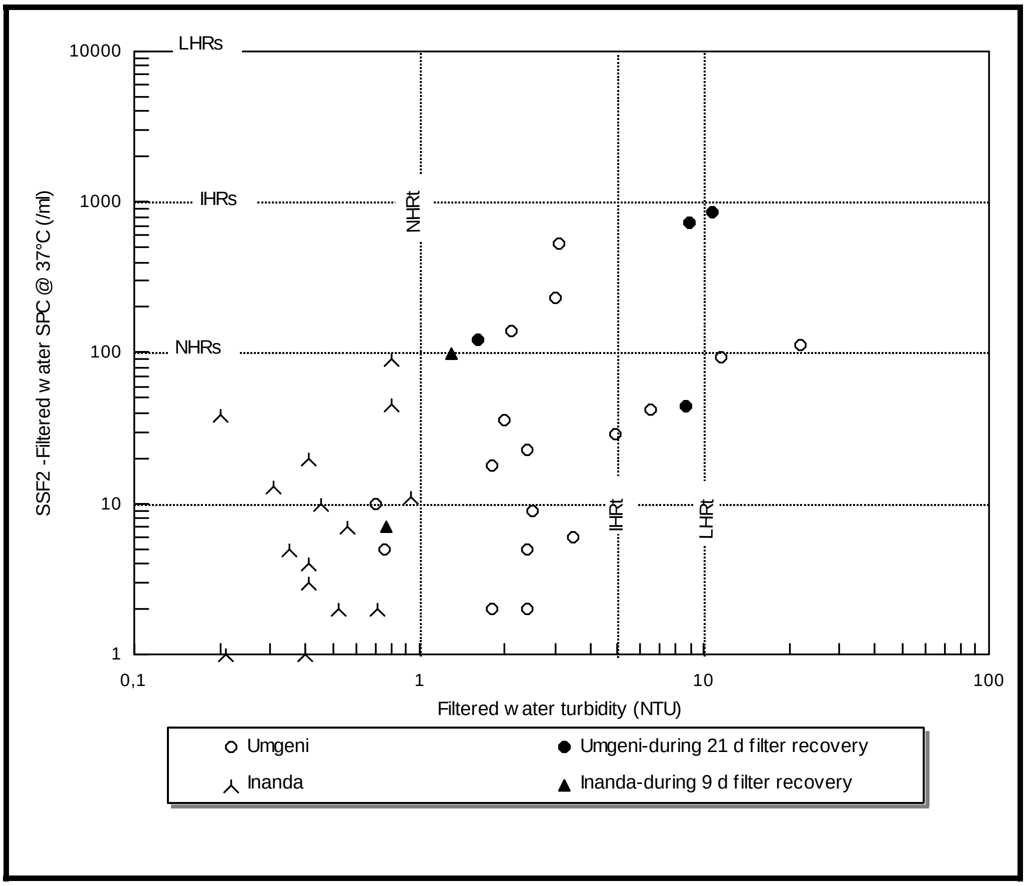


**Figure 6.27: Relationship between filtered water turbidity and filtered water SPC at 37°C for SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source.**

Figure 6.28 indicates that the minimum raw water turbidity corresponding to microbiological sampling was 1,52 NTU. The following observations were also made:

- There was a 100 % probability of the filtered water conforming to the NHRc and IHRs limits up to a raw water turbidities of 3,8 and 8 NTU respectively.
- There was a 100 % probability of the filtered water conforming to the LHRc limit up to a raw water turbidity of 73 NTU.

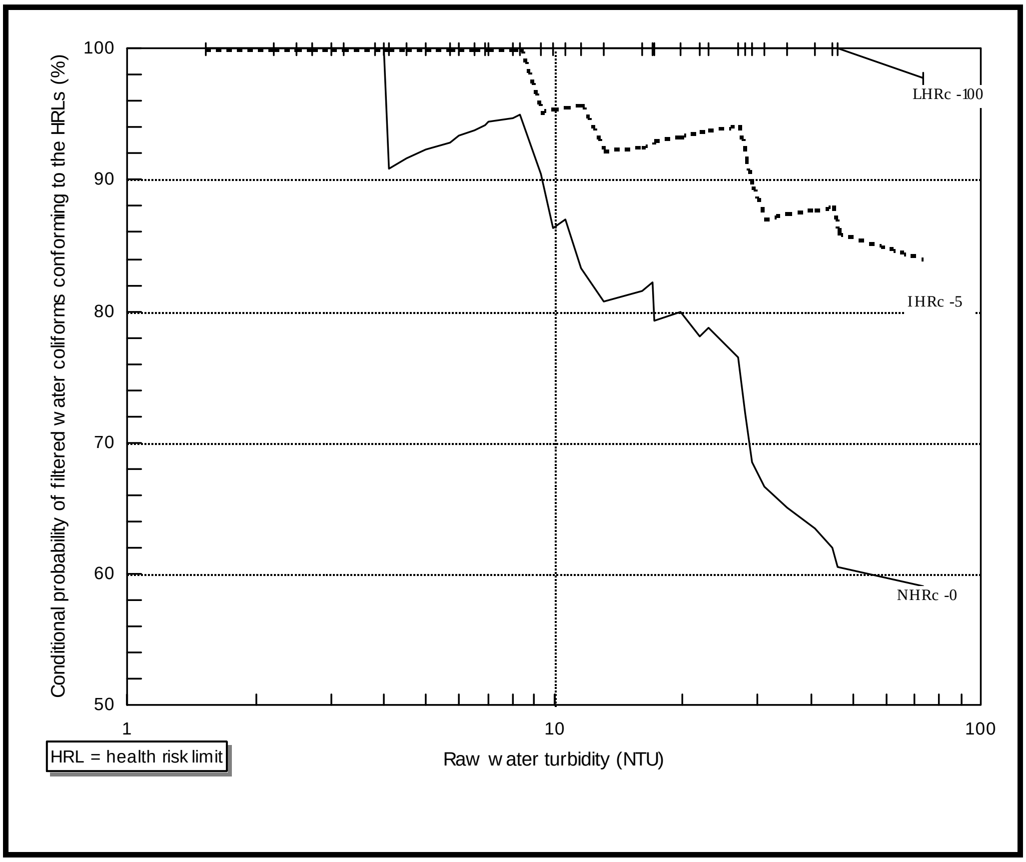


**Figure 6.28: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) total coliforms conforming to the HRLs as a function of raw water turbidity**

Observations made from Fig. 6.29 were as follows:

- *Inanda raw water* turbidity, resulting in the filtered water conforming to both NHRc and IHRc limits, can be extended from 3,8 and 8 NTU (as in Fig. 6.28) to 12 NTU if the filtered water had been post-chlorinated during the entire filtration cycle.
- *Umgeni raw water* turbidity up to 9 NTU conformed to both NHRc and IHRc limits without post-chlorination.
- Both post-chlorination during the entire filtration cycle and secondary filtration during *filter recovery* would ensure conformance to the NHRc and NHRt limits with respect to the *Inanda filtered water*.
- The exceeding of the LHRc limit was due to *Umgeni raw water* being high in total coliforms.

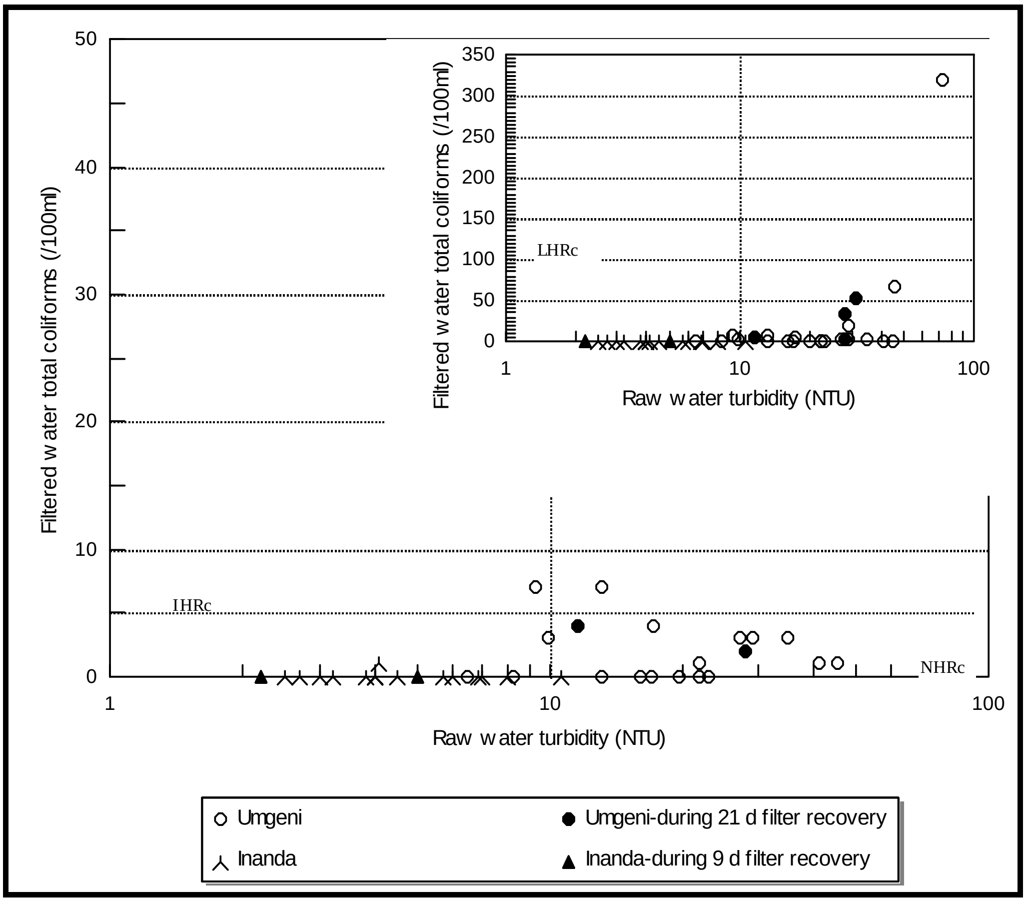


**Figure 6.29: Raw water turbidity influence on the total coliform removal of the plain sedimentation-SSF2 treatment train also showing the effect of filter cleaning and raw water source. The inset includes the outlying data.**

Fig. 6.30 indicates that the filtered water conformed to:

- the NHRs limit for a raw water turbidity up to 11 NTU.
- both the IHRs and LHRs limits for raw water turbidities up to 73 NTU.

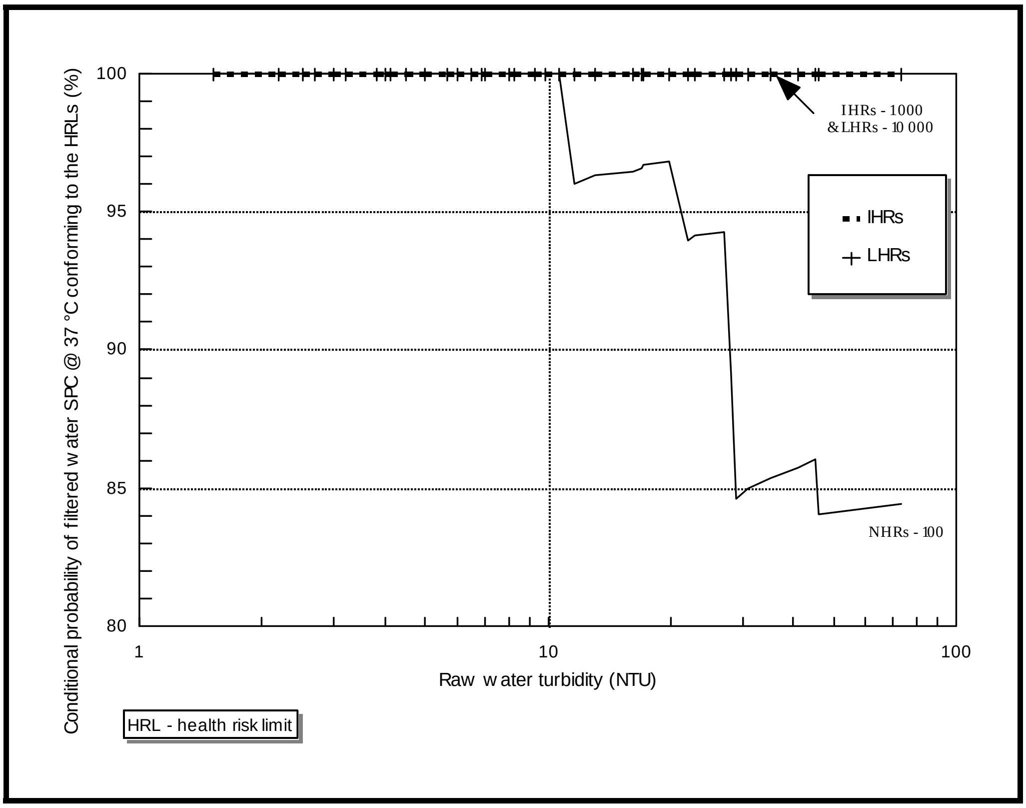


**Figure 6.30: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) SPC at 37 °C conforming to the HRLs as a function of raw water turbidity**

When comparing Figs. 6.30 and 6.31 one notes the following:

- *Umgeni raw water*, resulting in the filtered water conforming to the NHRs limit, can be extended from 11 to 25 NTU if the filtered water had been post-chlorinated during *filter recovery*.
- *Inanda filtered water* consistently conformed to the NHRs limit.

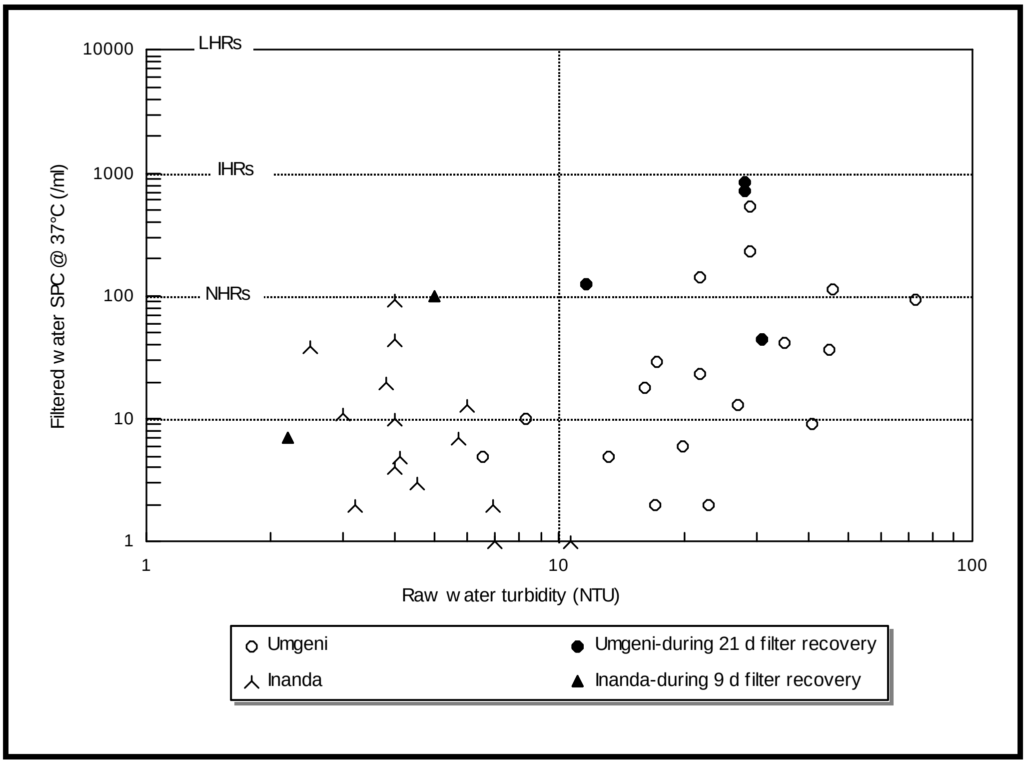


**Figure 6.31: Raw water turbidity influence on the SPC at 37 °C removal of the plain sedimentation-SSF2 treatment train also showing the effect of filter cleaning and raw water source**

Figure 6.32 shows that the minimum pre-treated water turbidity that corresponded to microbiological sampling was 1,1 NTU. In addition the following observations were made:

- The filtered water conformed to the NHRc limit up to a pre-treated water turbidity of 1,6 NTU.
- The filtered water conformed to the IHRc limit up to a pre-treated water turbidity of 6,5 NTU.
- The filtered water conformed to the LHRc limit up to a pre-treated water turbidity of 50 NTU.

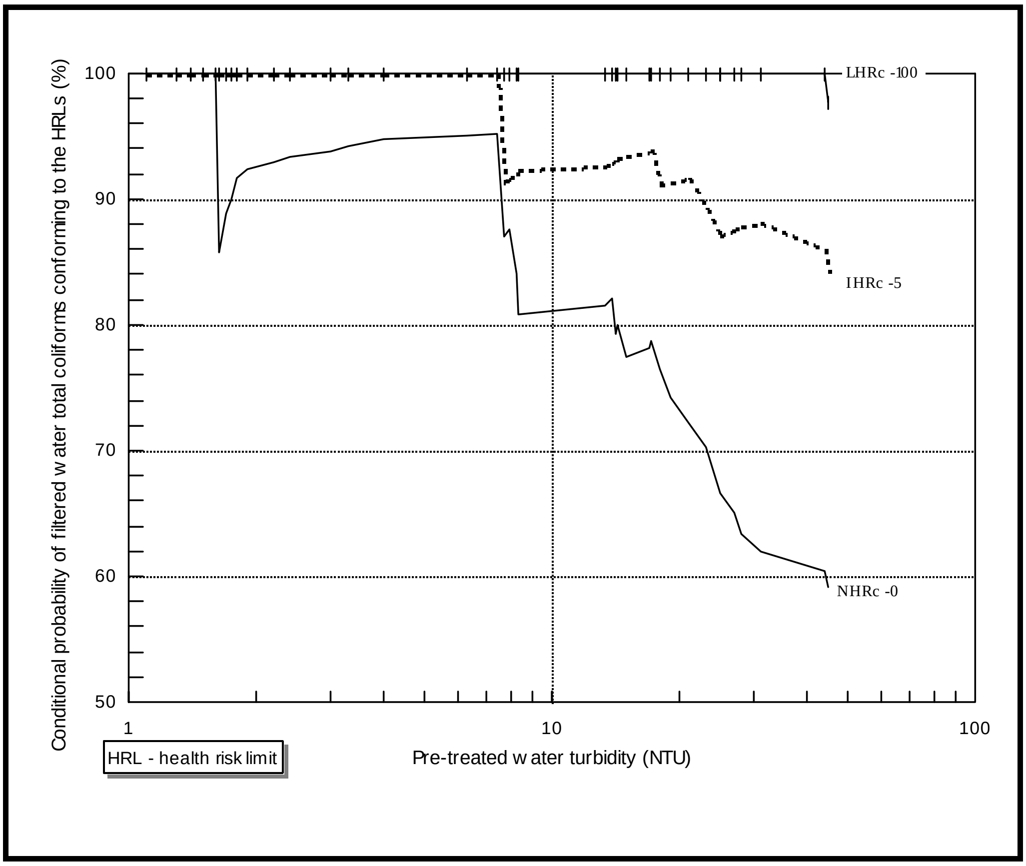


**Figure 6.32: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) total coliforms conforming to the HRLs as a function of pre-treated water turbidity**

A comparison of the results of Figs. 6.32 and 6.33 indicates the following:

- *Inanda pre-treated water* turbidity, resulting in a filtered water conforming to both the NHRc and IHRc limits, can be extended to 4 NTU if the filtered water had been post-chlorinated during the entire filtration cycle.
- *Umgeni filtered water* conformed to both NHRc and IHRc limits for a pre-treated water turbidity up to 7,5 NTU. However, there are no *Umgeni pre-treated water* turbidity data below about 5 NTU to prove otherwise.
- The *trough* occurring at an *Inanda pre-treated water* turbidity of 1,6 NTU is due to the total coliform breakthrough of the *outlier* of 1 cell/100 mℓ that was discussed in Section 6.3.1.2. The other *troughs*, resulting in an irregular trend, are due to total coliform breakthrough during *filter recovery* with respect to *Umgeni raw water* as well as the generally high total coliform content in the same raw water.

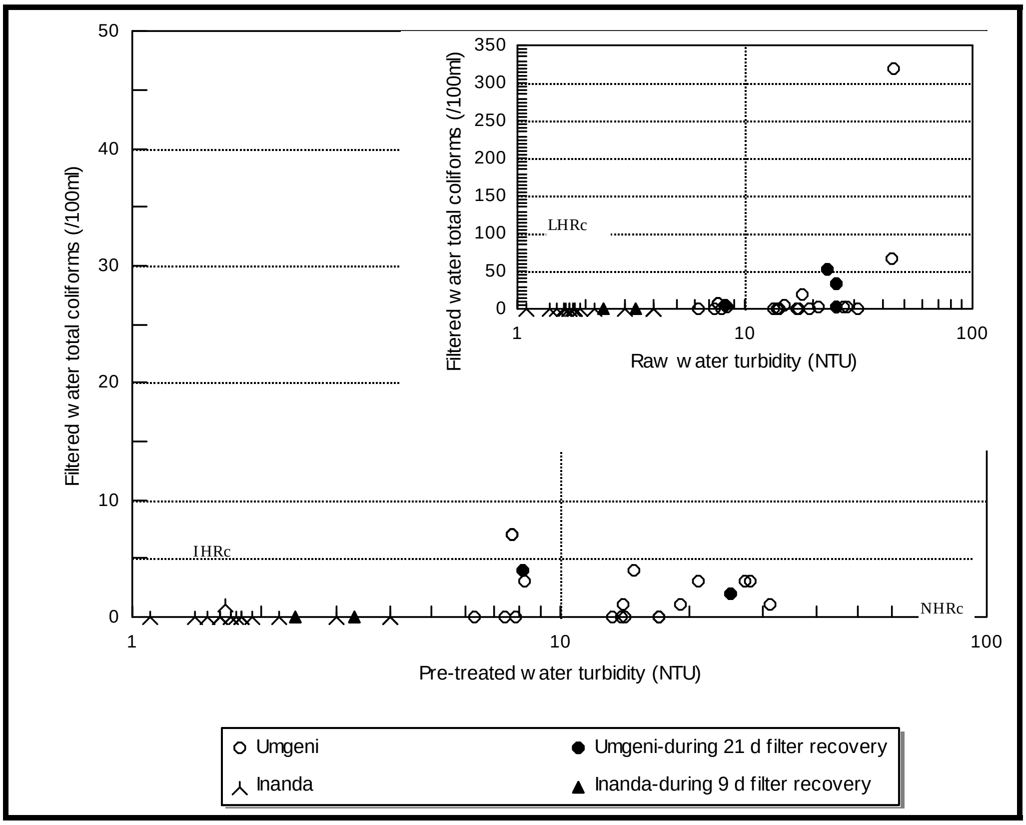


**Figure 6.33: Pre-treated water turbidity influence on total coliform removal of SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source. The inset includes the outlying data.**

A *Inanda raw* and *pre-treated water* turbidity of 12 and 4 NTU respectively would have resulted in the filtered water total coliforms conforming to the NHRc and IHRc limits if the *Inanda filtered water* was post-chlorinated. Therefore plain sedimentation and post-chlorination would have extended the *Inanda raw water* turbidity by 200 % with respect to total coliform removal. Plain sedimentation extended the *Umgeni raw water* turbidity by 20 % with respect to total coliform removal for both NHRc and IHRc limits. Indications are that a buffer storage tank with a residence time of least 6,6 h (see Table 4.1) will have a significant effect on total coliform removal.

Figure 6.34 shows that:

- the filtered water conformed to the NHRs limit when a pre-treated water turbidity of 8 NTU was not exceeded.
- the filtered water conformed to both the IHRs and LHRs limits when a pre-treated water turbidity of 50 NTU was not exceeded.

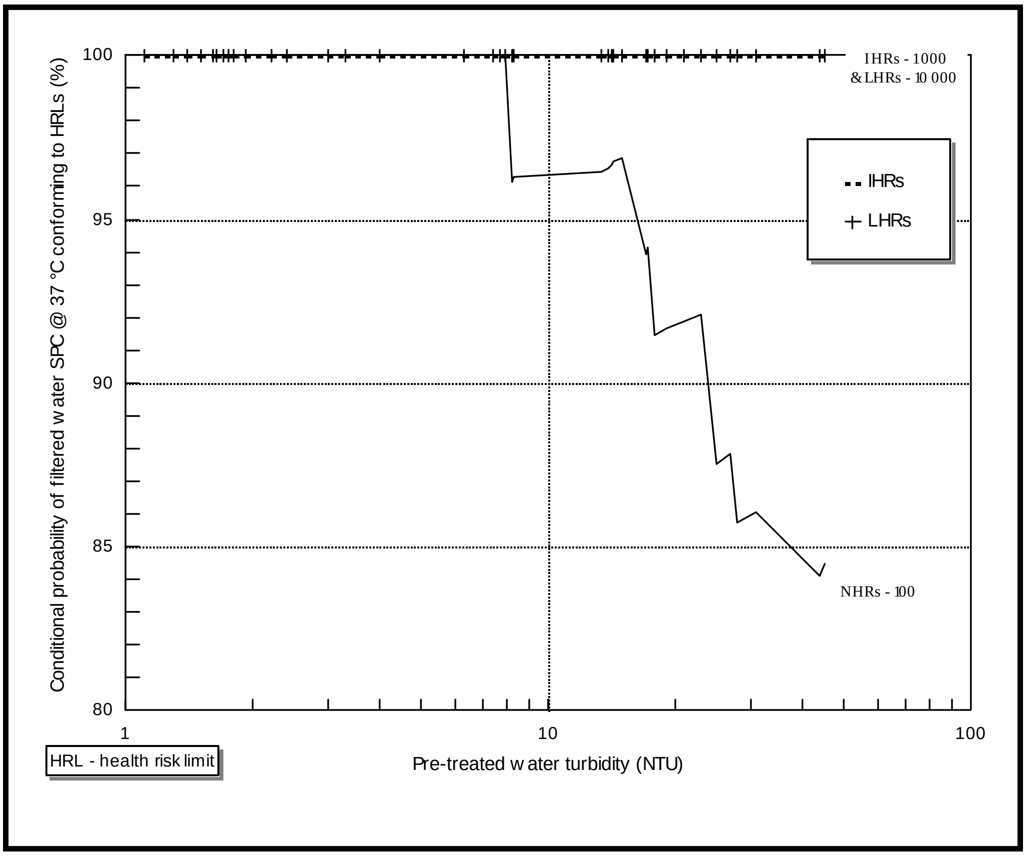


**Figure 6.34: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) SPC at 37 °C conforming to the HRLs as a function of pre-treated water turbidity**

When comparing the results of Figs. 6.34 and 6.35 it is observed that:

- *Umgeni pre-treated water* turbidity, resulting in the filtered water conforming to the NHRs limit, can be extended to approximately 19 NTU if the filtered water had been post-chlorinated during *filter recovery*.
- *Inanda pre-treated water* resulted in the filtered water consistently conforming to the NHRs limit.

A *Umgeni raw water* and *pre-treated water* turbidity of 25 and 19 NTU respectively resulted in the filtered water SPC at 37 ° C conforming to the NHRs limit during *normal filtration* i.e. after *filter recovery*. Therefore the plain sedimentation tank extended the *Umgeni raw water* turbidity by 31,6 % during *normal filtration* with respect to SPC at 37 ° C removal. Alternatively, the plain sedimentation tank would have extended the *Umgeni raw water* turbidity by 31,6 % if the filtered water was post-chlorinated with respect to SPC at 37 ° C. removal.

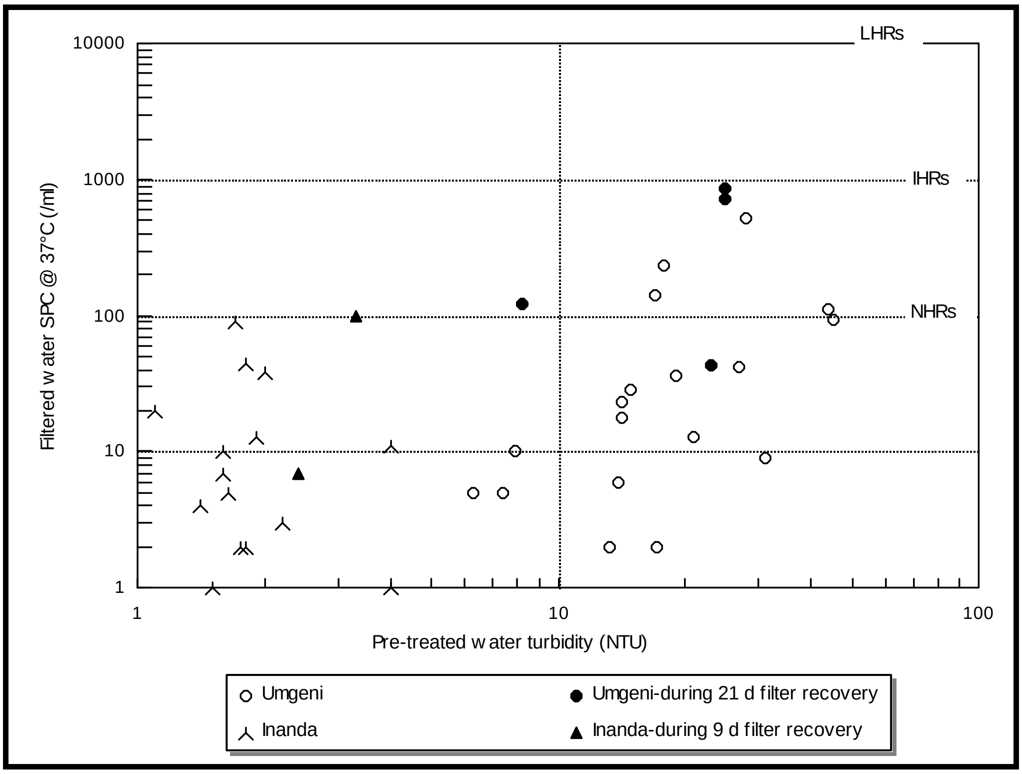


**Figure 6.35: Pre-treated water turbidity influence on SPC at 37 °C removal of SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source.**

#### 6.3.1.4 The effect of microbiological concentration and filter bed maturity on SSF performance

Although this section concentrates on the effect of microbiological concentration and filter bed maturity on performance, it also indicates the other microbiological results viz. *E. Coli*, *F. Strep*. and SPC at 22 °C.

Table 6.4 shows the microbiological removal by the sedimentation-SSF2 train as well as the filtered water microbiological counts. These results, in serial order from the start of experimentation, were used to determine the ability of a mature SSF bed to recover from microbiological disturbances in the raw water.

Bellamy *et al* (1985) showed that a microbiologically mature bed performs better than a new sand bed in removing *Giardia* cysts. A mature bed was found to be more resilient to disturbances of the sand bed. Table 6.4 indicates a similar trend for *E. Coli, F. Strep*. and total coliforms during the first 190 d of SSF operation. There was a consistent 100 % removal of *E. Coli, F. Strep*. and total coliforms during the latter 40 d of this period. *Umgeni raw water* was used during this period.

There was also a trend where the microbiological removal for SSF2, regarding *E. Coli, F. Strep*. and total coliforms, decreased after a filter clean and then increased to a 100 % removal until the next filter clean.

The overall period of experimentation also showed a microbiological removal trend for SSF2 that indicates filter bed maturity. However, this was also the point when the *Inanda raw water* was treated by the sedimentation-SSF train. This water source, as shown in Sections 6.2.1.2 and 6.3.1.3, was characterised by a low microbiological and turbidity content that was easily treated to conform to drinking water quality. Therefore one cannot state conclusively that the extent of filter bed maturity helped to improve filtered water quality after the *Inanda raw water* was on line.

Overall, the phenomenon of maturation is consistent with the view that the removal of bacteria is essentially a microbiolgical process.

**Table 6.4: Effect of SSF2 bed maturity on its performance**

| Serial time from start (d) | Time after clean/ start (d) | Source (season) | Total Coliforms | | *E. Coli* | | *Faecal Strep.* | | SPC at 22ºC | | SPC at 37ºC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | removal % | final /100 mℓ | removal % | final /100 mℓ | remov-al % | final /100 mℓ | remov-al % | final /mℓ | remov-al % | final /mℓ |
| *0.0* | *0.0* | *U(Win)* | *Start* | *Start* | *Start* | *Start* | *Start* | *Start* | *Start* | *Start* | *Start* | *Start* |
| 11.0 | 11.0 | U(Spr) | 91.4 | 7.0 | 97.0 | 1.0 | 94.1 | 1.0 | 29.6 | 276.0 | 100.0 | 0.0 |
| 28.0 | 28.0 | U(Spr) | 97.6 | 7.0 | 95.9 | 6.0 | 100.0 | 0.0 | -94.6 | 572.0 | 100.0 | 0.0 |
| 33.0 | 33.0 | U(Spr) | 96.8 | 3.0 | 100.0 | 0.0 | 100.0 | 0.0 | 65.8 | 256.0 | 100.0 | 0.0 |
| 37.0 | 37.0 | U(Spr) | 53.6 | 320.0 | 82.6 | 73.0 | -10.7 | 31.0 | -208.9 | 346.0 | 90.1 | 94.0 |
| 48.0 | 48.0 | U(Spr) | 67.3 | 66.0 | 80.2 | 40.0 | 76.1 | 42.0 | 87.7 | 7.0 | 65.0 | 112.0 |
| 69.0 | 69.0 | U(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 37.9 | 90.0 | 73.9 | 6.0 |
| 74.0 | 74.0 | U(Spr) | 98.3 | 4.0 | 100.0 | 0.0 | 100.0 | 0.0 | -37.0 | 315.0 | 77.7 | 29.0 |
| 82.0 | 82.0 | U(Spr) | 99.3 | 1.0 | 100.0 | 0.0 | 100.0 | 0.0 | 10.2 | 352.0 | 91.9 | 23.0 |
| 91.0 | 91.0 | U(Spr) | 99.3 | 1.0 | 98.5 | 1.0 | 100.0 | 0.0 | 97.7 | 76.0 | 70.5 | 36.0 |
| 102.0 | 102.0 | U(Sum) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 61.6 | 344.0 | 78.0 | 141.0 |
| 114.0 | 114.0 | U(Sum) | 90.7 | 20.0 | 97.2 | 4.0 | 100.0 | 0.0 | 60.0 | 350.0 | 34.1 | 232.0 |
| 135.0 | 135.0 | U(Sum) | 99.5 | 3.0 | 100.0 | 0.0 | 100.0 | 0.0 | 62.0 | 115.0 | 88.8 | 42.0 |
| 149.0 | 149.0 | U(Sum) | 99.3 | 3.0 | 100.0 | 0.0 | 100.0 | 0.0 | 90.4 | 146.0 | 88.7 | 13.0 |
| 168.0 | 168.0 | U(Sum) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 99.0 | 5.0 | 99.7 | 2.0 |
| 176.0 | 176.0 | U(Sum) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 24.8 | 88.0 | 99.4 | 5.0 |
| 190.0 | 190.0 | U(Aut) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 97.1 | 80.0 | 99.7 | 2.0 |
| 200.0 | 0.0 | U(Aut) | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* |
| 206.0 | 6.0 | U(Aut) | 98.7 | 2.0 | 98.7 | 2.0 | 100.0 | 0.0 | 8.3 | 88.0 | -154.9 | 854.0 |
| 207.0 | 7.0 | U(Aut) | 81.3 | 34.0 | 88.3 | 21.0 | 100.0 | 0.0 | 17.3 | 430.0 | -63.2 | 723.0 |
| 215.0 | 15.0 | U(Aut) | 96.5 | 52.0 | 98.2 | 19.0 | 100.0 | 0.0 | -17.9 | 33.0 | -120.0 | 44.0 |
| 234.0 | 34.0 | U(Aut) | 100.0 | - | - | - | - | - | - | - | - | - |
| 242.0 | 42.0 | U(Aut) | 98.3 | 3.0 | 98.3 | 1.0 | 100.0 | 0.0 | -219.6 | 489.0 | -14.5 | 528.0 |
| 255.0 | 55.0 | U(Aut) | 99.5 | 1.0 | 98.5 | 1.0 | 100.0 | 0.0 | 84.9 | 32.0 | 95.5 | 9.0 |
| 263.0 | 63.0 | U(Aut) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 59.4 | 43.0 | 89.8 | 18.0 |
| 291.0 | 91.0 | U(Win) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 98.9 | 2.0 | 96.5 | 10.0 |
| *292.0* | *0.0* | *U(Win)* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* |
| 296.0 | 4.0 | U(Win) | 99.0 | 4.0 | 99.7 | 1.0 | 100.0 | 0.0 | 90.3 | 34.0 | 87.7 | 123.0 |
| 312.0 | 20.0 | U(Win) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 99.1 | 1.0 | 99.4 | 5.0 |
| *323.0* | *0.0* | *I(Win)* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* |
| 324.0 | 1.0 | I(Win) | 100.0 | - | - | - | - | | - | - | - | - |
| 329.0 | 6.0 | I(Win) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 94.3 | 10.0 | 29.5 | 98.0 |
| 337.0 | 14.0 | I(Win) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 99.8 | 3.0 | 98.5 | 11.0 |
| *352.0* | *0.0* | *I(Win)* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* | *Clean* |

- no data available U=Umgeni I=Inanda Spr=Spring Sum=Summer Aut=Autumn Win=Winter continued on ffg. page

**Table 6.4: (continued)**

| Serial time from start (d) | Time after clean/ start (d) | Source (season) | Total Coliforms | | *E. Coli* | | Faecal Strep. | | SPC at 22ºC | | SPC at 37ºC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | removal % | final /100 mℓ | removal % | final /100 mℓ | remov -al % | final /100 mℓ | remov -al % | final /mℓ | remov-al % | final /mℓ |
| 359.0 | 7.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | - | 9.0 | - | 7.0 |
| 362.0 | 10.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 96.0 | 35.0 | 93.1 | 2.0 |
| 365.0 | 13.0 | I(Spr) | raw=0 | 9.0 | 100.0 | 0.0 | 100.0 | 0.0 | 111.0 | 568.0 | 35.7 | 45.0 |
| 366.0 | 14.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 44.4 | 476.0 | 13.2 | 92.0 |
| 371.0 | 19.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 96.4 | 72.0 | 96.7 | 10.0 |
| 376.0 | 24.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 99.7 | 1.0 | 100.0 | 0.0 |
| 382.0 | 30.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 96.0 | 1.0 | 91.7 | 2.0 |
| 385.0 | 33.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 98.2 | 8.0 | 92.3 | 3.0 |
| 390.0 | 38.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 92.9 | 5.0 | 75.0 | 4.0 |
| 398.0 | 46.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 98.4 | 10.0 | 99.8 | 1.0 |
| 403.0 | 51.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 78.4 | 16.0 | 97.9 | 7.0 |
| 408.0 | 56.0 | I(Spr) | 83.3 | 1.0 | 100.0 | 0.0 | - | | - | - | 99.0 | 5.0 |
| 415.0 | 63.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 93.6 | 14.0 | 100.0 | 0.0 |
| 422.0 | 70.0 | I(Spr) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 5.3 | 18.0 | 80.4 | 20.0 |
| 459.0 | 107.0 | I(Sum) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 98.7 | 29.0 | 99.4 | 13.0 |
| 482.0 | 330.0 | I(Sum) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 |
| 513.0 | 361.0 | I(Sum) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 98.8 | 25.0 | 99.9 | 1.0 |
| 516.0 | 364.0 | I(Sum) | 100.0 | - | - | - | - | - | - | - | 100.0 | - |
| 615.0 | 463.0 | I(Aut) | 100.0 | 0.0 | 100.0 | 0.0 | 100.0 | 0.0 | 55.2 | 172.0 | 82.9 | 39.0 |

- no data available U=Umgeni I=Inanda Spr=Spring Sum=Summer Aut=Autumn Win=Winter

Observations made from Fig. 6.36 were as follows:

- There was a 100 % probability of the filtered water total coliforms conforming to the NHRc limit when the raw water total coliforms did not exceed 4 cells/100 mℓ.
- There was a 100 % probability of the filtered water total coliforms conforming to the IHRc limit when the raw water total coliforms did not exceed 80 cells/100 mℓ.
- There was a steep decline in the probability of the filtered water coliforms conforming to the NHRc limit beyond a raw water total coliform content of 80 cells/100 mℓ.

- The *Inanda filtered water* total coliform *outlier* count of 1 cell/100 mℓ at a *Inanda raw water* total coliform count of 6 cells/100 mℓ, observed in Fig. 6.37, accounts for the *trough* below a raw water total coliform count of 10 cells/100 mℓ. This o*utlier* has been discussed in more detail in Section 6.3.1.2.

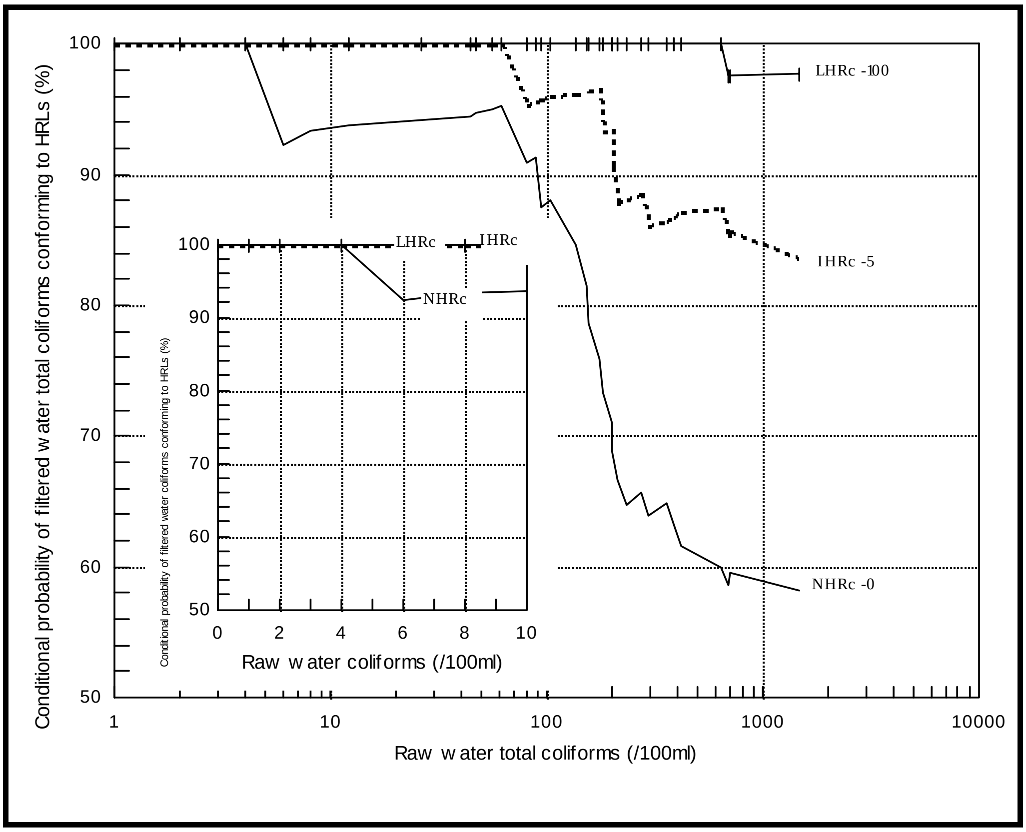


**Figure 6.36: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) total coliforms conforming to the respective HRLs as a function of raw water total coliforms. The inset shows the trend up to a raw water total coliform count of 10 cells/100 mℓ.**

Besides confirming the observations made from Fig. 6.36, Fig. 6.37 also shows that:

- *Inanda filtered water* would have conformed to the NHRc limit, for a raw water total coliform count up to 44 cells/100 mℓ, if the *outlier* of 1 cell/100 mℓ were neglected.
- *Umgeni raw water* conformed to the LHRc during *filter recovery*. The *outlier* at an Umgeni filtered water total coliform count of 325 cells/100 mℓ was probably due to a poor sampling procedure or bacterial regrowth in the sampling line as discussed in Section 6.3.1.2.
- The exceeding of the NHRc limit above a raw water count of 80 cells/100 mℓ occurred during the treatment of *Umgeni raw water*.

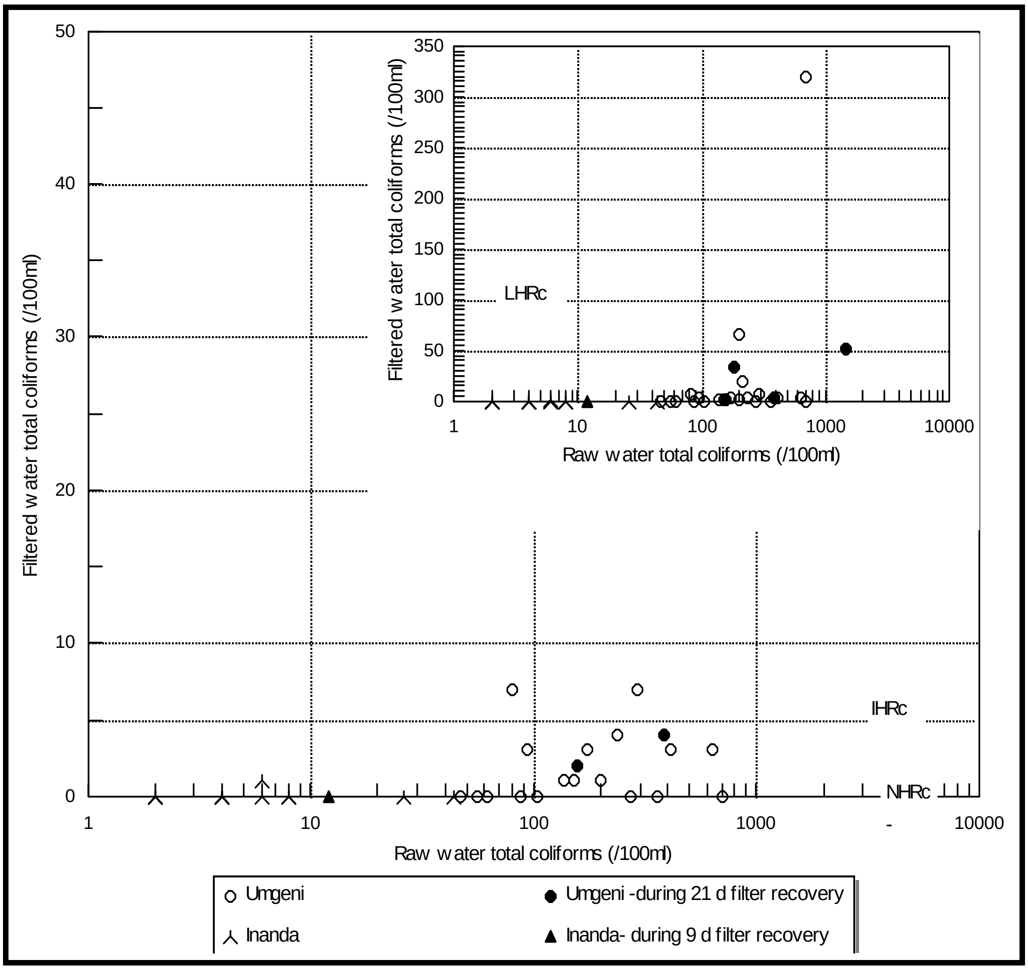


**Figure 6.37: Total coliform removal in sedimentation-SSF2 train with SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source. The inset includes the outlying data.**

Figure 6.38 confirms the observation of Fig. 6.37 that:

- the exceeding of the NHRc limit in the filtered water was more likely to occur when *Umgeni raw water* was treated by the sedimentation-SSF2 train.

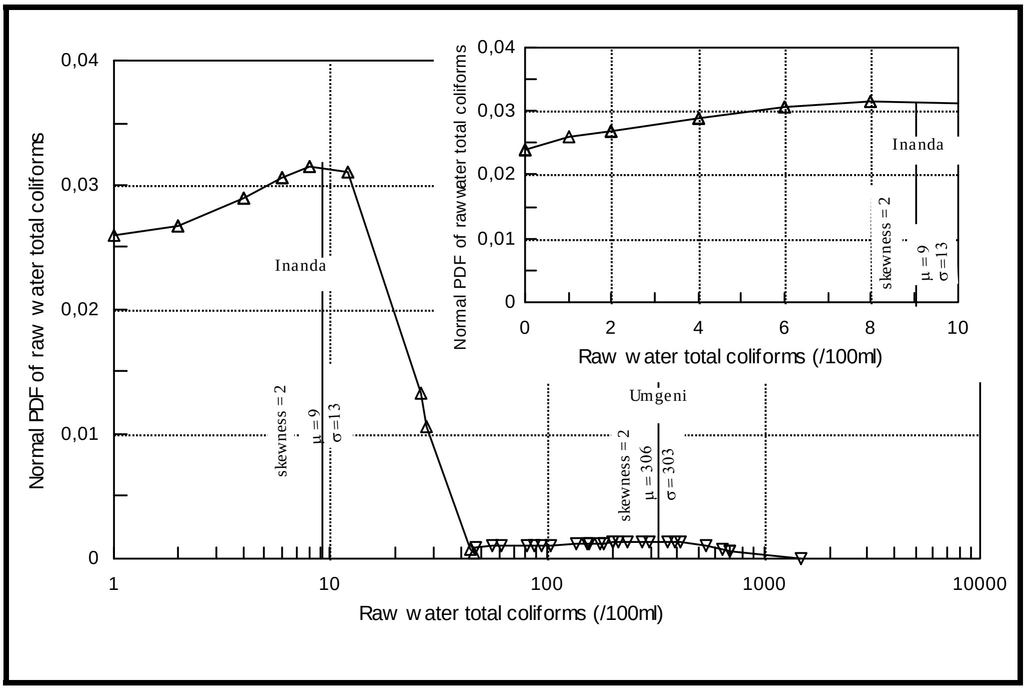


**Figure 6.38: Normal PDF distribution of total coliforms in the raw and filtered water of SSF2 operated at 0,1 m/h showing the effect of raw water source. The inset highlights *Inanda raw water* total coliform data up to 10 cells/100 mℓ.**

Figure 6.39 indicates the following observations:

- There was a 100 % probability of the filtered water conforming to the NHRs limit for a raw water SPC at 37 °C up to 300 cells/mℓ.
- There was a 100 % probability of the filtered water conforming to both the IHRs and LHRs limits for a raw water SPC at 37 °C concentrations up to 3 000 cells/mℓ.
- The sharp decline in the probability of the filtered water, conforming to the NHRs limit, beyond a raw water SPC at 37 °C concentration of 300 cells/mℓ indicates a sharp increase in the filtered water SPC at 37 °C in this region.
- The exceeding of the NHRs limit, shown in Fig. 6.40, for *Umgeni raw water* above a SPC at 37 °C of 300 cells/mℓ is also indicated by the *troughs,* in Fig. 6.39, occurring above a SPC at 37 °C of 300 cell/mℓ.

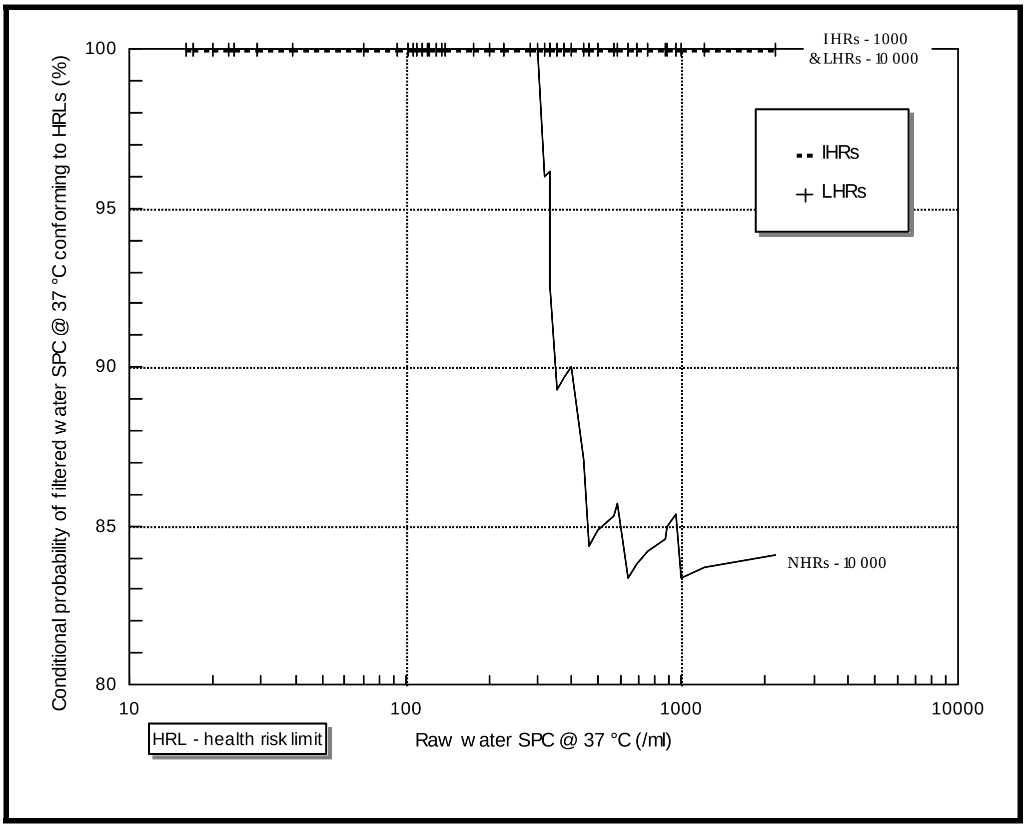


**Figure 6.39: Conditional probability of filtered water (SSF2 operated at 0,1 m/h) SPC at 37 °C conforming to the HRLs as a function of raw water total coliforms**

In addition to confirming the observations shown in Fig. 6.39, Fig. 6.40 also indicates the following observations:

- *Inanda filtered water* consistently conformed to the NHRs limit even during *filter recovery*.
- The exceeding of the NHRs limit occurred for the treatment of *Umgeni raw water* during both *filter recovery* and *normal filtration*.
- *Umgeni raw water*, however, conformed to the IHRs limit during both *filter recovery* and *normal filtration*.

Therefore the effect of filter cleaning was not significant for the treatment of *Umgeni* and *Inanda raw water* regarding the IHRs and NHRs limits respectively. The removal of SPC at 37°C is generally an indicator of treatment efficiency. The SSF treatment efficiency of both *Umgeni* and *Inanda raw water* can therefore be considered to be acceptable.

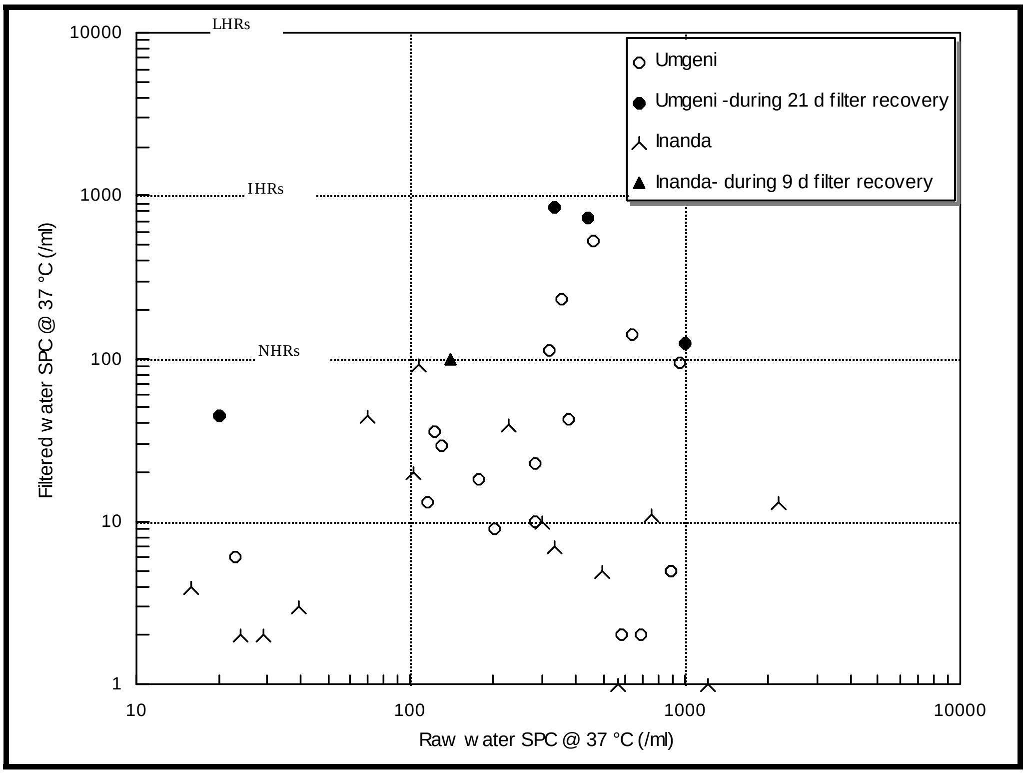


**Figure 6.40: SPC at 37 °C removal in sedimentation-SSF2 train with SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source.**

Figure 6.41 shows that:

- *Inanda raw water* had a slightly higher SPC at 37 °C concentration than *Umgeni raw water*, a mean of 446 cells/mℓ compared to 398 cells/mℓ respectively.
- The concentration of the SPC at 37 °C in *Inanda filtered water* was nevertheless still lower than that of the *Umgeni filtered water,* a mean of 18 cells/mℓ compared to 122 cells/mℓ respectively.

*Umgeni raw water* was treated for about 300 d before the *Inanda raw water* came on line. Therefore *Inanda raw water* was treated by a more mature SSF bed. The above observations indicates the role of a mature SSF bed in microbiological removal. Microbiological removal increases with increasing SSF bed maturity.

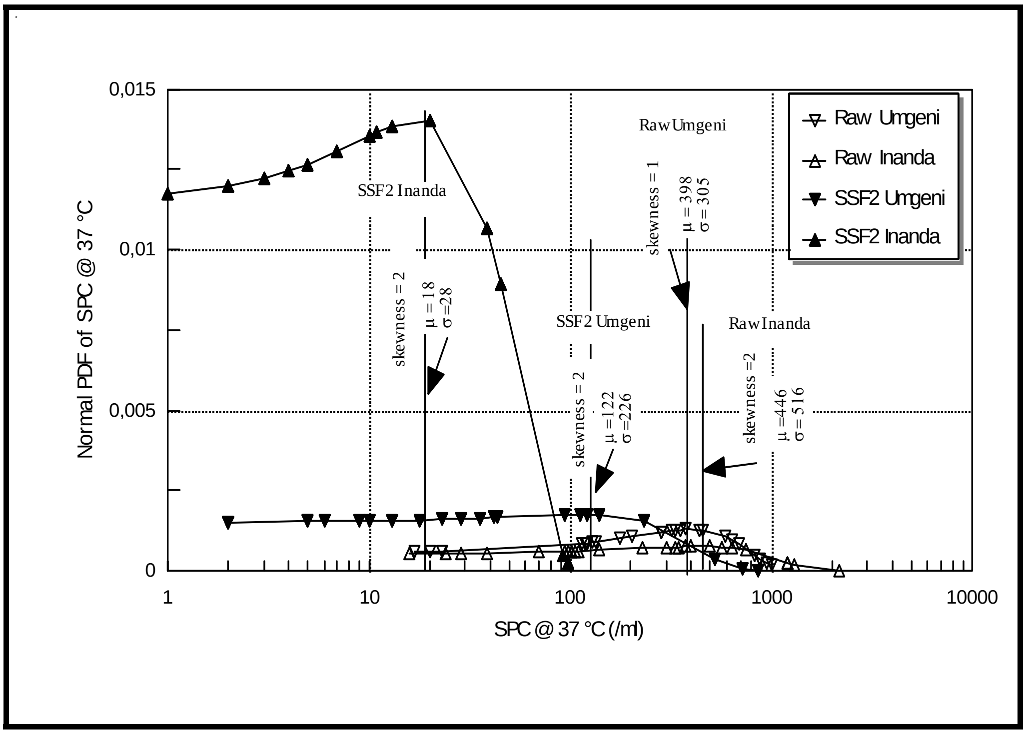


**Figure 6.41: Normal PDF distribution of SPC at 37 °C in the raw and filtered water of SSF2 operated at 0,1 m/h showing the effect of raw water source.**

Figures 6.36 to 6.41 all indicate an increase in the filtered water concentration of total coliform bacteria and SPC bacteria at 37 °C as a function of the respective raw water concentrations. This occurred above a raw water coliform and

SPC at 37 °C concentration of 80 cells/100 mℓ and 300 cells/mℓ respectively. The above trends conformed to those described by Bellamy *et al* (1985).

The most probable removal mechanism for bacteria, due to their size relative to the filter media, is absorption onto the SSF media biofilm. Thereafter the bacteria are destroyed by other predatory organisms that exist in the SSF [Huisman and Wood, 1974; Burman, 1978]. The abovementioned maximum raw water microbiological concentration, beyond which the filtered water of the sedimentation-SSF2 train exceeded the NHRc and NHRs limits, indicates either of the following:

- The biofilms on the sand of the SSF became saturated thus reducing the contact time of the pre-treated water microbiology with the SSF media.
- The predatory organism concentration of the SSF could not handle concentrations of total coliforms and SPC at 37 °C beyond 80 cells/100 mℓ and 300 cells/mℓ respectively.
- Channelling of the pre-treated water in some parts of the SSF media resulted in insufficient or no contact time with the biofilms on the SSF media. This can be related to air binding which is discussed by Seelaus *et al* (1986) and Huisman and Wood (1974). Fissures, within the sand media, allow water to pass through part of the SSF bed without adequate purification. Fissures can develop within the SSF media because of the following:
    - Large pressure drops across the *schmutzedecke* cause the dissolved oxygen in algae laden water to form bubbles. These bubbles eventually burst thus causing fissures..
    - The filling of water into the SSF, during commissioning or after filter cleaning, from above the sand media.

Figures 6.42 and 6.43 show the *E. Coli* and *F. Strep*. removal respectively. The insets of Figs. 6.42 and 6.43 show the *outliers* of *E. Coli* and *F. Strep*. removal respectively. The concentration effect of the raw water *E. Coli* followed a similar trend as the total coliforms. This should be expected since *E. Coli* forms part of the total coliform group. Datta and Chaudhuri (1991) observed that the SSF bed harbours a microbial population that is capable of inactivating enteric micro-organisms throughout the filter bed, with the top 100 to 250 mm of the bed being the most active layer.

The filtered water *F. Strep.* counts were almost consistently below the IHRf limit. This was possibly because the *F. Strep.* in the raw water was mainly below a 100 cells/100mℓ indicating little animal pollution of the raw water.

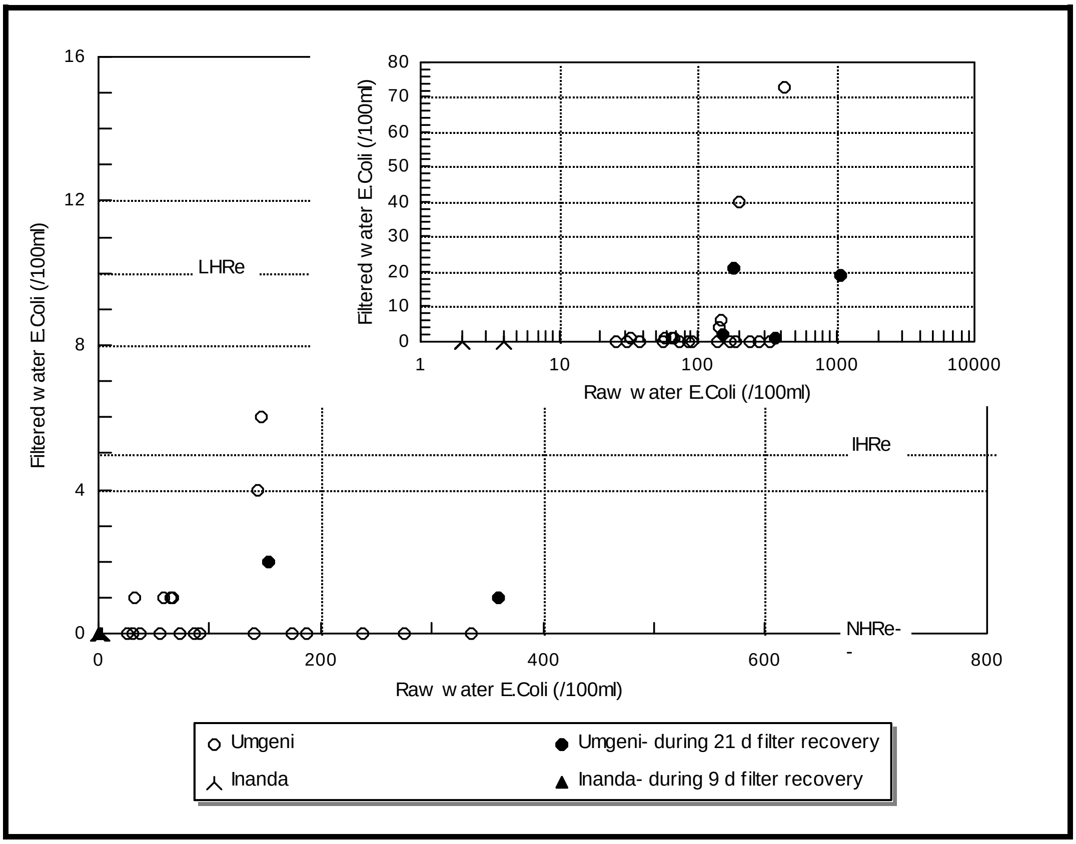


**Figure 6.42: *E. Coli* removal in sedimentation-SSF2 train with SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source. The inset includes outlying data.**

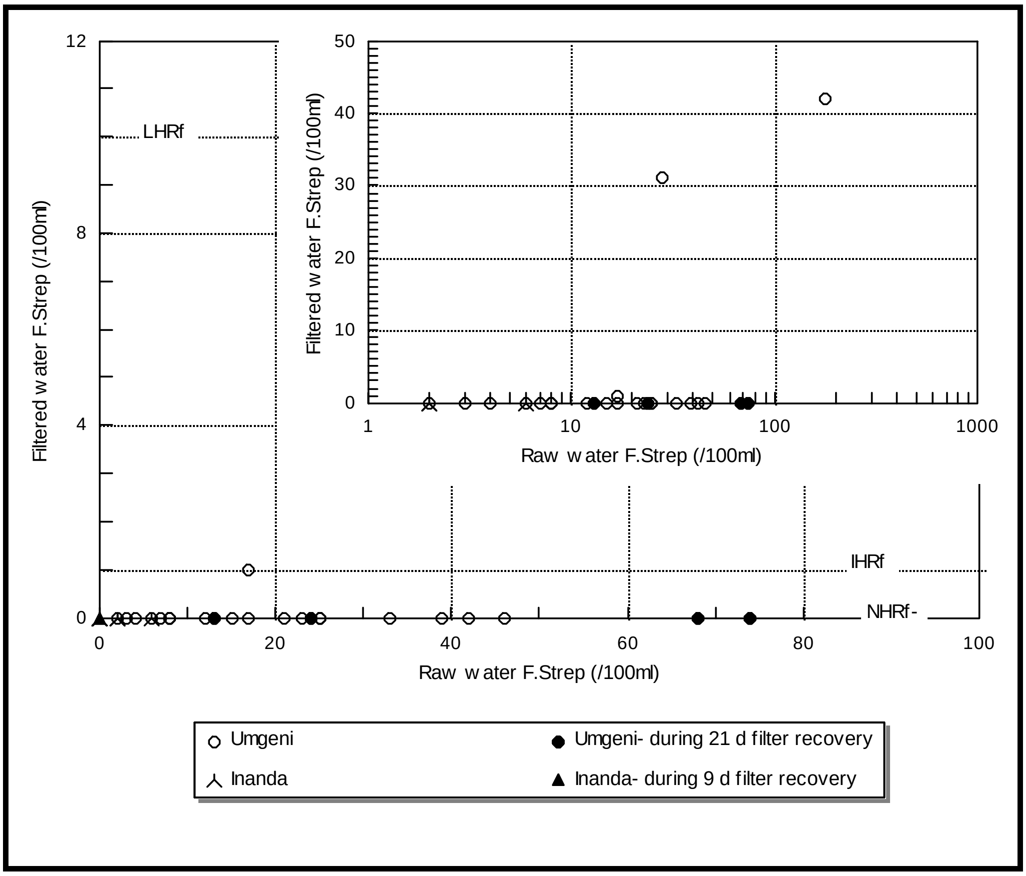


**Figure 6.43:** ***Faecal Strep.*** **removal in sedimentation-SSF2 train with SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source. The inset includes outlying data.**

Figure 6.44 shows the SPC at 22°C removal in the plain sedimentation-SSF2 train. The DOH did not specify HRLs for SPC at 22 °C. However it is observed that:

- filter cleaning generally did not cause a significant increase in the SPC at 22 °C of the filtered water.
- *Umgeni* and *Inanda raw waters* were both generally higher than a 100 cells/mℓ with respect to SPC at 22 °C.
- the SPC at 22 °C concentration of *Inanda filtered water* was, however, lower than the *Umgeni filtered water*. This can be seen more clearly in Fig. 6.45 which shows the normal probability distributions of the *Inanda filtered water* and *Umgeni filtered water* SPC at 22°C.

This again indicated the effect of the filter bed maturity on the improved performance of the SSF when the *Inanda raw water* came on line.

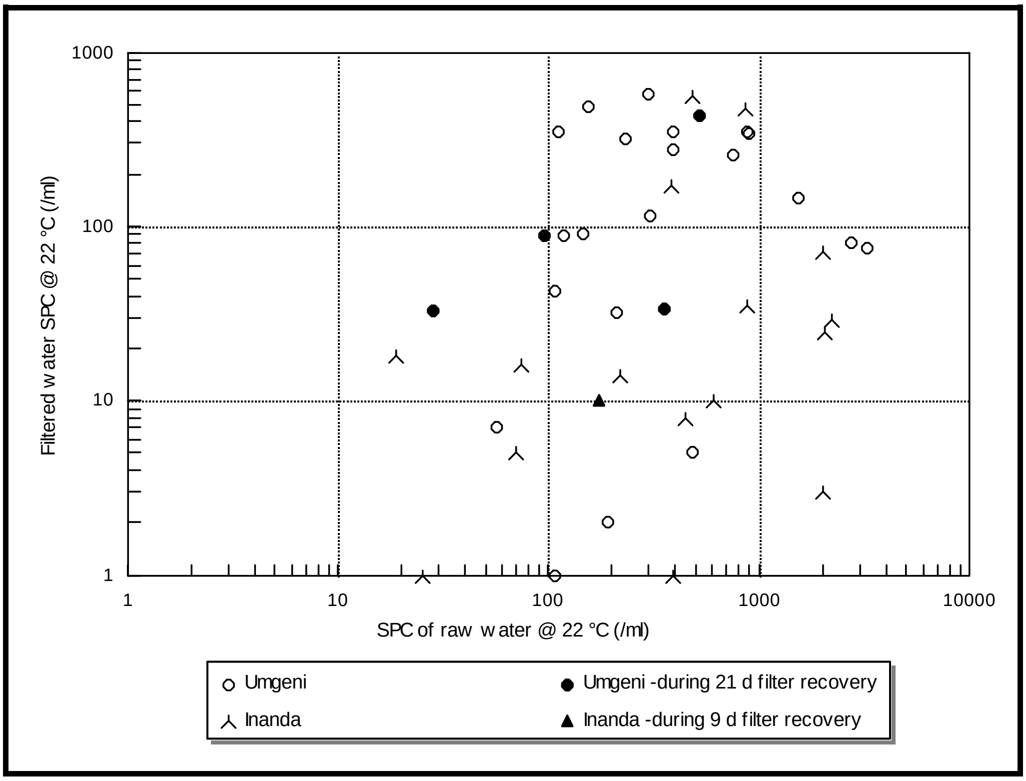


**Figure 6.44: SPC at 22 °C removal in the sedimentation-SSF2 train with SSF2 operated at 0,1 m/h also showing the effect of filter cleaning and raw water source.**

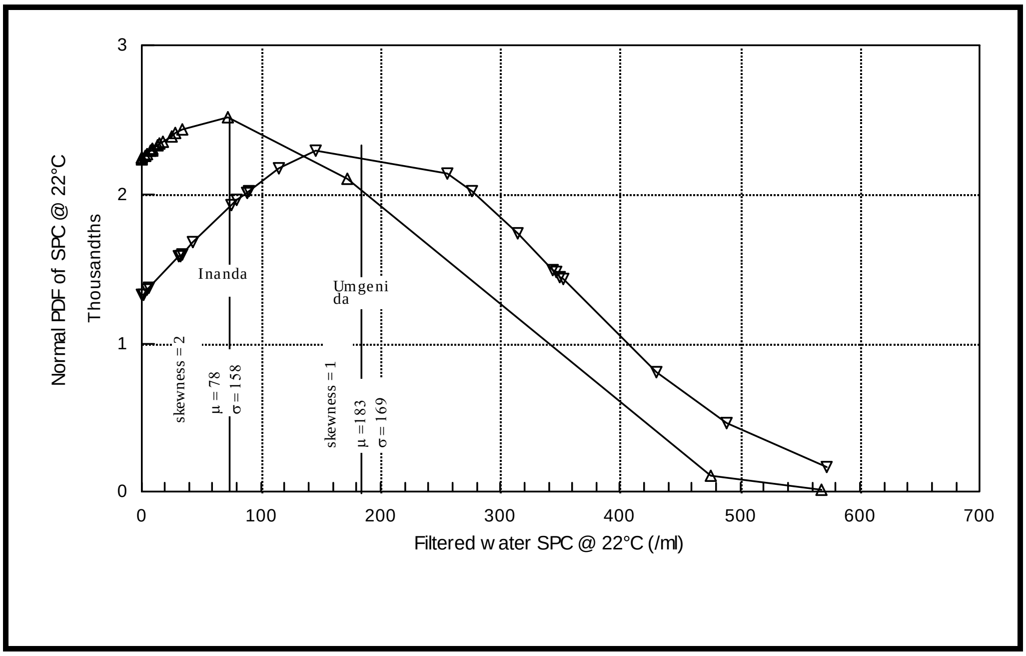


**Figure 6.45: Normal PDF distribution of SPC at 22 °C in the filtered water of SSF2 operated at 0,1 m/h showing the effect of raw water source.**

### 6.3.2 Biological removal of slow sand filter

The DOH does not indicate a limit for the algae content of drinking water. Nevertheless, Table 6.5 indicates a 100 % removal of algae by the SSF.

The two results for the plain sedimentation tank indicate a 30 % reduction on the one hand and a 167 % increase on the other. The plain sedimentation tank was poorly covered with black plastic and on numerous occasions it was left uncovered. The latter instance, in the summer, indicated algae growth in an uncovered plain sedimentation tank.

**Table 6.5: Algae concentration and removal in sedimentation tank, SSF1 and SSF2**

| Date | Sedimentation | | SSF1 | | SSF2 | |
|---|---|---|---|---|---|---|
| | concentration /mℓ | removal % | concentration /mℓ | removal % | concentration /mℓ | removal % |
| 07/02/94 | 88.0 | 30.3 | 0.0 | 100.0 | 0.0 | 100.0 |
| 17/02/94 | 270.0 | -167.3 | 0.0 | 100.0 | 0.0 | 100.0 |
| *06/01/95* | *380.0* | - | *0.0* | *100.0* | *0.0* | *100.0* |
| *26/01/95* | *51.0* | - | *0.0* | *100.0* | *0.0* | *100.0* |
| *23/03/95* | *1,622.0* | - | *0.0* | *100.0* | *0.0* | *100.0* |
| *14/03/95* | *716.0* | - | *0.0* | *100.0* | *0.0* | *100.0* |
| *27/03/95* | *3,676.0* | - | *0.0* | *100.0* | *0.0* | *100.0* |
| *16/05/95* | * | - | *0.0* | *100.0* | *0.0* | *100.0* |
| *20/06/95* | *337.0* | - | *0.0* | *100.0* | *0.0* | *100.0* |

- no raw water results    * no pre-treated water result. Umgeni and Inanda water sources indicated by normal and italic fonts respectively

Algae growth is generally a problem in a raw water impoundment despite its relatively better quality water when compared to a river. The penetration of light into an impoundment is a possible reason for its higher algae growth. The above results are an indication that the SSF is able to overcome the effects of algae growth in an impoundment, an uncovered raw water storage tank or an uncovered SSF. However, provision should normally be made for a cover when designing a raw water storage tank and a SSF.

## 6.4 EFFECT OF FILTRATION RATE AND UPFLOW RATE

The plants were first commissioned in August 1993 (0 d) and sampling was concluded in July 1995 (approximately 700 d). SSF2 operated almost consistently at a filtration rate of 0,1 m/h and therefore can be considered as the control filter. SSF1 was generally operated at 0,2 m/h and during the latter part of the run, from December 1995, it was operated at filtration rates as high as 0,5 m/h, as indicated in Fig. 6.46.

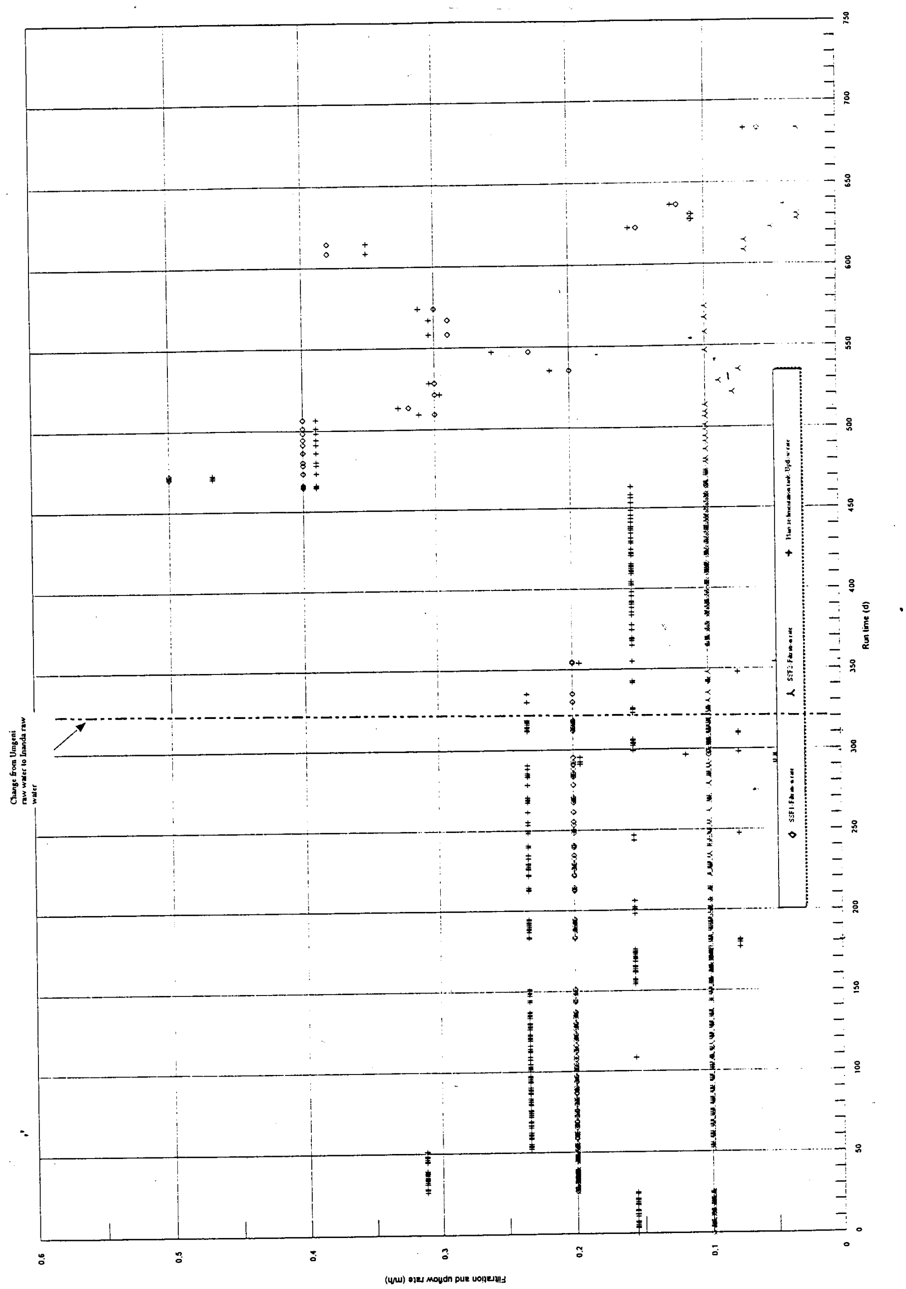

**Figure 6.46: Comaparison of filtration rates for SSF1 and SSF2 also showing the upflow rate of the plain sedimentation tank**

Figure 6.47 indicates the following observations:

- SSF1 and SSF2, which were operated at 0,1 to 0,5 and 0,1 m/h respectively, filtered pre-treated water turbidities up to 2 NTU and 4 NTU respectively. The resultant filtered water conformed to the NHRt.

- The filtered water turbidity with respect to the IHRt limit was not significantly affected by filtration rate.

Thus operation of the SSF at lower filtration rates was able to produce filtered water, conforming to the NHRt limit, from higher turbidity feed water.

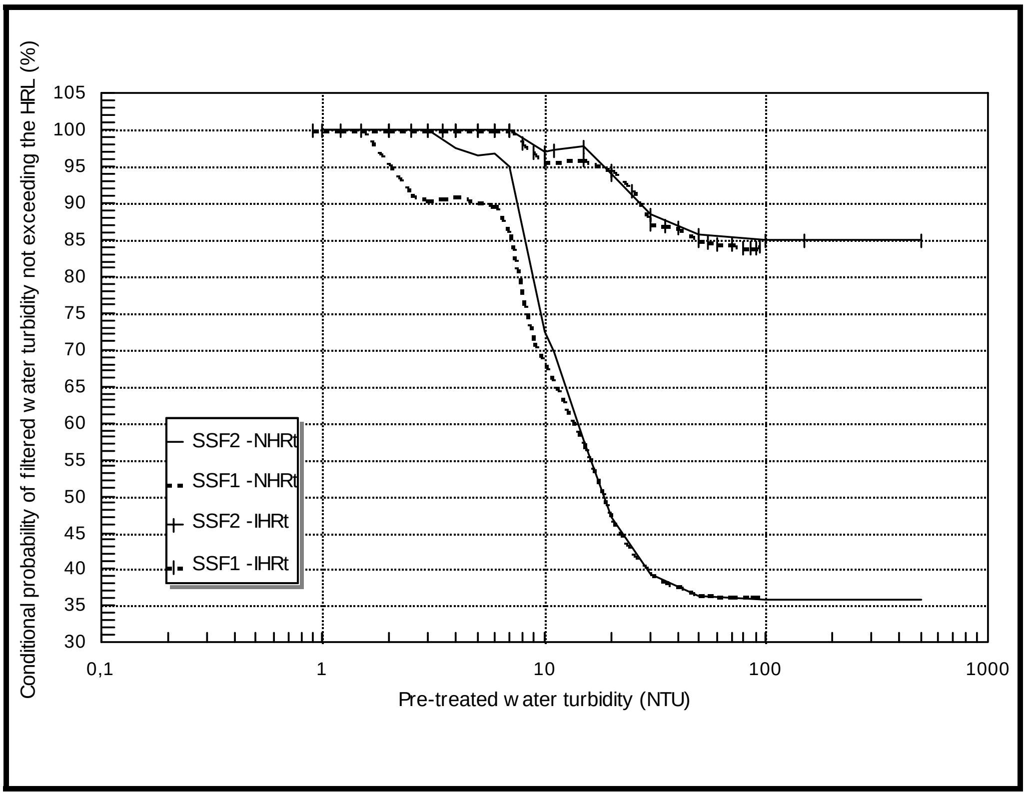


**Figure 6.47: Turbidity removal performance of SSF1 (0,1 to 0,5 m/h) and SSF2 (0,1 m/h) showing the effect of filtration rate.**

Tables 6.6 and 6.7 show the distribution characteristics of the filtered water of SSF1 and SSF2 respectively in an attempt to investigate the effect of raw water source and filter cleaning on the filtered water and to add to the observations made about filtration rate from Fig. 6.47. Only the data corresponding to filtration rates of 0,2 to 0,5 m/h was analysed for the distribution characteristics of SSF1 although it was sometimes operated at 0,1 m/h (see Fig. 6.46). The graphical format was not used because of the poor presentation caused by the following factors:

- There was a large difference in the distribution of data between *Umgeni* and *Inanda filtered water*. The narrow distribution of the *Inanda filtered water* data, added to its proximity to the y-axis, was not clearly presented.

- There was relatively fewer data during *filter recovery* relative to *normal filtration*. Thus the characteristic bell-shaped curve of the normal probability distribution could not be drawn with the data of the *filter recovery* period.

The following observations were made from Tables 6.6 and 6.7:

- *Inanda filtered water,* during *normal filtration,* did not exceed the NHRt limit despite the high filtration rates of SSF1.
- *Inanda filtered water* exceeded the NHRt limit during the *filter recovery* period of SSF1, although not very significantly. The mean *Inanda filtered water* turbidity was 1,1 NTU compared to the NHRt limit of 1 NTU. The skewness value of -0,3 indicates a *light turbidity tail* during the Inanda *filter recovery period* of SSF1. The upper 400 mm of SSF1 was resanded during the period of *Inanda raw water* filtration. Resanding of the filter bed poses a greater risk to exceeding the NHRt limit than filter cleaning where only the upper 20 to 30 mm of filter media is removed.
- *Umgeni filtered water* exceeded the NHRt limit at both the high and low filtration rates of SSF1 and SSF2 respectively during both *normal filtration* and *filter recovery.*

Thus the results of Fig. 6.47 showing that SSF1, operated at high filtration rates, was not able to filter high turbidity water occurred mainly during the period when *Umgeni raw water* was on line to the SSF. The high filtration rates between 0,2 and 0,5 m/h did not affect the SSF performance when the low turbidity *Inanda raw water* was on line except after a resanding operation.

**Table 6.6: Filtered water turbidity distribution characteristics of SSF1, operated at 0,2 to 0,5 m/h, indicating the effect of high filtration rates, raw water source and filter cleaning on filtered water turbidity**

| | *Umgeni filtered water* turbidity (NTU) | | *Inanda filtered water* turbidity (NTU) | |
|---|---|---|---|---|
| | during *normal filtration* | during *filter recovery* | during *normal filtration* | during *filter recovery* |
| Mean | 6.9 | 5.3 | 0.2 | 1.1 |
| Standard deviation | 20.9 | 7.2 | 0.1 | 0.1 |
| Skewness | 8.5 | 4.9 | 2.3 | -0.3 |

NHR = 1 NTU, IHR = 5 NTU, LHR = 10 NTU

**Table 6.7: Filtered water turbidity distribution characteristics of SSF2, operated at 0,1 m/h, indicating the effect of low filtration rates, raw water source and filter cleaning on filtered water turbidity**

| | *Umgeni filtered water* turbidity (NTU) | | *Inanda filtered water* turbidity (NTU) | |
|---|---|---|---|---|
| | during *normal filtration* | during *filter recovery* | during *normal filtration* | during *filter recovery* |
| Mean | 5.5 | 3.2 | 0.4 | 0.9 |
| Standard deviation | 15.3 | 3.5 | 0.1 | 0.4 |
| Skewness | 11.6 | 1.2 | 0.2 | 1.3 |

NHR = 1 NTU, IHR = 5 NTU, LHR = 10 NTU

The SPC at 37 °C is used to represent the general microbiology in this discussion on the effect of filtration rate on filtered water microbiology. SPC, in general, can be used as a measure of treatment efficiency [Department of Water Affairs and Forestry, 1993]. Figure 6.48 shows that:

- there were *troughs*, due to microbiological breakthrough in the SSF, representing a lower conditional probability of filtered water conforming to the respective HRLs than the general trend. The occurrence of the *troughs* is also explained in Sections 6.3.2.2 and 6.3.2.3.
- SSF1 and SSF2 filtered raw water SPC at 37 °C up to 25 and 300 cells/mℓ respectively to produce a filtered water conforming to the NHRs limit.

Thus operation of the SSF at lower filtration rates resulted in the filtration of higher feed microbiological content to produce filtered water conforming to the NHRs limit.

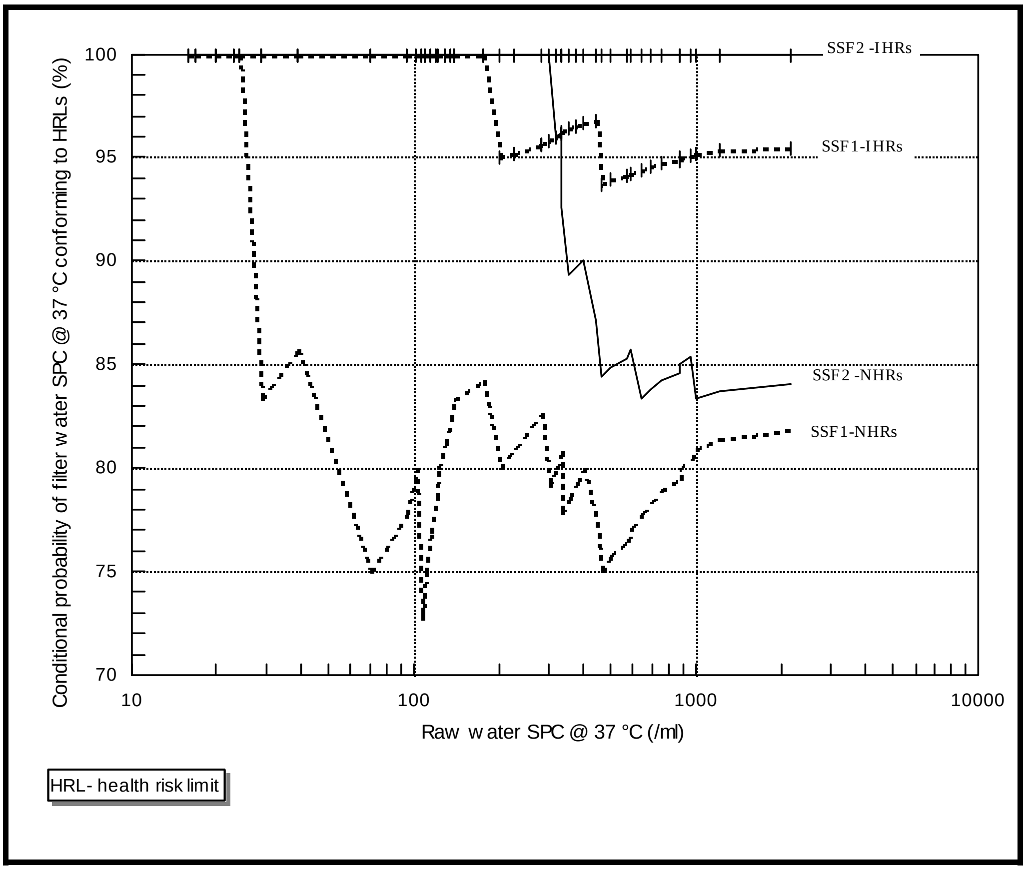


**Figure 6.48: Microbiological removal performance of SSF1 (0,1 to 0,5 m/h) and SSF2 (0,2 m/h) showing the effect of filtration rate.**

The following observations were made from Tables 6.8 and 6.9:

- The mean SPC at 37 °C of *Inanda filtered water* did not exceed the NHRs limit during both *filter recovery* and *normal filtration* at both low and high filtration rates.
- One notes that the SPC at 37 °C of *Inanda filtered water* exceeded the NHRs limit during *filter recovery* at both low and high filtration rates, when using three standard deviations around the mean to approximate 99 % of the total distribution.
- The SPC at 37 °C of *Inanda filtered water* was usually below the mean of 7 cells/mℓ during *normal filtration* at low flowrates of 0,1 m/h.

- *Umgeni filtered water* SPC at 37 °C exceeded the NHRs limit during *filter recovery* at both low and high filtration rates.
- The removal of SPC at 37 °C for both *Umgeni* and *Inanda filtered water* was more consistent when the SSF was operated at high filtration rates from 0,2 to 0,5 m/h.

The exceeding of the NHRs limit by *Inanda filtered water* can be attributed to the breakthrough of SPC at 37 °C after the resanding operation. Thus resanding a SSF, despite the low raw water microbiologically and low flowrate of 0,1 m/h, results in microbiological breakthrough. Again, one observes that the absence of the purification mechanism, discussed in Section 3.1.1.2, causes a deterioration in water quality. The *Inanda filtered water*, however, did not exceed the IHRs limit during both *normal filtration* and *filter recovery*.

**Table 6.8: Filtered water SPC at 37 °C distribution characteristics of SSF1, operated at 0,2 to 0,5 m/h, indicating the effect of high filtration rates, raw water source and filter cleaning on filtered water microbiology**

| | *Umgeni filtered water* SPC at 37 °C (/mℓ) | | *Inanda filtered water* SPC at 37°C (/mℓ) | |
|---|---|---|---|---|
| | during *normal filtration* | during *filter recovery* | during *normal filtration* | during *filter recovery* |
| Mean | 35.0 | 606.0 | 7.0 | 59.0 |
| Standard deviation | 30.0 | 735.0 | 2.0 | 45.0 |
| Skewness | 0.7 | 1.0 | -0.4 | * |

* skewness cannot be calculated since there were less than 3 samples

NHR = 100 cells/mℓ, IHR = 1 000 cells/mℓ, LHR = 10 000 cells/mℓ

**Table 6.9: Filtered water SPC at 37 °C distribution characteristics of SSF2, operated at 0,1 m/h, indicating the effect of low filtration rates, raw water source and filter cleaning on filtered water microbiology**

| | *Umgeni filtered water* SPC at 37 °C (/mℓ) | | *Inanda filtered water* SPC at 37°C (/mℓ) | |
|---|---|---|---|---|
| | during *normal filtration* | during *filter recovery* | during *normal filtration* | during *filter recovery* |
| Mean | 62.2 | 436.0 | 7.3 | 37.9 |
| Standard deviation | 119.1 | 356.6 | 10.7 | 38.4 |
| Skewness | 3.0 | 0.0 | 2.0 | 0.8 |

NHR = 100 cells/mℓ, IHR = 1 000 cells/mℓ, LHR = 10 000 cells/mℓ

A possible reason for the more consistent removal of SPC at 37 °C at the high filtration rates during *normal filtration* is that an increase in turbulence creates more contact with the microbial layers of the sand media. This was also observed by Kuntschik (1976) in an investigation on horizontal roughing filters. He suggested that the resultant increase in turbulence multiplies the chances of contact between the sand media surfaces and the suspended particles.

During *filter recovery*, the density of microbial layers is lower due to *schmutzedecke* removal. Therefore the increased contact between the suspended particles and the sand media does not assist in the removal of SPC at 37 °C during *filter recovery*.

There is a greater risk of the NHRs and IHRs limits being exceeded by *Umgeni filtered water* than *Inanda filtered water*. Indications are that *Inanda filtered water* is microbiologically and aesthetically safe even when the SSF is operated at flowrates as high as 0,5 m/h during *normal filtration*. This is significant since there is potential for an increase in potable water demand to be satisfied when *Inanda raw water* is treated.

The following observations were made from Table 6.10:

- SSF1 and SSF2 were cleaned 8 and 4 times respectively.
- The average filtration cycle time of SSF1 with respect to *Umgeni raw water* was 57 d (taking the first 5 filter cleans since the filter should have been resanded thereafter).
- The average filtration cycle time of SSF2 with respect to *Umgeni raw water* was a 108 d.
- The filtration cycle times of both filters for *Inanda raw water* was approximately one year.

Therefore the frequency of filter cleanings increased at higher filtration rates. This also implies that the filter cycle times decreased at higher filtration rates. Ellis (1987) and Fraser *et al* (1988) observed that filtration rates had a greater effect on filter cycle times rather than water quality. In addition, filtration cycle times indicate an inverse trend regarding raw water turbidity i.e. high raw water turbidities result in shorter filtration cycle times or vice versa.

**Table 6.10: Frequency of filter cleaning and the total volume of filtered water per cycle of the SSFs**

| SSF 1 | | | | SSF 2 | | | |
|---|---|---|---|---|---|---|---|
| Date | Serial time from start (d) | Filtration cycle time (d) | Total filtered water per cycle ($m^3$) | Date | Serial time from start (d) | Filtration cycle time (d) | Total filtered water per cycle ($m^3$) |
| 07/12/93 | 108.0 | 108.0 | 53.0 | | | | |
| 18/02/94 | 177.0 | 69.0 | 31.0 | | | | |
| 22/03/94 | 200.0 | 23.0 | 9.0 | 22/03/94 | 200.0 | 200.0 | 63.0 |
| 03/05/94 | 241.0 | 21.0 | 21.0 | 23/06/94 | 292.0 | 92.0 | 26.0 |
| 04/07/94 | 303.0 | 62.0 | 31.0 | | | | |
| 25/07/94 | 323.0 | 20.0 | 6.0 | 25/07/94 | 323.0 | 31.0 | 8.0 |
| *16/08/94* | *342.0* | *19.0* | 8.0 | *23/08/94* | *349.0* | *26.0* | 7.0 |
| *26/08/94* ** | *352.0* | *10.0* | 2.0 | | | | |
| *end of study* | *700.0* | *348.0* | 199.0 | *end of study* | *700.0* | *351.0* | 76.0 |

** resanded     Italics - Inanda period

The other observations made from Table 6.10 are as follows:

- Indications are that both SSFs were not able to treat the high turbidity *Umgeni raw water* by the third filtration cycle. Filtration cycle times gradually decreased to below 10 d before the *Inanda raw water* came on line. The filtration cycle time *outlier* of 62 d for SSF1 occurred because this filter was kept on line for about 21 d after the filtration rate decreased from 0,2 to 0,1 m/h. SSF1 was operated at 0,2 m/h and should have been cleaned immediately after the filtration rate dropped from 0,2 m/h.
- The treatment of high turbidity *Umgeni raw water* together with a filtration rates of twice that of SSF1 led to the resanding of SSF1. The filtration cycle time of SSF1 eventually decreased to 10 d when resanding became necessary. Resanding was also necessary when it was noticed that:
  - the filtration rate continued to fall below 0,1 m/h even after *schmutzedecke* removal thus indicating a blocked SSF.

Therefore only the first 3 filtration cycles were considered when calculating the average volume of water filtered by each of the SSFs. The average volume of filtered water for the first 3 filtration cycles were 31 and 32 $m^3$ for SSF1 and SSF2 respectively. Indications are that the SSFs produce the about the same total volume of water despite being operated at different filtration rates. Rachwal *et al* (1988) have also observed that the total volume of water filtered per cycle was essentially the same for SSFs operated at different filtration rates.

Figure 6.49 shows the filtered water turbidity data of SSF1 for 22 and 28 d after filter cleaning and resanding respectively. These periods were chosen since the literature, Huisman and Wood (1974) amongst others, indicates *filter recovery* and *ripening* periods of about 21d and 1 month respectively. The *filter recovery* periods of SSF1 were conservatively estimated, against the NHRt limit, for turbidity removal and high operating flowrates. Results, just exceeding the NHRt limit, were however taken into account. The observations were as follows:

- The *filter recovery* period exceeded 22 d with respect to *Umgeni raw water*.
- The *filter recovery* time was about 4 d with respect to *Inanda raw water*. Note, however, that there are no samples to prove that the *filter recover*y time was less than 4 d.
- The filter *ripening* time, after resanding, was 16 d for *Inanda raw water.*

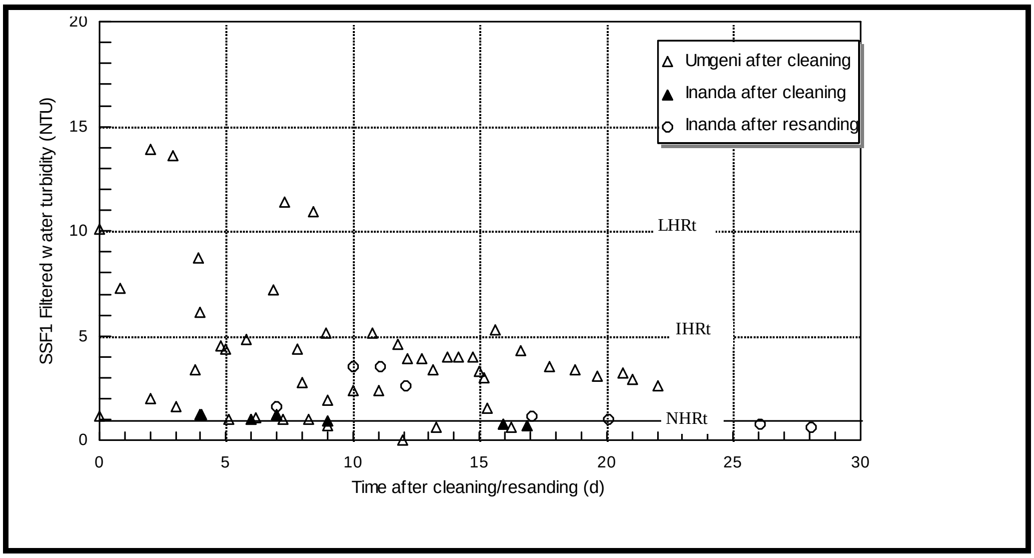


**Fig 6.49: Filtered water turbidity of SSF1, operated at 0,1 to 0,5 m/h, during 21 d after filter cleaning and 28 d after resanding, showing the time taken for *filter recovery*, filter *ripening* and the effect of raw water source.**

Figure 6.50 shows the filtered water total coliforms data of SSF1 during 22 d after filter cleaning and resanding. Note that the choice, of the period chosen to investigate the *filter recovery* and filter *ripening* times, were not consistent. This was because the sampling frequency was not consistent. The focus of this study on SSF was on water quality rather than operation.

Filtered water total coliforms was chosen to represent the general filtered water microbiology. *Filter recovery* times were conservatively estimated, against the NHRc limit, for microbiological removal and high operating flowrates. The observations , from Fig. 6.50, were as follows:

- The *filter recovery* time was about 4 d for *Inanda raw water*. There were no samples to prove that the *filter recovery* time was less than 4 d. This result tallies with the *filter recovery* time for turbidity removal.
- The filter *ripening* time, after resanding, was 22 d for *Inanda raw water*.
- The *filter recovery* time was about 22 d for *Umgeni raw water*. No samples were taken between 17 and 22 d to prove that the *filter recovery* time was less than 22 d.

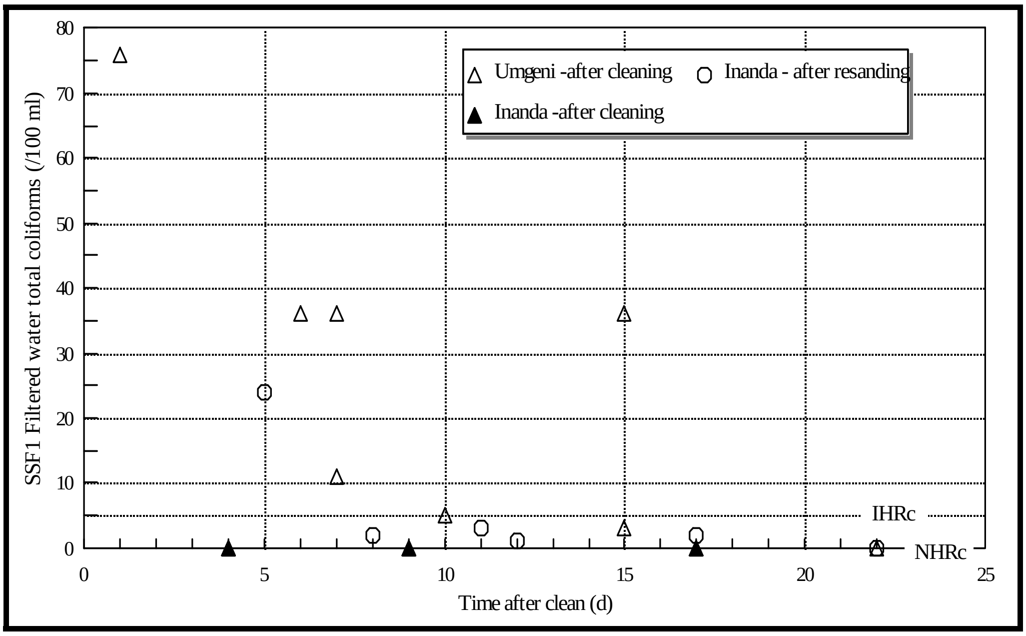


**Fig 6.50: Filtered water total coliforms of SSF1, operated at 0,1 to 0,5 m/h, during 22 d after filter cleaning and resanding, showing the time taken for *filter recovery*, filter *ripening* and the effect of raw water source.**

Now, considering both the filtered water turbidity and microbiology results for SSF1, one notes the following conservative estimates of *filter recovery* times:

- The *filter recovery* time for the treatment of *Umgeni raw water* exceeded 22 d.
- The *filter recovery* time for the treatment of *Inanda raw water* was 4 d.
- The time taken for filter *ripening* was 22 d for the treatment of *Inanda raw water.*

Section 6.3.1.2 indicated overall *filter recovery* times of 9 d and over 21 d for *Inanda* and *Umgeni raw water* respectively. These *filter recovery* times were for SSF2 operated at 0,1 m/h. Note that SSF1 was operated at higher filtration rates from 0,1 to 0,5 m/h. The observations, with respect to both SSF1 and SSF2, were as follows:

- The treatment of high turbidity *Umgeni raw water,* at filtration rates of 0,1 to 0, 5 m/h, resulted in a *filter recovery* time of over 21 d.
- The reason for the difference in *filter recovery* times between SSF1 and SSF2, for *Inanda raw water,* was the frequency of sampling. The soonest that SSF1 and SSF2 were sampled, after filter cleaning, were 4 and 8 d respectively. Thus the treatment of *Inanda raw water*, despite the high filtration rates up to 0,5 m/h, resulted in a *filter recovery* time of 4 d. This *filter recovery* time can potentially be less than 4 d considering that no samples were taken prior to this to prove otherwise.

It is thus operationally beneficial to treat *Inanda raw water* since it results in over a 57% lower filter downtime than *Umgeni raw water,* considering *filter recovery* times of 9 and over 21 d respectively. The downtime for the treatment of *Inanda raw water* can be over 81 % lower than that of *Umgeni raw water,* considering *filter recovery* times of 4 and over 21 d respectively. In addition, the *filter recovery* time, for the treatment of *Inanda raw water*, can be reduced to 0 d if post-disinfection is practised during this time and if one is prepared to accept an occasional filtered water turbidity within the IHRt range. One must note that the general IHR limit is still a relatively safe limit according to the DOH (1994).

An attempt was made to confirm the influence of the upflow rate of the plain sedimentation step on microbiological removal despite the limited data available in Table 6.11. The results of Table 6.11 are from samples taken after the changeover to *Inanda raw water*.

The exceeding of the design upflow rate of 0,3 m/h in the plain sedimentation step, resulted in low total coliform removals of 0 to 50 %. These increases in upflow rate occurred during the period when the filtration rate of SSF1 was increased to above 0,3 m/h. There was no effect of the increase in upflow rate of the plain sedimentation step on the total coliform removal of the SSFs.

There was an increase in total coliforms of 512 % on one occasion. This could have been as a result of:

- contamination on the open water surface of the sedimentation tank
- not following the correct sampling procedure viz. flushing sample point with sampled water for 5 minutes and heating the sample pipe with a flame. This is related to bacterial regrowth in the sample pipe.
- laboratory measurement error or sample switching.

Although the plain sedimentation step removed from 0 to 93,5 % of the total coliforms, the total coliforms counts in the *Inanda raw water* were too low to state confidently that plain sedimentation had a major influence in improving the microbiological removal of SSFs.

**Table 6.11: Individual coliform removal in the plain sedimentation tank and the SSFs with respect to the *Inanda raw water* source**

| **Raw water** | **Sedimentation tank** upflow rate (m/h) | removal (%) | conc. (/100mℓ) | **SSF 1** conc. (/100mℓ) | removal % | **SSF 2** conc. (/100mℓ) | removal % |
|---|---|---|---|---|---|---|---|
| 2.0 | 0.5 | 50.0 | 1.0 | - | - | - | - |
| 4.0 | 0.4 | 0.0 | 4.0 | - | - | 0.0 | 100.0 |
| 6.0 | 0.4 | 0.0 | 6.0 | 0.0 | 100.0 | - | - |
| 0.0 | 0.2 | 0.0 | 0.0 | - | - | 0.0 | 100.0 |
| 46.0 | 0.1 | 93.5 | 3.0 | 0.0 | 100.0 | - | 1.2 |
| 12.0 | 0.1 | 83.3 | 2.0 | 0.0 | 100.0 | - | - |
| 6.0 | 0.4 | -512.0 | 37.0 | - | - | - | - |

- no data available   conc. - concentration

# 7 CONCLUSIONS

The overall objective of this thesis was to investigate the quality of water obtained by slow sand filtration of Umgeni river and Inanda impoundment water. A general distinction was made between health and aesthetic water quality.

An attempt was made by the DOH (1994) to be more pragmatic and to rather impose a set of provisional guidelines and not water quality standards. These guidelines are divided into a set of four health risk ranges viz. :

i) The *no health risk* (NHR) range which is the primary limit which ideally should be striven for.

ii) The *insignificant health risk* (IHR) range which is a less stringent secondary limit. This range is still a safe one but should not normally be exceeded. Where the concentration of a particular determinand exceeds the IHR limit, the planning/action to reduce the concentration of the determinand should be instituted without delay.

iii) The *low health risk* (LHR) range which constitutes minimal risk to individuals.

iv) The *unacceptable health risk* (UHR) range at which serious health effects may occur if the water is consumed for any length of time.

Only the NHR, IHR and LHR ranges have been indicated in this study. The performance of the SSF in producing potable water quality was, however, evaluated against its conformance to the NHR and IHR ranges. Where possible, an investigation was also made on the operating and design parameters that produce water of potable quality.

Detailed **objectives** were to investigate the relationship between:

i) raw water source and the performance of the SSF.

ii) raw water turbidity and the performance of plain sedimentation as well as the performance of the entire treatment system.

iii) pre-treated water turbidity and the performance of the SSF.

iv) bacteria concentration in the raw water and the performance of the whole treatment system.

v) turbidity and microbiological content of the raw water.

Other objectives included determining:

vi) the quality of the raw and pre-treated water that could be treated to produce potable water by the plain sedimentation-SSF train and SSF respectively.

vii) treatment variations that include SSF if potable water quality guidelines are not met.

viii) the effect of filter cleaning on the filtered water quality.

ix) the effect of filtration rates on the filtered water quality.

x) the effect of the level of microbiological maturity in the filters on the filtered water quality.

xi) the effect of the time lag, caused by the residence time in the sedimentation tank and SSF, on sampling.

The **conclusions** are listed as follows:

(1) Overall this thesis has found that the change from the high turbidity Umgeni river water to the low turbidity Inanda impoundment water was suited to a simple treatment process like SSF. The treatment of *Inanda raw water* was beneficial in terms of both SSF operation and filtered water quality. Indications are that *Inanda filtered water* is microbiologically and aesthetically safe even when the SSF is operated at filtration rates as high as 0,5 m/h during *normal filtration* i.e. after *filter recovery*. Thus SSF is a useful treatment process for an impounded water source where natural treatment processes like settling are already taking place. Slezak and Sims (1984) and Rook (1976) have also reported that SSF can best be used to treat an impounded water source. Visscher (1990) mentioned that the filtration rate can be increased up to 0,6 m/h if very good quality raw water is being treated.

(2) Overall, a slow sand filter feed water turbidity of 7 NTU resulted in the filtered water conforming to both aesthetic and microbiological guidelines (see Tables 7.1 and 7.2). Post-disinfection of the filtered water is still necessary for this feed water turbidity, especially during *filter recovery*. Microbiological breakthrough, which accompanies turbidity breakthrough, results during *filter recovery*.

(3) The exceeding of the NHR limit by filtered water microbiology and turbidity was attributed mainly to *Umgeni raw water*. *Umgeni raw water* was higher in turbidity than *Inanda raw water*. Thus *Umgeni raw water* consisted of a higher suspended solids content than *Inanda raw water*. Micro-organisms tend to attach onto these suspended solids.

The turbidity of *Umgeni raw water*, rather than *Inanda raw water*, was more affected by seasonal changes. The turbidity in rivers can be attributed mainly to soil erosion which occurs in the rainy spring and summer seasons. The settling of solids that takes place in an impounded water source has a dampening effect on the high solids loading of the rainy seasons.

(4) The raw and pre-treated water turbidity values resulting in the conformance to the respective HRLs, with a probability of 100 %, with respect to a SSF operated at 0,1 m/h are summarised in Table 7.1.

**Table 7.1: Summary of raw and pre-treated water turbidity values resulting in the conformance to the filtered water turbidity health risk limits, with a probability of 100 %, in a SSF operated at 0,1 m/h.**

| Raw water turbidity (NTU) | | | | | | | | Pre-treated water turbidity (NTU) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NHRt | | | | IHRt | | | | NHRt | | | | IHRt | | | |
| *Filter recovery* included | | *Filter recovery* excluded | | *Filter recovery* included | | *Filter recovery* excluded | | *Filter recovery* included | | *Filter recovery* excluded | | *Filter recovery* included | | *Filter recovery* excluded | |
| U | I | U | I | U | I | U | I | U | I | U | I | U | I | U | I |
| 75.0 | 4.0 | 7.5 | 12.0 | 10.0 | 12.0 | 10.0 | 12.0 | 6.0 | 3.0 | 6.5 | 7.0 | 7.5 | 7.0 | 7.5 | 7.0 |

NHRt = 1 NTU, IHRt = 5 NTU

(5) The SSF did not handle high turbidity shock loads as indicated by an incident where the raw water turbidity peaked at 4000 NTU (refer to discussion on Fig. 6.15) and the increasing trend of filtered water turbidity with both raw and pre-treated water turbidity. Cullen and Letterman (1985) mentioned that the factor that seemed to have the most significant effect on the filtered water quality was the amount and nature of the particulate material present in the raw water. Section 6.2.1.1 indicated that a higher turbidity *Inanda raw water*, than *Umgeni raw water*, resulted in a filtered water turbidity that did not exceed the NHRt limit.

} A possible reason for this was that *Umgeni raw water* was composed of clay or colloidal material that passed through the plain sedimentation tank and SSF. This is in line with findings by Fraser *et al* (1988) that a deterioration in filtered water quality was caused by high levels of colloidal material present in the raw water.

(6) Conclusions on raw water microbiology are as follows:

} Levels of *E. Coli*, total coliforms and *F. Stre*p were lower in *Inanda raw water* than *Umgeni raw water*.

} Levels of SPC at 22°C and 37 °C were similar for both *Umgeni* and *Inanda raw water*.

} There was a general increase in *Umgeni raw water* microbiology during the summer. There is a greater chance of micro-organisms attaching to the higher turbidity (or suspended solids) of the raw water during the summer season (see Conclusion 3).

} There was no noticeable seasonal effect on the *Inanda raw water* microbiology. A possible reason for this is the dampening effect of settling of suspended solids, and the attached micro-organisms, in an impounded water source.

(7) It is much simpler and convenient to monitor turbidity than microbiology. Turbidity monitoring is especially useful in rural water treatment applications.

Since the aesthetic water quality is usually the first and simple warning indicator of an unhealthy water supply, it will be useful to develop a rough idea of microbiological water quality by monitoring turbidity in the raw, pre-treated and filtered waters. Conclusions on the relationship between turbidity and microbiology are as follows:

} There was an exponential increase of raw water total coliforms up to a raw water turbidity of 10 NTU. The total coliforms above a raw water turbidity of 10 NTU were reasonably constant.

} The raw, pre-treated and filtered water turbidity values that resulted in conformance to the filtered water microbiological HRLs, with a probability of 100 %, with respect to the SSF operated at 0,1 m/h are summarised in Table 7.2. *Umgeni raw, pre-treated* and *filtered waters* were seldom within the low turbidity ranges reached by the respective *Inanda water*. This does not mean that the treatment of higher turbidity *Umgeni raw water* by the SSF resulted in the same potable quality filtered water as that of the treatment of low turbidity *Inanda raw water*. A distinction between *Umgeni* and *Inanda water* was therefore not made in this instance since it would be misleading.

**Table 7.2: Summary of raw, pre-treated and filtered water turbidity values resulting in the conformance to the filtered water microbiology HRLs, with a probability of 100 %, in a SSF operated at 0,1m/h.**

| | Turbidity wrt filtered water total coliforms HRL | | | | Turbidity wrt filtered water SPC at 37 °C HRL | | | |
|---|---|---|---|---|---|---|---|---|
| | NHRc | | IHRc | | NHRs | | IHRs | |
| | *Filter recovery* included | *Filter recovery* excluded | *Filter recovery* included | *Filter recovery* excluded | *Filter recovery* included | *Filter recovery* excluded | *Filter recovery* included | *Filter recovery* excluded |
| raw water | 3.8 | 8.0 | 3.8 | 8.0 | 11.0 | 25.0 | 73.0 | 73.0 |
| pre-treated water | 1.6 | 8.0 | 1.8 | 8.0 | 8.0 | 19.0 | 50.0 | 50.0 |
| filtered water | * | 3.0 | * | 3.0 | 1.5 | 2.5 | 30.0 | 30.0 |

wrt - with respect to HRL - health risk limit * no results with respect to 100 % removal

NHRc = 0 cells/100ml, IHRc = 5 cells/100ml, NHRs = 100 cells/ml, IHRs = 1 000 cells/ml

(8) Conclusions with respect to filter cleaning, by removal of the upper 20 to 30 mm of *schmutzedecke*, for filtration rates of 0,1 to 0,5 m/h, are as follows:

- There was an increasing trend of filter cleaning frequency with respect to raw water turbidity.
- Filter cleaning had no effect on the filtration of the already high turbidity and high microbiology *Umgeni raw water* which generally exceeded the respective NHR and IHR limits.
- Filter cleaning affected the filtration of the low turbidity *Inanda raw water* which otherwise conformed to the NHRt limit. Filter cleaning, however, did not affect the filtration of the *Inanda raw water* microbiology which consistently conformed to the NHRt limit during *filter recovery* when the SSF was operated at 0,1 m/h.
- The *filter recovery* period for *Umgeni raw water* exceeded 21 d. The *filter recovery* period for *Inanda raw water* was 4 d. The treatment of *Inanda raw water* , compared to *Umgeni raw water,* therefore resulted in over a 81 % saving in downtime.

(9) Resanding, of the upper 400 mm of the sand bed, was more detrimental than filter cleaning. This can be expected in the light of findings made by Huisman and Deazevedonetti (1981) and Poynter and Slade (1977). The former pair found that full microbiological activity extends over a depth of 600 mm of the SSF media. The latter pair pointed out that bacterial removal is a microbiological process.

Resanding of the SSF resulted in both turbidity and microbiological breakthrough for the treatment of *Inanda raw water*. This led to the exceeding of the turbidity and microbiological NHR limits by the *Inanda filtered water*. The *Inanda filtered water*, however, did not exceed the turbidity and microbiological IHR limits after resanding.

(10) Conclusions with respect to filter bed maturity are as follows:

} A higher turbidity *Inanda raw water* than *Umgeni raw water*, resulted in a filtered water turbidity that conformed to the NHRt limit. The SSF treated *Umgeni raw water* for about 300 d before the *Inanda raw water* came on line. It is possible that the deeper and more mature part of the SSF, during the period of *Inanda raw water* treatment, improved the turbidity removal.

} Microbiological removal increases with an increase in filter bed maturity. *Inanda raw water* despite being higher in SPC at 37 °C and 22°C than the *Umgeni raw water*, was treated by the SSF to produce filtered water conforming to the NHRs limit. The filtration of *Umgeni raw water* produced filtered water SPC at 37 °C and 22°C exceeding the NHRs limit but conforming to the IHRs limit. This indicated that the progressive maturity of the deeper layers of the sand bed increased the microbiological removal when I*nanda raw water* was treated by SSF.

The above conclusions were also made by Bellamy *et al* (1985a) who demonstrated that the maturity of the microbiological population throughout the sand bed and gravel support improves the removal of total coliform bacteria and *Giardia* cysts.

(11) The following conclusions are made with respect to the plain sedimentation tank:

} Performance of the sedimentation tank was characterised by a general increasing trend of pre-treated water turbidity with raw water turbidity. In addition, the plain sedimentation tank significantly reduced a peak *Umgeni raw water* of 4 000 NTU to 40 NTU (see Fig. 6.11). Thus the performance of plain sedimentation was enhanced when treating high turbidity raw water. Ahmad *et al* (1984) have also stated that it is easier to clarify a water of high turbidity than that of a low turbidity.

- Increases in the upflow rate of the sedimentation tank, above its design rate of 0,3 m/h, resulted in increases in pre-treated water turbidity above that of the raw water turbidity. The plain sedimentation tank design upflow rate was exceeded when the filtration rate of SSF1 was deliberately increased to above 0,3 m/h. This was done to test the effect of filtration rate on filtered water quality.
- The high upflow rates of the sedimentation tank, above the design upflow rate of 0,3 m/h, resulted in low total coliform removals of 0 to 50 % in the sedimentation tank. However, the total coliform removal of the SSF was not affected by the increase in upflow rate of the sedimentation tank.
- The lack of a cover on the sedimentation tank resulted in inconsistent turbidity removal.
- Section 3.2.1.3 indicated that plain sedimentation extended by 200 % the *Inanda raw water* turbidity that could be treated by the SSF to produce filtered water conforming to both the NHRc and IHRc limits. Plain sedimentation extended by 20 % the Umgeni raw water turbidity with respect to the removal of total coliforms by SSF for both NHRc and IHRc limits.
- Section 3.2.1.3 indicated that plain sedimentation extended by 31,6 % the *Umgeni raw water* turbidity that could be treated by the SSF to produce filtered water conforming to the NHRs limit. *Inanda filtered water* consistently conformed to the NHRs limit. Therefore plain sedimentation had no effect on *Inanda raw water* turbidity with respect to the removal of SPC at 37 °C by SSF.

(12) The relationship between bacteria concentration of the raw water and the performance of the plain sedimentation-SSF train indicated that:

- there were maximum total coliform and SPC at 37 °C concentrations of 80 cells/100mℓ and 300 cells/mℓ respectively, beyond which the filtered water of the plain sedimentation-SSF train exceeded the NHRc and NHRs limits.

Possible reasons for these maximum total coliforms and SPC at 37 °C concentrations are that:

- the biofilm attached to the SSF media became saturated thus reducing the contact time of the pre-treated water microbiology with the SSF media.
- the predatory organisms concentration of the SSF was insufficient to handle concentrations of total coliforms and SPC at 37 °C beyond 80 cells/100mℓ and 300 cells/mℓ.
- channelling of the pre-treated water in some parts of the SSF media resulted in insufficient or no contact time with the biofilm on the SSF media. Seelaus *et al* (1986) have mentioned that fissures formed in the sand bed, by the collapsing of air pockets, result in the channelling of untreated water past parts of the SSF bed. These pockets of air formed when the SSF was filled with water, during commissioning or after filter cleaning, instead through the bottom of the SSF bed than from the top.

(13) Conclusions related to filtration rates of the SSF are as follows:

- Indications are that *Inanda filtered water* is microbiologically and aesthetically safe even when the SSF is operated at filtration rates as high as 0,5 m/h during *normal filtration* i.e. after *filter recovery*. The operation of the SSF at higher filtration rates, between 0,2 and 0,5 m/h, did not affect its successful performance when *Inanda raw water* was on line except for a brief period after resanding. The operation of the SSF at lower filtration rates up to 0,2 m/h resulted in the successful treatment of higher raw water turbidity and microbiology, more especially that of *Umgeni raw water* (see Figs. 6.47 and 6.48).

- The frequency of filter cleanings increased with an increase in filtration rate. Therefore there was a consequent decrease in the filtration cycle time. However, the total volume of filtered water per filtration cycle remained essentially the same (see discussion on Table 6.10), as also observed by Rachwal *et al* (1988).
- The average filtration cycle times of the SSF operated at 0,1 m/h and 0,2 to 0,5 m/h, with respect to *Umgeni raw water*, were 108 d and 57 d respectively.
- The average filtration cycle time of the SSF operated overall from 0,1 to 0,5 m/h, with respect to *Inanda raw water*, was 1 year. This indicates the operational benefit of treating *Inanda raw water* with SSF.

The findings with respect to *Inanda raw water* are in accordance those of Ellis (1987) and Fraser *et al* (1988). They found that filtered water quality was not sensitive to filtration rates. In addition they mention that filtration rates have a greater effect on filtration cycle times than filtered water quality.

(14) *Inanda raw water* was generally lower than *Umgeni raw water* in colour, Fe and Mn. However both *Inanda* and *Umgeni raw waters* were generally treated by the SSFs to produce filtered water colour, Fe and Mn conforming to the respective NHR limits. The only exceptions to the filtered water exceeding the respective NHR limits occurred during *filter recovery*. This is in line with the findings of Eighmy *et al* (1998) that extractable Fe and Mn is complexed to the bacterial biomass of the *schmutzedecke* and deeper layers of the sand media. The respective IHR limits were, however, not exceeded.

(15) The consistent 100 % removal of *Inanda raw water* algae by the SSF indicated that the SSF was able to overcome the effects of algae growth in an impoundment, an uncovered raw water storage tank or an uncovered SSF.

(16) Conclusions on sampling are as follows:

- There were also indications that an improper sampling procedure, i.e. not flushing the sample pipe with sampled water for 5 minutes and not heating the edge of sample pipe, sometimes led to the microbiological content of the filtered water exceeding its respective HRL.
- Sampling of the raw, pre-treated and filtered water were performed within 10 minutes apart. However, the time lag, caused by the residence time of the sedimentation tank and SSFs, ranged from 16 to 22 h. The effect of neglecting this time lag, during sampling, did not significantly affect the results of filtered water quality.
- As a result of the less frequent microbiological sampling compared to turbidity sampling, relationships between microbiological and turbidity results were only valid up to a raw water turbidity of 73 NTU.

# 8 RECOMMENDATIONS

The **recommendations**, expressed as general guidelines, are as follows:

(1) It is recommended that an impounded water source be used to supply a SSF with raw water. This is in accordance with findings of Slezak and Sims (1984). A pre-treatment step may not be necessary thus saving on capital and operating costs.

(2) If a river is the only available raw water source then a pre-treatment step, such as roughing filtration, will be necessary. Wegelin *et al* (1991) have successfully used a combination of horizontal roughing filtration and SSF to treat high turbidity river water.

(3) The raw water storage tank can be designed to function as a plain sedimentation pre-treatment step for SSF. The raw water entry and clarified water outlet may be positioned at the bottom and top of the tank respectively. A baffle, positioned at 90° to the raw water entry, will assist in the dissipation of energy and also minimise disturbances of the settling of particulate matter taking place within the tank. The base of the tank should be sloped downwards and away from the raw water entry point thus allowing for sludge removal at the other end. Note, however, that another pre-treatment step, such as roughing filtration, will still be needed for SSF if a high turbidity river water source is being treated.

(4) A SSF, operated at 0,1 m/h and treating impounded water, should be cleaned at an average of once every year. The filtration rate can be safely increased to 0,5 m/h, except during *filter recovery*, when the demand for potable water increases. Visscher (1990) has recommended that a SSF be operated at filtration rates as high as 0,6 m/h if the feed water is of very good quality.

(5) The *filter recovery* period, for the treatment of impounded water, can be reduced to 0 d if the filtered water is post-disinfected. Post-chlorination during

the entire filtration cycle is recommended. This will prevent bacterial growth in the distribution system by residual levels of chlorine in the filtered water.

Post-chlorination during *filter recovery* only will result in operating cost savings. The local authority will then have to accept the occasional exceeding of the respective NHR limit. However, based on the experience of this study on the treatment of impounded water, the filtered water will conform to the respective IHR limit.

Di Bernado (1991) recommends post-chlorination during both *filter recovery* and *normal filtration* in all treatment trains that include SSF despite the fact that SSF can remove a large proportion of the bacterial content of water. Vaillant (1981) also recommends an obligatory disinfection step even if the raw water is of a high standard.

The filtered water turbidity, during *filter recovery*, may occasionally exceed the NHRt limit although staying within the IHRt range. If this is not acceptable to the local authority then some form of secondary filtration, in addition to post-disinfection can be practised during this period. Thus drinking water that satisfies both the aesthetic and health criteria can be produced by treating impounded water with SSF, also resulting in minimum downtime.

(6) The treatment of river water by the SSF, operated at a filtration rate of 0,2 m/h, should be cleaned at an average of once every 57 d, i.e. once every 2 months. The SSF, treating river water and operated at a filtration rate of 0,1 m/h, should be cleaned at an average of once every 108 d, i.e. once every 3,5 months.

(7) The design daily water demand, for filtration of river water by a SSF, should be increased by 55 % and 25 % for flowrates of 0,2 m/h and 0,1 m/h respectively. The filtration cycle times, on which these increases in design daily water demand are based, are 2 and 3,5 months respectively. This is to account for a *filter recovery* period of 21 d.

Although there may be no need to increase the design daily water demand, for the filtration of impounded water by a SSF, a 20 % increase is recommended.

(8) The SSF and pre-treatment steps should be covered to prevent algae growth and windborne and faecal contamination Huisman and Wood (1974) recommend the use of grass matting, placed on bearers immediately above the water level, in tropical and subtropical climates. The reason for covering in these climates is to prevent algae growth. Filters that are vulnerable to windborne contamination, bird droppings [Schellart, 1988] and flying insects [Phillips *et al*, 1985] should also be covered.

However, it is difficult to prevent the entry of algae into the treatment system from an algae loaded raw water source. Thus part of the cleaning procedure during shutdowns should include brushing the sides of all vessels used in the treatment train..

(9) Water should be filled through the bottom of the SSF, during commissioning and after filter cleaning, to prevent air pockets from forming within the sand bed. This was also recommended by Seelaus *et al* (1986).

(10) Distribution or sample taps should preferably be made of carbon steel or other similar materials. This will allow the proper sampling procedures to take place, more especially the heating of the distribution or sample taps prior to sampling.

(11) The measurement of drinking water turbidity, in a rural area, may be a simple and economic way of monitoring the overall drinking water quality. Thus it is recommended that the first 6 months to a year be used to sample both the turbidity and microbiology of the drinking water to establish a relationship between the two. Thereafter, overall water treatment costs can be reduced by routine on-site turbidity measurements to monitor both aesthetic and microbiological water quality. This recommendation will be more practical in a SSF plant that practises post-disinfection.

(12) The sampling times of raw, pre-treated and filtered water should be staggered in such a manner as to account for the time lag caused by the residence times in the respective vessels.

(13) Although algae levels of the Inanda impoundment water, during this study, were not consistently high, these should increase to consistently high levels over the longer term. Therefore future work should investigate the long term effects of impounded water algae on the performance of SSF. Cleasby *et al* (1984) observed that high algal loads in the raw water source resulted in shorter filtration cycle times but did not generally affect the filtered water quality.

(14) Future research work on the treatment of river water by SSF can include experiments on a pilot scale SSF that includes a filter mat, made of non-woven fabric, placed on the sand surface. Alternatively, one can investigate the benefits of pre-treatment with a filter mat by performing a campaign run on a fully operational SSF located in a rural area. Graham and Mbwette (1990) have found an increase in filtration cycle time of up to eight times for SSF operated with a filter mat pre-treatment step when compared to using SSF alone. The filter mat has operational (long filter runs) as well as economic (reduced bed depths) benefits. SSF alone is already capable of producing high quality filtered water.

(15) Future research work on SSF should include residence time distribution (RTD) tracer studies. A RTD will indicate if channelling is a possible cause of microbiological and turbidity breakthrough. It will also be useful to carry out RTD studies during the commissioning of full scale SSFs. This will indicate if the sand media is properly set into the SSF vessel.

(16) During this experimentation it was realised that a particle size analysis of the raw and filtered water would have been a useful tool to add to the turbidity analysis. A low raw water turbidity can be misleading in predicting treatment performance if it is composed of fine clay or microbiological particles that pass through an unaided physical separation process like SSF. Although it was

suspected that particles within the size range of fine clay particles were responsible for filtered water turbidities exceeding the NHRt limit, it was not possible to prove this without a particle size analysis of the filtered water. A particle size analysis can also be used as a general predictive tool in predicting the type of chemical, biological and microbiological species that may be present in the raw and filtered waters. Therefore a suggested future experiment would be to characterise the raw water by means of a particle size analysis and then measure the lower limit of particle size that can be removed by the various treatment processes, including SSF.

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# APPENDIX A

## *Experimental results for turbidity*

TABLE A1: TURBIDITY RESULTS - RAW DATA

| Date | Time | Time elapsed (days) | Raw water turbidity (NTU) | Pre-treated water turbidity (NTU) | Filter 1 turbidity (NTU) | Filter 2 turbidity (NTU) | Filter 1+2 turbidity (NTU) | Filter 1 turbidity removal (%) | Filter 2 turbidity removal (%) | Sed. Tank turbidity removal (%) | System1 turbidity removal (%) | System2 turbidity removal (%) | Filter 1 Flow rate m/h | Filter 2 Flow rate m/h | Sed. tank Upflow rate m/h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 08/20/93 | 08:00 | 0 | | | | | | | | | | | 0,10 | 0,10 | 0,16 |
| 08/23/93 | 12:00 | 3 | 26,00 | 9,30 | 6,90 | 8,50 | 7,80 | 25,81 | 8,60 | 64,23 | 73,46 | 67,31 | 0,10 | 0,10 | 0,16 |
| 08/24/93 | 15:00 | 4 | 14,40 | 9,80 | 6,50 | 7,20 | 7,60 | 33,67 | 26,53 | 31,94 | 54,86 | 50,00 | 0,10 | 0,10 | 0,16 |
| 08/25/93 | 14:40 | 5 | 11,00 | 7,70 | 5,10 | 5,20 | 5,10 | 33,77 | 32,47 | 30,00 | 53,64 | 52,73 | 0,10 | 0,10 | 0,16 |
| 08/26/93 | 14:30 | 6 | 13,00 | 9,20 | 4,70 | 4,60 | 5,10 | 48,91 | 50,00 | 29,23 | 63,85 | 64,62 | 0,10 | 0,10 | 0,16 |
| 08/27/93 | 12:10 | 7 | 9,80 | 8,00 | 4,50 | 4,40 | 4,30 | 43,75 | 45,00 | 18,37 | 54,08 | 55,10 | 0,10 | 0,10 | 0,16 |
| 08/30/93 | 14:20 | 10 | 13,10 | 7,70 | 3,10 | 3,10 | 3,20 | 59,74 | 59,74 | 41,22 | 76,34 | 76,34 | 0,10 | 0,10 | 0,16 |
| 08/31/93 | 14:10 | 11 | 10,00 | 9,20 | 2,60 | 2,60 | 3,50 | 71,74 | 71,74 | 8,00 | 74,00 | 74,00 | 0,10 | 0,10 | 0,16 |
| 09/01/93 | 12:25 | 12 | 14,40 | 8,90 | 2,80 | 3,10 | 2,80 | 68,54 | 65,17 | 38,19 | 80,56 | 78,47 | 0,10 | 0,10 | 0,16 |
| 09/02/93 | 12:30 | 13 | 10,70 | 8,70 | 2,90 | 2,50 | 2,80 | 66,67 | 71,26 | 18,69 | 72,90 | 76,64 | 0,10 | 0,10 | 0,16 |
| 09/03/93 | 12:00 | 14 | 19,70 | 8,20 | 3,00 | 2,70 | 3,70 | 63,41 | 67,07 | 58,38 | 84,77 | 86,29 | 0,10 | 0,10 | 0,16 |
| 09/06/93 | 12:30 | 17 | 10,40 | 8,90 | 4,10 | 5,10 | 4,40 | 53,93 | 42,70 | 14,42 | 60,58 | 50,96 | 0,10 | 0,10 | 0,16 |
| 09/07/93 | 15:00 | 18 | 8,10 | 8,20 | 4,50 | 4,70 | 6,10 | 45,12 | 42,68 | -1,23 | 44,44 | 41,98 | 0,10 | 0,10 | 0,16 |
| 09/08/93 | 14:00 | 19 | 9,10 | 7,20 | 4,40 | 4,00 | 4,50 | 38,89 | 44,44 | 20,88 | 51,65 | 56,04 | 0,10 | 0,10 | 0,16 |
| 09/09/93 | 14:35 | 20 | 11,00 | 7,20 | 5,10 | 4,20 | 4,70 | 29,17 | 41,67 | 34,55 | 53,64 | 61,82 | 0,10 | 0,10 | 0,16 |
| 09/10/93 | 14:30 | 21 | 9,90 | 8,50 | 5,40 | 4,70 | 5,10 | 36,47 | 44,71 | 14,14 | 45,45 | 52,53 | 0,10 | 0,10 | 0,16 |
| 09/13/93 | 14:30 | 24 | 7,50 | 9,00 | 5,20 | 4,80 | 4,70 | 42,22 | 46,67 | -20,00 | 30,67 | 36,00 | 0,10 | 0,10 | 0,16 |
| 09/14/93 | 12:30 | 25 | 12,00 | 7,30 | 4,40 | 4,10 | 4,30 | 39,73 | 43,84 | 39,17 | 63,33 | 65,83 | 0,10 | 0,10 | 0,16 |
| 09/15/93 | 12:30 | 26 | 8,70 | 10,20 | 4,10 | 3,70 | 4,10 | 59,80 | 63,73 | -17,24 | 52,87 | 57,47 | 0,20 | 0,20 | 0,31 |
| 09/16/93 | 14:30 | 27 | 9,30 | 7,70 | 4,10 | 4,20 | 4,20 | 46,75 | 45,45 | 17,20 | 55,91 | 54,84 | 0,20 | 0,20 | 0,31 |
| 09/17/93 | 12:30 | 28 | 9,80 | 8,60 | 3,70 | 3,80 | 3,80 | 56,98 | 55,81 | 12,24 | 62,24 | 61,22 | 0,20 | 0,20 | 0,31 |
| 09/20/93 | 12:20 | 31 | 7,40 | 6,80 | 3,20 | 3,80 | 3,80 | 52,94 | 44,12 | 8,11 | 56,76 | 48,65 | 0,20 | 0,20 | 0,31 |
| 09/21/93 | 14:20 | 32 | 9,90 | 8,30 | 3,20 | 3,40 | 3,30 | 61,45 | 59,04 | 16,16 | 67,68 | 65,66 | 0,20 | 0,20 | 0,31 |
| 09/22/93 | 12:30 | 33 | 11,00 | 7,50 | 2,50 | 2,80 | 2,60 | 66,67 | 62,67 | 31,82 | 77,27 | 74,55 | 0,20 | 0,20 | 0,31 |
| 09/23/93 | 12:20 | 34 | 13,20 | 12,00 | 2,20 | 2,60 | 2,40 | 81,67 | 78,33 | 9,09 | 83,33 | 80,30 | 0,20 | 0,20 | 0,31 |
| 09/23/93 | 15:05 | 34 | 4000,00 | 12,70 | 2,20 | 2,80 | 2,40 | 82,68 | 77,95 | 99,68 | 99,95 | 99,93 | 0,20 | 0,20 | 0,31 |
| 09/27/93 | 13:00 | 35 | 35,00 | 40,00 | 200,00 | 200,00 | 200,00 | -400,00 | -400,00 | -14,29 | -471,43 | -471,43 | 0,20 | 0,20 | 0,31 |
| 09/28/93 | 10:20 | 36 | 73,00 | 45,00 | 30,00 | 31,00 | 30,00 | 33,33 | 31,11 | 38,36 | 58,90 | 57,53 | 0,20 | 0,20 | 0,31 |
| 09/29/93 | 10:05 | 37 | 62,00 | 30,00 | 13,40 | 11,60 | 12,40 | 55,33 | 61,33 | 51,61 | 78,39 | 81,29 | 0,20 | 0,20 | 0,31 |
| 09/29/93 | 15:00 | 37 | 31,00 | 29,00 | 12,40 | 11,10 | 11,70 | 57,24 | 61,72 | 6,45 | 60,00 | 64,19 | 0,20 | 0,20 | 0,31 |
| 09/30/93 | 09:35 | 38 | 34,00 | 26,00 | 9,20 | 8,40 | 8,80 | 64,62 | 67,69 | 23,53 | 72,94 | 75,29 | 0,20 | 0,20 | 0,31 |
| 10/01/93 | 10:00 | 39 | 47,00 | 23,00 | 8,10 | 7,40 | 7,80 | 64,78 | 67,83 | 51,06 | 82,77 | 84,26 | 0,20 | 0,20 | 0,31 |
| 10/04/93 | 13:00 | 44 | 32,00 | 28,00 | 10,20 | 9,70 | 10,10 | 63,57 | 65,36 | 12,50 | 68,13 | 69,69 | 0,20 | 0,20 | 0,31 |
| 10/05/93 | 14:00 | 45 | 31,00 | 21,00 | 7,70 | 7,00 | 7,60 | 63,33 | 66,67 | 32,26 | 75,16 | 77,42 | 0,20 | 0,20 | 0,31 |
| 10/06/93 | 14:15 | 46 | 30,00 | 27,00 | 7,90 | 7,00 | 7,40 | 70,74 | 74,07 | 10,00 | 73,67 | 76,67 | 0,20 | 0,20 | 0,31 |
| 10/07/93 | 12:20 | 47 | 46,00 | 44,00 | 11,80 | 11,50 | 11,60 | 73,18 | 73,86 | 4,35 | 74,35 | 75,00 | 0,20 | 0,20 | 0,31 |
| 10/08/93 | 12:00 | 48 | 77,00 | 72,00 | 21,00 | 22,00 | 21,00 | 70,83 | 69,44 | 6,49 | 72,73 | 71,43 | 0,20 | 0,20 | 0,31 |
| 10/11/93 | 12:20 | 51 | 48,00 | 17,70 | 9,70 | 13,70 | 11,20 | 45,20 | 22,60 | 63,13 | 79,79 | 71,46 | 0,20 | 0,20 | 0,31 |
| 10/12/93 | 10:00 | 52 | 39,00 | 17,20 | 7,50 | 12,30 | 8,80 | 56,40 | 28,49 | 55,90 | 80,77 | 68,46 | 0,20 | 0,10 | 0,23 |
| 10/13/93 | 12:45 | 53 | 19,00 | 15,80 | 9,90 | 6,10 | 7,40 | 37,34 | 61,39 | 16,84 | 47,89 | 67,89 | 0,20 | 0,10 | 0,23 |
| 10/14/93 | 10:00 | 54 | 25,00 | 17,00 | 5,40 | 8,20 | 6,60 | 68,24 | 51,76 | 32,00 | 78,40 | 67,20 | 0,20 | 0,10 | 0,23 |
| 10/15/93 | 12:30 | 55 | 21,00 | 15,80 | 5,00 | 7,70 | 6,30 | 68,35 | 51,27 | 24,76 | 76,19 | 63,33 | 0,20 | 0,10 | 0,23 |
| 10/18/93 | 11:30 | 58 | 17,80 | 16,40 | 3,40 | 5,60 | 4,10 | 79,27 | 65,85 | 7,87 | 80,90 | 68,54 | 0,20 | 0,10 | 0,23 |
| 10/19/93 | 10:00 | 59 | 20,00 | 15,40 | 3,10 | 5,30 | 3,70 | 79,87 | 65,58 | 23,00 | 84,50 | 73,50 | 0,20 | 0,10 | 0,23 |
| 10/20/93 | 11:30 | 60 | 16,20 | 13,40 | 3,30 | 5,00 | 3,60 | 75,37 | 62,69 | 17,28 | 79,63 | 69,14 | 0,20 | 0,10 | 0,23 |
| 10/21/93 | 10:00 | 61 | 16,80 | 12,80 | 3,20 | 4,80 | 3,80 | 75,00 | 62,50 | 23,81 | 80,95 | 71,43 | 0,20 | 0,10 | 0,23 |
| 10/22/93 | 12:30 | 62 | 19,30 | 14,90 | 3,00 | 4,60 | 3,30 | 79,87 | 69,13 | 22,80 | 84,46 | 76,17 | 0,20 | 0,10 | 0,23 |
| 10/25/93 | 12:00 | 65 | 23,00 | 17,60 | 3,40 | 3,70 | 3,55 | 80,68 | 78,98 | 23,48 | 85,22 | 83,91 | 0,20 | 0,10 | 0,23 |
| 10/26/93 | 15:30 | 66 | 18,70 | 14,70 | 3,30 | 3,90 | 3,60 | 77,55 | 73,47 | 21,39 | 82,35 | 79,14 | 0,20 | 0,10 | 0,23 |
| 10/27/93 | 10:30 | 67 | 17,10 | 14,30 | 2,90 | 3,50 | 3,20 | 79,72 | 75,52 | 16,37 | 83,04 | 79,53 | 0,20 | 0,10 | 0,23 |

Shaded area - filter cleaning and 21d thereafter

Dates in bold - Inanda raw water

TABLE A1: TURBIDITY RESULTS - RAW DATA (CONTINUED)

| Date | Time | Time elapsed | Raw water turbidity | Pre-treated water turbidity | Filter 1 turbidity | Filter 2 turbidity | Filter 1+2 turbidity | Filter 1 turbidity removal | Filter 2 turbidity removal | Sed. Tank turbidity removal | System1 turbidity removal | System2 turbidity removal | Filter 1 Flow rate | Filter 2 Flow rate | Sed. tank Upflow rate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (days) | (NTU) | (NTU) | (NTU) | (NTU) | (NTU) | (%) | (%) | (%) | (%) | (%) | m/h | m/h | m/h |
| 10/28/93 | 12:30 | 68 | 19,80 | 13,90 | 2,60 | 3,90 | 3,25 | 81,29 | 71,94 | 29,80 | 86,87 | 80,30 | 0,20 | 0,10 | 0,23 |
| 10/29/93 | 11:30 | 69 | 19,10 | 18,10 | 2,30 | 3,50 | 3,00 | 87,29 | 80,66 | 5,24 | 87,96 | 81,68 | 0,20 | 0,10 | 0,23 |
| 11/01/93 | 10:30 | 72 | 31,00 | 12,30 | 2,20 | 3,40 | 2,90 | 82,11 | 72,36 | 60,32 | 92,90 | 89,03 | 0,20 | 0,10 | 0,23 |
| 11/02/93 | 12:45 | 73 | 17,20 | 14,90 | 2,00 | 4,80 | 3,60 | 86,58 | 67,79 | 13,37 | 88,37 | 72,09 | 0,20 | 0,10 | 0,23 |
| 11/03/93 | 10:30 | 74 | 17,90 | 13,90 | 2,00 | 4,90 | 3,50 | 85,61 | 64,75 | 22,35 | 88,83 | 72,63 | 0,20 | 0,10 | 0,23 |
| 11/04/93 | 14:15 | 75 | 19,10 | 15,30 | 1,90 | 4,40 | 3,20 | 87,58 | 71,24 | 19,90 | 90,05 | 76,96 | 0,20 | 0,10 | 0,23 |
| 11/05/93 | 14:30 | 76 | 19,10 | 15,60 | 2,10 | 3,70 | 3,00 | 86,54 | 76,28 | 18,32 | 89,01 | 80,63 | 0,20 | 0,10 | 0,23 |
| 11/08/93 | 12:45 | 79 | 78,00 | 13,50 | 1,90 | 3,50 | 2,70 | 85,93 | 74,07 | 82,69 | 97,56 | 95,51 | 0,20 | 0,10 | 0,23 |
| 11/09/93 | 11:45 | 80 | 19,90 | 15,30 | 1,60 | 3,70 | 2,60 | 89,54 | 75,82 | 23,12 | 91,96 | 81,41 | 0,20 | 0,10 | 0,23 |
| 11/10/93 | 12:45 | 81 | 22,00 | 14,10 | 1,60 | 3,10 | 2,50 | 88,65 | 78,01 | 35,91 | 92,73 | 85,91 | 0,20 | 0,10 | 0,23 |
| 11/11/93 | 11:45 | 82 | 19.2 | 16,50 | 1,50 | 2,40 | 1,80 | 90,91 | 85,45 | ERR | ERR | ERR | 0,20 | 0,10 | 0,23 |
| 11/12/93 | 14:55 | 83 | 21,00 | 17,40 | 1,40 | 2,40 | 2,50 | 91,95 | 86,21 | 17,14 | 93,33 | 88,57 | 0,20 | 0,10 | 0,23 |
| 11/15/93 | 11:45 | 86 | 24,00 | 18,70 | 1,60 | 1,00 | 1,30 | 91,44 | 94,65 | 22,08 | 93,33 | 95,83 | 0,20 | 0,10 | 0,23 |
| 11/16/93 | 11:45 | 87 | 23,00 | 15,70 | 1,40 | 2,90 | 2,00 | 91,08 | 81,53 | 31,74 | 93,91 | 87,39 | 0,20 | 0,10 | 0,23 |
| 11/17/93 | 11:45 | 88 | 65,00 | 20,00 | 1,50 | 2,10 | 1,70 | 92,50 | 89,50 | 69,23 | 97,69 | 96,77 | 0,20 | 0,10 | 0,23 |
| 11/18/93 | 12:00 | 89 | 34,00 | 19,90 | 1,40 | 2,10 | 1,70 | 92,96 | 89,45 | 41,47 | 95,88 | 93,82 | 0,20 | 0,10 | 0,23 |
| 11/19/93 | 11:45 | 90 | 45,00 | 19,10 | 1,50 | 1,90 | 1,70 | 92,15 | 90,05 | 57,56 | 96,67 | 95,78 | 0,20 | 0,10 | 0,23 |
| 11/22/93 | 11:45 | 93 | 66,00 | 18,20 | 1,60 | 2,00 | 1,80 | 91,21 | 89,01 | 72,42 | 97,58 | 96,97 | 0,20 | 0,10 | 0,23 |
| 11/23/93 | 12:00 | 94 | 69,00 | 22,00 | 1,30 | 1,70 | 1,60 | 94,09 | 92,27 | 68,12 | 98,12 | 97,54 | 0,20 | 0,10 | 0,23 |
| 11/24/93 | 11:45 | 95 | 48,00 | 21,00 | 1,70 | 1,60 | 1,80 | 91,90 | 92,38 | 56,25 | 96,46 | 96,67 | 0,20 | 0,10 | 0,23 |
| 11/25/93 | 12:00 | 96 | 37,00 | 19,70 | 1,90 | 1,80 | 1,90 | 90,36 | 90,86 | 46,76 | 94,86 | 95,14 | 0,20 | 0,10 | 0,23 |
| 11/26/93 | 12:45 | 97 | 24,00 | 18,70 | 1,90 | 2,30 | 2,10 | 89,84 | 87,70 | 22,08 | 92,08 | 90,42 | 0,20 | 0,10 | 0,23 |
| 11/29/93 | 12:45 | 100 | 114,00 | 19,70 | 1,80 | 2,40 | 1,90 | 90,86 | 87,82 | 82,72 | 98,42 | 97,89 | 0,20 | 0,10 | 0,23 |
| 11/30/93 | 12:00 | 101 | 22,00 | 17,00 | 1,70 | 2,10 | 1,90 | 90,00 | 87,65 | 22,73 | 92,27 | 90,45 | 0,20 | 0,10 | 0,23 |
| 12/01/93 | 11:30 | 102 | 41,00 | 18,10 | 1,60 | 2,10 | 1,90 | 91,16 | 88,40 | 55,85 | 96,10 | 94,88 | 0,20 | 0,10 | 0,23 |
| 12/02/93 | 12:00 | 103 | 21,00 | 18,60 | 1,50 | 2,20 | 1,90 | 91,94 | 88,17 | 11,43 | 92,86 | 89,52 | 0,20 | 0,10 | 0,23 |
| 12/03/93 | 13:00 | 104 | 46,00 | 24,00 | 1,40 | 2,40 | 1,90 | 94,17 | 90,00 | 47,83 | 96,96 | 94,78 | 0,20 | 0,10 | 0,23 |
| 12/06/93 | 12:30 | 107 | 308,00 | 42,00 | 5,40 | 11,60 | 8,30 | 87,14 | 72,38 | 86,36 | 98,25 | 96,23 | 0,20 | 0,10 | 0,23 |
| 12/07/93 | 12:00 | 108 | 56,00 | 41,00 | **10,10** | 8,80 | 8,70 | **75,37** | 78,54 | 26,79 | **81,96** | 84,29 | **0,20** | 0,10 | 0,23 |
| 12/10/93 | 12:30 | 109 | 40,00 | 24,00 | 7,30 | 9,60 | 8,70 | 69,58 | 60,00 | 40,00 | 81,75 | 76,00 | 0,20 | 0,10 | 0,23 |
| 12/13/93 | 12:30 | 112 | 123,00 | 19,80 | 3,40 | 6,20 | 4,80 | 82,83 | 68,69 | 83,90 | 97,24 | 94,96 | 0,20 | 0,10 | 0,23 |
| 12/14/93 | 12:30 | 113 | 29,00 | 17,90 | 4,50 | 4,30 | 4,40 | 74,86 | 75,98 | 38,28 | 84,48 | 85,17 | 0,20 | 0,10 | 0,23 |
| 12/15/93 | 12:15 | 114 | 24,00 | 17,80 | 4,80 | 3,00 | 3,80 | 73,03 | 83,15 | 25,83 | 80,00 | 87,50 | 0,20 | 0,10 | 0,23 |
| 12/17/93 | 12:30 | 116 | 52,00 | 19,20 | 4,40 | 5,40 | 4,80 | 77,08 | 71,88 | 63,08 | 91,54 | 89,62 | 0,20 | 0,10 | 0,23 |
| 12/20/93 | 12:00 | 119 | 69,00 | 19,80 | 5,10 | 4,70 | 5,00 | 74,24 | 76,26 | 71,30 | 92,61 | 93,19 | 0,20 | 0,10 | 0,23 |
| 12/21/93 | 12:30 | 120 | 27,00 | 23,00 | 4,60 | 4,50 | 4,40 | 80,00 | 80,43 | 14,81 | 82,96 | 83,33 | 0,20 | 0,10 | 0,23 |
| 12/22/93 | 11:00 | 121 | 61,00 | 24,00 | 3,90 | 3,90 | 3,90 | 83,75 | 83,75 | 60,66 | 93,61 | 93,61 | 0,20 | 0,10 | 0,23 |
| 12/23/93 | 10:30 | 122 | 26,00 | 25,00 | 4,00 | 4,30 | 4,10 | 84,00 | 82,80 | 3,85 | 84,62 | 83,46 | 0,20 | 0,10 | 0,23 |
| 12/24/93 | 10:30 | 123 | 28,00 | 23,00 | 4,00 | 4,00 | 4,00 | 82,61 | 82,61 | 17,86 | 85,71 | 85,71 | 0,20 | 0,10 | 0,23 |
| 12/27/93 | 12:00 | 126 | 24,00 | 18,20 | 3,50 | 3,00 | 3,20 | 80,77 | 83,52 | 24,17 | 85,42 | 87,50 | 0,20 | 0,10 | 0,23 |
| 12/28/93 | 12:30 | 127 | 25,00 | 21,00 | 3,40 | 3,20 | 3,40 | 83,81 | 84,76 | 16,00 | 86,40 | 87,20 | 0,20 | 0,10 | 0,23 |
| 12/29/93 | 12:30 | 128 | 536,00 | 95,00 | 3,50 | 3,20 | 3,30 | 96,32 | 96,63 | 82,28 | 99,35 | 99,40 | 0,20 | 0,10 | 0,23 |
| 12/30/93 | 12:15 | 129 | 119,00 | 57,00 | 31,00 | 12,10 | 21,00 | 45,61 | 78,77 | 52,10 | 73,95 | 89,83 | 0,20 | 0,10 | 0,23 |
| 12/31/93 | 10:30 | 130 | 55,00 | 47,00 | 30,00 | 25,00 | 28,00 | 36,17 | 46,81 | 14,55 | 45,45 | 54,55 | 0,20 | 0,10 | 0,23 |
| 01/03/94 | 09:30 | 133 | 30,00 | 24,00 | 8,50 | 7,20 | 8,00 | 64,58 | 70,00 | 20,00 | 71,67 | 76,00 | 0,20 | 0,10 | 0,23 |
| 01/04/94 | 14:30 | 134 | 35,00 | 27,00 | 9,30 | 6,40 | 8,50 | 65,56 | 76,30 | 22,86 | 73,43 | 81,71 | 0,20 | 0,10 | 0,23 |
| 01/05/94 | 12:00 | 135 | 41,00 | 26,00 | 5,80 | 6,50 | 6,00 | 77,69 | 75,00 | 36,59 | 85,85 | 84,15 | 0,20 | 0,10 | 0,23 |
| 01/06/94 | 12:00 | 136 | 30,00 | 24,00 | 5,30 | 5,40 | 5,30 | 77,92 | 77,50 | 20,00 | 82,33 | 82,00 | 0,20 | 0,10 | 0,23 |
| 01/07/94 | 12:00 | 137 | 31,00 | 26,00 | 5,20 | 3,80 | 4,50 | 80,00 | 85,38 | 16,13 | 83,23 | 87,74 | 0,20 | 0,10 | 0,23 |
| 01/13/94 | 14:00 | 143 | 48,00 | 54,00 | 13,50 | 16,00 | 14,00 | 75,00 | 70,37 | -12,50 | 71,88 | 66,67 | 0,20 | 0,10 | 0,23 |

Shaded area - filter cleaning and 21d thereafter

Dates in bold - Inanda raw water

TABLE A1: TURBIDITY RESULTS - RAW DATA (CONTINUED)

| Date | Time | Time elapsed (days) | Raw water turbidity (NTU) | Pre-treated water turbidity (NTU) | Filter 1 turbidity (NTU) | Filter 2 turbidity (NTU) | Filter 1+2 turbidity (NTU) | Filter 1 turbidity removal (%) | Filter 2 turbidity removal (%) | Sed. Tank turbidity removal (%) | System1 turbidity removal (%) | System2 turbidity removal (%) | Filter 1 Flow rate m/h | Filter 2 Flow rate m/h | Sed. tank Upflow rate m/h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01/14/94 | 15:00 | 144 | 60,00 | 31,00 | 7,50 | 8,00 | 7,60 | 75,81 | 74,19 | 48,33 | 87,50 | 86,67 | 0,20 | 0,10 | 0,23 |
| 01/17/94 | 12:45 | 147 | 27,00 | 20,00 | 4,20 | 4,20 | 4,20 | 79,00 | 79,00 | 25,93 | 84,44 | 84,44 | 0,20 | 0,10 | 0,23 |
| 01/18/94 | 12:15 | 148 | 27,00 | 21,00 | 3,70 | 4,60 | 3,60 | 82,38 | 78,10 | 22,22 | 86,30 | 82,96 | 0,20 | 0,10 | 0,23 |
| 01/19/94 | 15:00 | 149 | 56,00 | 21,00 | 3,70 | 5,10 | 3,90 | 82,38 | 75,71 | 62,50 | 93,39 | 90,89 | 0,20 | 0,10 | 0,23 |
| 01/20/94 | 15:00 | 150 | 23,00 | 23,00 | 3,50 | 4,20 | 3,90 | 84,78 | 81,74 | 0,00 | 84,78 | 81,74 | 0,20 | 0,10 | 0,23 |
| 01/21/94 | 15:00 | 151 | 26,00 | 19,20 | 3,30 | 3,90 | 3,50 | 82,81 | 79,69 | 26,15 | 87,31 | 85,00 | 0,20 | 0,10 | 0,23 |
| 01/24/94 | 15:00 | 154 | 23,00 | 17,70 | 2,40 | 3,60 | 2,80 | 86,44 | 79,66 | 23,04 | 89,57 | 84,35 | 0,10 | 0,10 | 0,16 |
| 01/25/94 | 15:00 | 155 | 24,00 | 17,50 | 2,80 | 3,40 | 3,10 | 84,00 | 80,57 | 27,08 | 88,33 | 85,83 | 0,10 | 0,10 | 0,16 |
| 01/26/94 | 15:00 | 156 | 26,00 | 16,00 | 3,00 | 3,60 | 3,20 | 81,25 | 77,50 | 38,46 | 88,46 | 86,15 | 0,10 | 0,10 | 0,16 |
| 01/27/94 | 15:00 | 157 | 21,00 | 15,30 | 3,00 | 3,80 | 4,00 | 80,39 | 75,16 | 27,14 | 85,71 | 81,90 | 0,10 | 0,10 | 0,16 |
| 01/31/94 | 15:00 | 161 | 26,00 | 13,10 | 2,60 | 3,10 | 2,90 | 80,15 | 76,34 | 49,62 | 90,00 | 88,08 | 0,10 | 0,10 | 0,16 |
| 02/01/94 | 15:00 | 162 | 28,00 | 11,50 | 2,60 | 2,90 | 2,70 | 77,39 | 74,78 | 58,93 | 90,71 | 89,64 | 0,10 | 0,10 | 0,16 |
| 02/02/94 | 15:00 | 163 | 17,00 | 11,00 | 2,50 | 2,80 | 2,70 | 77,27 | 74,55 | 35,29 | 85,29 | 83,53 | 0,10 | 0,10 | 0,16 |
| 02/03/94 | 15:00 | 164 | 27,00 | 11,30 | 2,20 | 2,70 | 2,50 | 80,53 | 76,11 | 58,15 | 91,85 | 90,00 | 0,10 | 0,10 | 0,16 |
| 02/04/94 | 15:00 | 165 | 25,00 | 10,00 | 2,10 | 2,60 | 2,30 | 79,00 | 74,00 | 60,00 | 91,60 | 89,60 | 0,10 | 0,10 | 0,16 |
| 02/07/94 | 15:00 | 168 | 17,00 | 13,30 | 2,40 | 1,80 | 2,00 | 81,95 | 86,47 | 21,76 | 85,88 | 89,41 | 0,10 | 0,10 | 0,16 |
| 02/08/94 | 15:00 | 169 | 37,00 | 11,40 | 1,70 | 2,30 | 2,00 | 85,09 | 79,82 | 69,19 | 95,41 | 93,78 | 0,10 | 0,10 | 0,16 |
| 02/09/94 | 15:00 | 170 | 71,00 | 11,00 | 1,80 | 2,30 | 2,10 | 83,64 | 79,09 | 84,51 | 97,46 | 96,76 | 0,10 | 0,10 | 0,16 |
| 02/10/94 | 15:00 | 171 | 28,00 | 11,00 | 1,90 | 2,40 | 2,10 | 82,73 | 78,18 | 60,71 | 93,21 | 91,43 | 0,10 | 0,10 | 0,16 |
| 02/11/94 | 15:00 | 172 | 48,00 | 11,10 | 1,80 | 2,30 | 2,10 | 83,78 | 79,28 | 76,88 | 96,25 | 95,21 | 0,10 | 0,10 | 0,16 |
| 02/14/94 | 14:45 | 173 | 21,00 | 7,50 | 1,70 | 2,20 | 2,10 | 77,33 | 70,67 | 64,29 | 91,90 | 89,52 | 0,10 | 0,10 | 0,16 |
| 02/15/94 | 15:45 | 174 | 14,20 | 10,20 | 1,70 | 2,20 | 1,90 | 83,33 | 78,43 | 28,17 | 88,03 | 84,51 | 0,10 | 0,10 | 0,16 |
| 02/16/94 | 15:00 | 175 | 13,10 | 7,40 | 1,20 | 2,40 | 1,80 | 83,78 | 67,57 | 43,51 | 90,84 | 81,68 | 0,10 | 0,10 | 0,16 |
| 02/17/94 | 14:30 | 176 | 19,20 | 7,12 | 1,60 | 2,40 | 2,00 | 77,53 | 66,29 | 62,92 | 91,67 | 87,50 | 0,10 | 0,10 | 0,16 |
| 02/18/94 | 15:00 | 177 | 23,00 | 12,00 | | 2,30 | 2,30 | | 80,83 | 47,83 | | 90,00 | | 0,10 | 0,08 |
| 02/21/94 | 15:15 | 180 | 7,00 | 7,70 | | 2,20 | 2,20 | | 71,43 | -10,00 | | 68,57 | | 0,10 | 0,08 |
| 02/22/94 | 15:00 | 181 | 22,00 | 14,60 | | 1,80 | 1,80 | | 87,67 | 33,64 | | 91,82 | | 0,10 | 0,08 |
| 02/23/94 | 15:00 | 182 | 29,00 | 16,40 | | 2,20 | 2,20 | | 86,59 | 43,45 | | 92,41 | | 0,10 | 0,08 |
| 02/24/94 | 15:00 | 183 | 42,00 | 15,00 | **6,10** | 2,10 | 4,10 | **59,33** | 86,00 | 64,29 | **85,48** | 95,00 | **0,20** | 0,10 | 0,23 |
| 02/25/94 | 15:00 | 184 | 17,50 | 14,90 | 4,40 | 2,00 | 3,10 | 70,47 | 86,58 | 14,86 | 74,86 | 88,57 | 0,20 | 0,10 | 0,23 |
| 02/28/94 | 15:00 | 187 | 31,00 | 9,80 | 2,80 | 1,90 | 2,10 | 71,43 | 80,61 | 68,39 | 90,97 | 93,87 | 0,20 | 0,10 | 0,23 |
| 03/01/94 | 15:00 | 188 | 14,00 | 15,00 | 1,90 | 2,80 | 2,30 | 87,33 | 81,33 | -7,14 | 86,43 | 80,00 | 0,20 | 0,10 | 0,23 |
| 03/02/94 | 15:00 | 189 | 23,00 | 17,10 | 2,40 | 1,90 | 2,10 | 85,96 | 88,89 | 25,65 | 89,57 | 91,74 | 0,20 | 0,10 | 0,23 |
| 03/03/94 | 15:00 | 190 | 36,00 | 21,00 | 2,40 | 2,40 | 2,60 | 88,57 | 88,57 | 41,67 | 93,33 | 93,33 | 0,20 | 0,10 | 0,23 |
| 03/04/94 | 14:00 | 191 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | ERR | ERR | ERR | ERR | ERR | 0,20 | 0,10 | 0,23 |
| 03/07/94 | 15:00 | 191 | 39,00 | 41,00 | 3,90 | 2,30 | 2,80 | 90,49 | 94,39 | -5,13 | 90,00 | 94,10 | 0,20 | 0,10 | 0,23 |
| 03/08/94 | 15:15 | 192 | 106,00 | 29,00 | 3,40 | 2,30 | 2,90 | 88,28 | 92,07 | 72,64 | 96,79 | 97,83 | 0,20 | 0,10 | 0,23 |
| 03/09/94 | 15:00 | 193 | 33,00 | 27,00 | 4,00 | 2,10 | 2,80 | 85,19 | 92,22 | 18,18 | 87,88 | 93,64 | 0,20 | 0,10 | 0,23 |
| 03/10/94 | 15:15 | 194 | 132,00 | 39,00 | 3,00 | 2,10 | 2,50 | 92,31 | 94,62 | 70,45 | 97,73 | 98,41 | 0,20 | 0,10 | 0,23 |
| 03/11/94 | 15:00 | 195 | 44,00 | 49,00 | 9,70 | 4,10 | 6,60 | 80,20 | 91,63 | -11,36 | 77,95 | 90,68 | 0,20 | 0,10 | 0,23 |
| 03/14/94 | 15:30 | 198 | 35,00 | 27,00 | 3,00 | 3,00 | 3,00 | 88,89 | 88,89 | 22,86 | 91,43 | 91,43 | 0,10 | 0,10 | 0,16 |
| 03/16/94 | 15:45 | 200 | 28,00 | 22,00 | 2,20 | 2,40 | 2,20 | 90,00 | 89,09 | 21,43 | 92,14 | 91,43 | 0,10 | 0,10 | 0,16 |
| 03/17/94 | 14:30 | 201 | 33,00 | 22,00 | 2,20 | 2,30 | 2,30 | 90,00 | 89,55 | 33,33 | 93,33 | 93,03 | 0,10 | 0,10 | 0,16 |
| 03/18/94 | 15:00 | 202 | 30,00 | 22,00 | 2,10 | 2,30 | 2,10 | 90,45 | 89,55 | 26,67 | 93,00 | 92,33 | 0,10 | 0,10 | 0,16 |
| 03/22/24 | 15:00 | 206 | | | **1,20** | **1,50** | **1,40** | **ERR** | **ERR** | **ERR** | **ERR** | **ERR** | **0,10** | **0,10** | 0,16 |
| 03/28/94 | 15:25 | 212 | 28,00 | 25,00 | 49,00 | 10,70 | 7,70 | -96,00 | 57,20 | 10,71 | -75,00 | 61,79 | 0,20 | 0,10 | 0,23 |
| 03/29/94 | 15:10 | 213 | 35,00 | 30,00 | 11,40 | 8,90 | 10,20 | 62,00 | 70,33 | 14,29 | 67,43 | 74,57 | 0,20 | 0,10 | 0,23 |
| 03/31/94 | 10:00 | 214 | 52,00 | 34,00 | 10,90 | 11,20 | 10,90 | 67,94 | 67,06 | 34,62 | 79,04 | 78,46 | 0,20 | 0,10 | 0,23 |
| 04/07/94 | 14:30 | 221 | 31,00 | 23,00 | 5,30 | 8,70 | 6,80 | 76,96 | 62,17 | 25,81 | 82,90 | 71,94 | 0,20 | 0,10 | 0,23 |
| 04/08/94 | 15:00 | 222 | 36,00 | 34,00 | 4,30 | 7,10 | 5,60 | 87,35 | 79,12 | 5,56 | 88,06 | 80,28 | 0,20 | 0,10 | 0,23 |

Shaded area - filter cleaning and 21d thereafter

Dates in bold - Inanda raw water

TABLE A1: TURBIDITY RESULTS - RAW DATA (CONTINUED)

| Date | Time | Time elapsed (days) | Raw water turbidity (NTU) | Pre-treated water turbidity (NTU) | Filter 1 turbidity (NTU) | Filter 2 turbidity (NTU) | Filter 1+2 turbidity (NTU) | Filter 1 turbidity removal (%) | Filter 2 turbidity removal (%) | Sed. Tank turbidity removal (%) | System1 turbidity removal (%) | System2 turbidity removal (%) | Filter 1 Flow rate m/h | Filter 2 Flow rate m/h | Sed. tank Upflow rate m/h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 04/11/94 | 14:45 | 225 | 35,00 | 31,00 | 3,10 | 4,00 | 3,50 | 90,00 | 87,10 | 11,43 | 91,14 | 88,57 | 0,20 | 0,10 | 0,23 |
| 04/12/94 | 15:00 | 226 | 39,00 | 33,00 | 3,20 | 3,90 | 3,60 | 90,30 | 88,18 | 15,38 | 91,79 | 90,00 | 0,20 | 0,10 | 0,23 |
| 04/13/94 | 15:00 | 227 | 77,00 | 43,00 | 3,10 | 4,30 | 3,80 | 92,79 | 90,00 | 44,16 | 95,97 | 94,42 | 0,20 | 0,10 | 0,23 |
| 04/14/94 | 14:30 | 228 | 46,00 | 39,00 | 3,10 | 3,40 | 3,20 | 92,05 | 91,28 | 15,22 | 93,26 | 92,61 | 0,20 | 0,10 | 0,23 |
| 04/15/94 | 15:00 | 229 | 52,00 | 33,00 | 2,60 | 3,80 | 3,20 | 92,12 | 88,48 | 36,54 | 95,00 | 92,69 | 0,20 | 0,10 | 0,23 |
| 04/18/94 | 15:00 | 232 | 40,00 | 23,00 | 2,30 | 2,70 | 2,40 | 90,00 | 88,26 | 42,50 | 94,25 | 93,25 | 0,20 | 0,10 | 0,23 |
| 04/20/94 | 15:15 | 234 | 82,00 | 31,00 | 1,90 | 2,30 | 2,10 | 93,87 | 92,58 | 62,20 | 97,68 | 97,20 | 0,20 | 0,10 | 0,23 |
| 04/25/94 | 15:00 | 239 | 45,00 | 46,00 | 1,50 | 5,50 | 3,40 | 96,74 | 88,04 | -2,22 | 96,67 | 87,78 | 0,20 | 0,10 | 0,23 |
| 04/26/94 | 15:20 | 240 | 37,00 | 39,00 | 1,30 | 4,30 | 2,80 | 96,67 | 88,97 | -5,41 | 96,49 | 88,38 | 0,20 | 0,10 | 0,23 |
| 04/29/94 | 14:40 | 243 | 24,00 | 29,00 | 0,99 | 2,40 | 1,60 | 96,59 | 91,72 | -20,83 | 95,88 | 90,00 | 0,10 | 0,10 | 0,16 |
| 05/02/94 | 15:30 | 246 | 35,00 | 26,00 | 1,20 | 2,20 | 1,60 | 95,38 | 91,54 | 25,71 | 96,57 | 93,71 | 0,10 | 0,10 | 0,16 |
| 05/03/94 | 15:45 | 247 | 29,00 | 28,00 | | 32,00 | 32,00 | | -14,29 | 3,45 | | -10,34 | | 0,10 | 0,08 |
| 05/04/94 | 15:35 | 248 | 28,00 | 27,00 | 13,90 | 3,10 | 8,70 | 48,52 | 88,52 | 3,57 | 50,36 | 88,93 | 0,20 | 0,10 | 0,23 |
| 05/05/94 | 13:00 | 249 | 28,00 | 27,00 | 13,60 | 2,60 | 8,30 | 49,63 | 90,37 | 3,57 | 51,43 | 90,71 | 0,20 | 0,10 | 0,23 |
| 05/06/94 | 12:50 | 250 | 30,00 | 29,00 | 8,70 | 2,00 | 5,30 | 70,00 | 93,10 | 3,33 | 71,00 | 93,33 | 0,20 | 0,10 | 0,23 |
| 05/09/94 | 11:45 | 253 | 40,00 | 30,00 | 7,20 | 2,00 | 4,50 | 76,00 | 93,33 | 25,00 | 82,00 | 95,00 | 0,20 | 0,10 | 0,23 |
| 05/11/94 | 13:00 | 255 | 25,00 | 25,00 | 5,10 | 2,30 | 3,70 | 79,60 | 90,80 | 0,00 | 79,60 | 90,80 | 0,20 | 0,10 | 0,23 |
| 05/17/94 | 15:15 | 261 | 41,00 | 31,00 | 3,30 | 2,50 | 2,90 | 89,35 | 91,94 | 24,39 | 91,95 | 93,90 | 0,20 | 0,10 | 0,23 |
| 05/23/94 | 14:50 | 267 | 18,70 | 13,40 | 2,90 | 1,40 | 2,10 | 78,36 | 89,55 | 28,34 | 84,49 | 92,51 | 0,20 | 0,10 | 0,23 |
| 05/24/94 | 15:20 | 268 | 16,10 | 14,20 | 2,60 | 1,60 | 2,00 | 81,69 | 88,73 | 11,80 | 83,85 | 90,06 | 0,20 | 0,10 | 0,23 |
| 05/25/94 | 13:15 | 269 | 18,60 | 16,90 | 1,90 | 1,80 | 1,90 | 88,76 | 89,35 | 9,14 | 89,78 | 90,32 | 0,20 | 0,10 | 0,23 |
| 05/26/94 | 14:50 | 270 | 12,00 | 14,80 | 1,70 | 1,40 | 1,70 | 88,51 | 90,54 | -23,33 | 85,83 | 88,33 | 0,20 | 0,10 | 0,23 |
| 06/03/94 | 15:00 | 278 | 15,00 | 13,00 | 0,80 | 1,20 | 1,00 | 93,85 | 90,77 | 13,33 | 94,67 | 92,00 | 0,20 | 0,10 | 0,23 |
| 06/08/94 | 15:00 | 283 | 10,50 | 11,70 | 0,78 | 1,02 | 0,93 | 93,33 | 91,28 | -11,43 | 92,57 | 90,29 | 0,20 | 0,10 | 0,23 |
| 06/09/94 | 15:00 | 284 | 8,50 | 7,90 | 1,26 | 0,98 | 1,00 | 84,05 | 87,59 | 7,06 | 85,18 | 88,47 | 0,20 | 0,10 | 0,23 |
| 06/10/94 | 15:00 | 285 | 13,40 | 12,10 | 0,77 | 1,14 | 0,96 | 93,64 | 90,58 | 9,70 | 94,25 | 91,49 | 0,20 | 0,10 | 0,23 |
| 06/13/94 | 15:00 | 288 | 8,30 | 7,50 | 0,75 | 1,41 | 1,08 | 90,00 | 81,20 | 9,64 | 90,96 | 83,01 | 0,20 | 0,10 | 0,23 |
| 06/15/94 | 14:40 | 290 | 10,40 | 8,90 | 0,90 | 1,20 | 0,90 | 89,89 | 86,52 | 14,42 | 91,35 | 88,46 | 0,20 | 0,10 | 0,23 |
| 06/16/94 | 12:40 | 291 | 8,80 | 6,50 | 0,60 | 0,90 | 0,90 | 90,77 | 86,15 | 26,14 | 93,18 | 89,77 | 0,20 | 0,05 | 0,20 |
| 06/17/94 | 13:15 | 292 | 9,50 | 6,50 | 0,60 | 0,90 | 0,70 | 90,77 | 86,15 | 31,58 | 93,68 | 90,53 | 0,20 | 0,05 | 0,20 |
| 06/20/94 | 13:30 | 295 | 14,00 | 10,60 | 0,50 | 0,80 | 0,70 | 95,28 | 92,45 | 24,29 | 96,43 | 94,29 | 0,20 | 0,05 | 0,20 |
| 06/21/94 | 13:00 | 296 | 8,30 | 7,90 | 0,60 | 0,70 | 0,70 | 92,41 | 91,14 | 4,82 | 92,77 | 91,57 | 0,10 | 0,05 | 0,12 |
| 06/23/94 | 10:10 | 298 | 10,10 | 8,10 | 0,50 | | | 93,83 | | 19,80 | 95,05 | | 0,10 | | 0,08 |
| 06/24/94 | 13:10 | 299 | 14,70 | 10,60 | 0,50 | 2,60 | 1,60 | 95,28 | 75,47 | 27,89 | 96,60 | 82,31 | 0,10 | 0,10 | 0,16 |
| 06/27/94 | 13:00 | 302 | 11,60 | 8,20 | 0,74 | 1,60 | 1,24 | 90,98 | 80,49 | 29,31 | 93,62 | 86,21 | 0,10 | 0,10 | 0,16 |
| 06/28/94 | 14:25 | 303 | 12,40 | 9,70 | 0,50 | 1,30 | 0,80 | 94,85 | 86,60 | 21,77 | 95,97 | 89,52 | 0,10 | 0,10 | 0,16 |
| 06/29/94 | 12:30 | 304 | 8,20 | 7,50 | 0,40 | 1,10 | 0,60 | 94,67 | 85,33 | 8,54 | 95,12 | 86,59 | 0,10 | 0,10 | 0,16 |
| 06/30/94 | 15:45 | 305 | 7,40 | 6,10 | 0,47 | 1,06 | 0,69 | 92,30 | 82,62 | 17,57 | 93,65 | 85,68 | 0,10 | 0,10 | 0,16 |
| 07/01/94 | 10:00 | 306 | 6,80 | 5,60 | 0,35 | 0,85 | 0,63 | 93,75 | 84,82 | 17,65 | 94,85 | 87,50 | 0,10 | 0,10 | 0,16 |
| 07/04/94 | 15:30 | 309 | 6,50 | 4,30 | | 0,82 | 0,82 | | 80,93 | 33,85 | | 87,38 | | 0,10 | 0,08 |
| 07/05/94 | 15:30 | 310 | 7,60 | 4,90 | | 0,92 | 0,92 | | 81,22 | 35,53 | | 87,89 | | 0,10 | 0,08 |
| 07/06/94 | 08:30 | 311 | 6,80 | 5,70 | 2,00 | 0,93 | 1,62 | 64,91 | 83,68 | 16,18 | 70,59 | 86,32 | 0,20 | 0,10 | 0,23 |
| 07/07/94 | 08:30 | 312 | 9,10 | 8,20 | 1,66 | 0,81 | 1,23 | 79,76 | 90,12 | 9,89 | 81,76 | 91,10 | 0,20 | 0,10 | 0,23 |
| 07/08/94 | 09:45 | 313 | 7,10 | 6,80 | 1,26 | 0,67 | 1,13 | 81,47 | 90,15 | 4,23 | 82,25 | 90,56 | 0,20 | 0,10 | 0,23 |
| 07/11/94 | 11:45 | 315 | 8,00 | 6,90 | 1,05 | 0,84 | 0,92 | 84,78 | 87,83 | 13,75 | 86,88 | 89,50 | 0,20 | 0,10 | 0,23 |
| 07/12/94 | 13:00 | 316 | 9,60 | 6,80 | 1,09 | 0,65 | 0,96 | 83,97 | 90,44 | 29,17 | 88,65 | 93,23 | 0,20 | 0,10 | 0,23 |
| 07/13/94 | 15:30 | 317 | 6,50 | 6,30 | 1,04 | 0,73 | 0,97 | 83,49 | 88,41 | 3,08 | 84,00 | 88,77 | 0,20 | 0,10 | 0,23 |
| 07/14/94 | 15:10 | 318 | 26,00 | 11,50 | 1,01 | 0,76 | 0,93 | 91,22 | 93,39 | 55,77 | 96,12 | 97,08 | 0,20 | 0,10 | 0,23 |
| 07/15/94 | 09:05 | 318 | 62,00 | 15,80 | 0,75 | 0,58 | 0,71 | 95,25 | 96,33 | 74,52 | 98,79 | 99,06 | 0,20 | 0,10 | 0,23 |
| 07/19/94 | 15:40 | 323 | 69,00 | 4,90 | 0,65 | 0,63 | 0,61 | 86,73 | 87,14 | 92,90 | 99,06 | 99,09 | 0,10 | 0,10 | 0,16 |

Shaded area - filter cleaning and 21d thereafter

Dates in bold - Inanda raw water

TABLE A1: TURBIDITY RESULTS - RAW DATA (CONTINUED)

| Date | Time | Time elapsed (days) | Raw water turbidity (NTU) | Pre-treated water turbidity (NTU) | Filter 1 turbidity (NTU) | Filter 2 turbidity (NTU) | Filter 1+2 turbidity (NTU) | Filter 1 turbidity removal (%) | Filter 2 turbidity removal (%) | Sed. Tank turbidity removal (%) | System1 turbidity removal (%) | System2 turbidity removal (%) | Filter 1 Flow rate m/h | Filter 2 Flow rate m/h | Sed. tank Upflow rate m/h |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 07/21/94 | 15:50 | 325 | 8,90 | 7,40 | 1,56 | 0,59 | 1,34 | 78,92 | 92,03 | 16,85 | 82,47 | 93,37 | 0,10 | 0,10 | 0,16 |
| 07/22/94 | 15:25 | 326 | 4,80 | 5,40 | 0,64 | 0,67 | 0,67 | 88,15 | 87,59 | -12,50 | 86,67 | 86,04 | 0,10 | 0,10 | 0,16 |
| **07/29/94** | 15:15 | 330 | 5,60 | 4,50 | **1,21** | **1,89** | 1,63 | **73,11** | **58,00** | 19,64 | **78,39** | **66,25** | **0,20** | **0,10** | 0,23 |
| **08/03/94** | 15:00 | 335 | 5,00 | 3,30 | 0,95 | 1,30 | 1,10 | 71,21 | 60,61 | 34,00 | 81,00 | 74,00 | 0,20 | 0,10 | 0,23 |
| **08/10/94** | 12:30 | 342 | 3,00 | 4,00 | 0,81 | 1,03 | 0,82 | 79,75 | 74,25 | -33,33 | 73,00 | 65,67 | 0,10 | 0,10 | 0,16 |
| **08/11/94** | 12:30 | 343 | 4,20 | 3,00 | 0,70 | 0,93 | 0,85 | 76,67 | 69,00 | 28,57 | 83,33 | 77,86 | 0,10 | 0,10 | 0,16 |
| **08/16/94** | 11:30 | 348 | 2,70 | 2,30 | | 0,70 | 0,70 | | 69,57 | 14,81 | 100,00 | 74,07 | | 0,10 | 0,08 |
| **08/22/94** | 15:30 | 354 | 3,40 | 2,40 | **1,05** | 0,64 | 0,82 | **56,25** | 73,33 | 29,41 | **69,12** | 81,18 | **0,20** | 0,05 | 0,20 |
| **08/23/94** | 14:50 | 355 | 2,50 | 2,40 | 1,23 | | 1,23 | 48,75 | | 4,00 | 50,80 | | 0,20 | | 0,16 |
| **09/02/94** | 12:30 | 365 | 2,20 | 2,40 | **1,60** | **0,77** | **1,17** | **33,33** | **67,92** | -9,09 | **27,27** | **65,00** | **0,10** | **0,10** | 0,16 |
| **09/05/94** | 14:00 | 368 | 3,20 | 1,75 | 3,50 | 0,71 | 2,30 | -100,00 | 59,43 | 45,31 | -9,38 | 77,81 | 0,10 | 0,10 | 0,16 |
| **09/06/94** | 15:30 | 369 | 3,40 | 2,60 | 3,50 | 0,90 | 2,40 | -34,62 | 65,38 | 23,53 | -2,94 | 73,53 | 0,10 | 0,10 | 0,16 |
| **09/07/94** | 15:00 | 370 | 4,00 | 1,80 | 2,60 | 0,80 | 1,80 | -44,44 | 55,56 | 55,00 | 35,00 | 80,00 | 0,10 | 0,10 | 0,16 |
| **09/12/94** | 15:30 | 375 | 5,10 | 1,60 | 1,17 | 0,51 | 0,99 | 26,88 | 68,13 | 68,63 | 77,06 | 90,00 | 0,10 | 0,10 | 0,16 |
| **09/15/94** | 15:30 | 378 | 3,90 | 1,70 | 0,99 | 0,45 | 0,76 | 41,76 | 73,53 | 56,41 | 74,62 | 88,46 | 0,10 | 0,10 | 0,16 |
| **09/21/94** | 15:00 | 384 | 9,00 | 1,70 | 0,76 | 0,47 | 0,61 | 55,29 | 72,35 | 81,11 | 91,56 | 94,78 | 0,10 | 0,10 | 0,16 |
| **09/23/94** | 15:30 | 386 | 4,40 | 1,60 | 0,67 | 0,54 | 0,60 | 58,13 | 66,25 | 63,64 | 84,77 | 87,73 | 0,10 | 0,10 | 0,16 |
| **09/26/94** | 13:00 | 388 | 6,90 | 1,80 | 0,61 | 0,52 | 0,56 | 66,11 | 71,11 | 73,91 | 91,16 | 92,46 | 0,10 | 0,10 | 0,16 |
| **09/28/94** | 14:15 | 391 | 4,50 | 2,20 | 0,52 | 0,45 | 0,50 | 76,36 | 79,55 | 51,11 | 88,44 | 90,00 | 0,10 | 0,10 | 0,16 |
| **09/29/94** | 11:00 | 391 | 4,10 | 2,30 | 0,53 | 0,41 | 0,46 | 76,96 | 82,17 | 43,90 | 87,07 | 90,00 | 0,10 | 0,10 | 0,16 |
| **09/30/94** | 10:45 | 392 | 6,60 | 2,00 | 0,75 | 0,45 | 0,60 | 62,50 | 77,50 | 69,70 | 88,64 | 93,18 | 0,10 | 0,10 | 0,16 |
| **10/03/94** | 16:00 | 396 | 4,00 | 1,40 | 0,65 | 0,41 | 0,51 | 53,57 | 70,71 | 65,00 | 83,75 | 89,75 | 0,10 | 0,10 | 0,16 |
| **10/07/94** | 10:15 | 398 | 3,90 | 1,80 | 0,56 | 0,40 | 0,43 | 68,89 | 77,78 | 53,85 | 85,64 | 89,74 | 0,10 | 0,10 | 0,16 |
| **10/11/94** | 10:00 | 402 | 10,60 | 1,50 | 0,51 | 0,28 | 0,35 | 66,00 | 81,33 | 85,85 | 95,19 | 97,36 | 0,10 | 0,10 | 0,16 |
| **10/12/94** | 15:00 | 404 | 2,90 | 1,70 | 0,57 | 0,40 | 0,45 | 66,47 | 76,47 | 41,38 | 80,34 | 86,21 | 0,10 | 0,10 | 0,16 |
| **10/13/94** | 15:30 | 405 | 5,60 | 1,86 | 0,55 | 0,43 | 0,51 | 70,43 | 76,88 | 66,79 | 90,18 | 92,32 | 0,10 | 0,10 | 0,16 |
| **10/18/94** | 13:30 | 409 | 5,70 | 1,60 | 0,60 | 0,56 | 0,57 | 62,50 | 65,00 | 71,93 | 89,47 | 90,18 | 0,10 | 0,10 | 0,16 |
| **10/19/94** | 15:00 | 411 | 11,60 | 1,80 | 0,49 | 0,48 | 0,49 | 72,78 | 73,33 | 84,48 | 95,78 | 95,86 | 0,10 | 0,10 | 0,16 |
| **10/20/94** | 13:00 | 411 | 3,00 | 1,84 | 0,44 | 0,60 | 0,52 | 76,09 | 67,39 | 38,67 | 85,33 | 80,00 | 0,10 | 0,10 | 0,16 |
| **10/21/94** | 13:15 | 412 | 4,20 | 1,80 | 0,45 | 0,60 | 0,52 | 75,00 | 66,67 | 57,14 | 89,29 | 85,71 | 0,10 | 0,10 | 0,16 |
| **10/24/94** | 14:30 | 413 | 4,10 | 1,64 | 0,44 | 0,46 | 0,46 | 73,17 | 71,95 | 60,00 | 89,27 | 88,78 | 0,10 | 0,10 | 0,16 |
| **10/25/94** | 15:00 | 414 | 3,30 | 1,40 | 0,38 | 0,35 | 0,36 | 72,86 | 75,00 | 57,58 | 88,48 | 89,39 | 0,10 | 0,10 | 0,16 |
| **10/26/94** | 14:00 | 415 | 5,10 | 1,40 | 0,50 | 0,54 | 0,51 | 64,29 | 61,43 | 72,55 | 90,20 | 89,41 | 0,10 | 0,10 | 0,16 |
| **10/31/94** | 15:45 | 421 | 2,70 | 1,80 | 0,40 | 0,60 | 0,50 | 77,78 | 66,67 | 33,33 | 85,19 | 77,78 | 0,10 | 0,10 | 0,16 |
| **11/01/94** | 14:45 | 421 | 6,90 | 1,90 | 0,55 | 0,45 | 0,50 | 71,05 | 76,32 | 72,46 | 92,03 | 93,48 | 0,10 | 0,10 | 0,16 |
| **11/02/94** | 14:45 | 422 | 2,90 | 1,54 | 0,48 | 0,42 | 0,45 | 68,83 | 72,73 | 46,90 | 83,45 | 85,52 | 0,10 | 0,10 | 0,16 |
| **11/04/94** | 14:00 | 424 | 5,70 | 1,70 | 0,52 | 0,52 | 0,52 | 69,41 | 69,41 | 70,18 | 90,88 | 90,88 | 0,10 | 0,10 | 0,16 |
| **11/08/94** | 12:30 | 428 | 3,80 | 1,10 | 0,46 | 0,41 | 0,42 | 58,18 | 62,73 | 71,05 | 87,89 | 89,21 | 0,10 | 0,10 | 0,16 |
| **11/09/94** | 12:30 | 429 | 5,70 | 1,38 | 0,37 | 0,33 | 0,35 | 73,19 | 76,09 | 75,79 | 93,51 | 94,21 | 0,10 | 0,10 | 0,16 |
| **11/11/94** | 13:30 | 431 | 6,40 | 1,37 | 0,38 | 0,38 | 0,38 | 72,26 | 72,26 | 78,59 | 94,06 | 94,06 | 0,10 | 0,10 | 0,16 |
| **11/14/94** | 15:00 | 434 | 5,70 | 1,22 | 0,36 | 0,37 | 0,36 | 70,49 | 69,67 | 78,60 | 93,68 | 93,51 | 0,10 | 0,10 | 0,16 |
| **11/16/94** | 13:30 | 436 | 5,80 | 1,94 | 0,44 | 0,42 | 0,41 | 77,32 | 78,35 | 66,55 | 92,41 | 92,76 | 0,10 | 0,10 | 0,16 |
| **11/17/94** | 15:00 | 437 | 3,80 | 1,73 | 0,38 | 0,43 | 0,41 | 78,03 | 75,14 | 54,47 | 90,00 | 88,68 | 0,10 | 0,10 | 0,16 |
| **11/18/94** | 14:30 | 438 | 4,80 | 1,40 | 0,32 | 0,38 | 0,35 | 77,14 | 72,86 | 70,83 | 93,33 | 92,08 | 0,10 | 0,10 | 0,16 |
| **11/21/94** | 13:30 | 441 | 6,10 | 1,14 | 0,29 | 0,37 | 0,35 | 74,56 | 67,54 | 81,31 | 95,25 | 93,93 | 0,10 | 0,10 | 0,16 |
| **11/23/94** | 12:00 | 443 | 5,60 | 1,50 | 0,30 | 0,37 | 0,33 | 80,00 | 75,33 | 73,21 | 94,64 | 93,39 | 0,10 | 0,10 | 0,16 |
| **11/25/94** | 14:30 | 445 | 3,30 | 1,23 | 0,30 | 0,40 | 0,35 | 75,61 | 67,48 | 62,73 | 90,91 | 87,88 | 0,10 | 0,10 | 0,16 |
| **11/28/94** | 16:00 | 448 | 3,40 | 1,42 | 0,35 | 0,46 | 0,40 | 75,35 | 67,61 | 58,24 | 89,71 | 86,47 | 0,10 | 0,10 | 0,16 |
| **11/30/94** | 15:30 | 450 | 3,30 | 1,48 | 0,32 | 0,44 | 0,37 | 78,38 | 70,27 | 55,15 | 90,30 | 86,67 | 0,10 | 0,10 | 0,16 |
| **12/02/94** | 14:00 | 453 | 4,20 | 1,85 | 0,39 | 0,48 | 0,44 | 78,92 | 74,05 | 55,95 | 90,71 | 88,57 | 0,10 | 0,10 | 0,16 |

Shaded area - filter cleaning and 21d thereafter

Dates in bold - Inanda raw water

TABLE A1: TURBIDITY RESULTS - RAW DATA (CONTINUED)

| Date | Time | Time | Raw water | Pre-treated water | Filter 1 | Filter 2 | Filter 1+2 | Filter 1 | Filter 2 | Sed. Tank | System1 | System2 | Filter 1 | Filter 2 | Sed. tank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | elapsed | turbidity | turbidity | turbidity | turbidity | turbidity | turbidity removal | turbidity removal | turbidity removal | turbidity removal | turbidity removal | Flow rate | Flow rate | Upflow rate |
| | | (days) | (NTU) | (NTU) | (NTU) | (NTU) | (NTU) | (%) | (%) | (%) | (%) | (%) | m/h | m/h | m/h |
| **12/05/94** | 15:00 | 456 | 3,90 | 1,39 | 0,55 | 0,41 | 0,48 | 60,43 | 70,50 | 64,36 | 85,90 | 89,49 | 0,10 | 0,10 | 0,16 |
| **12/07/94** | 14:30 | 458 | 6,50 | 1,34 | 0,27 | 0,35 | 0,31 | 79,85 | 73,88 | 79,38 | 95,85 | 94,62 | 0,10 | 0,10 | 0,16 |
| **12/12/94** | 15:30 | 463 | 7,90 | 1,45 | 0,31 | 0,52 | 0,41 | 78,62 | 64,14 | 81,65 | 96,08 | 93,42 | 0,10 | 0,10 | 0,16 |
| **12/13/94** | 15:30 | 464 | 6,00 | 1,91 | 0,66 | 0,50 | 0,56 | 65,45 | 73,82 | 68,17 | 89,00 | 91,67 | 0,40 | 0,10 | 0,39 |
| **12/14/94** | 15:30 | 465 | 4,50 | 1,70 | 0,39 | 0,31 | 0,35 | 77,06 | 81,76 | 62,22 | 91,33 | 93,11 | 0,40 | 0,10 | 0,39 |
| **12/15/94** | 15:00 | 466 | 2,60 | 1,89 | 0,34 | 0,28 | 0,31 | 82,01 | 85,19 | 27,31 | 86,92 | 89,23 | 0,40 | 0,10 | 0,39 |
| **12/19/94** | 09:00 | 470 | 3,10 | 1,23 | 0,25 | 0,17 | 0,20 | 79,67 | 86,18 | 60,32 | 91,94 | 94,52 | 0,50 | 0,10 | 0,47 |
| **12/20/94** | 11:30 | 471 | 3,40 | 0,99 | 0,24 | 0,26 | 0,25 | 75,76 | 73,74 | 70,88 | 92,94 | 92,35 | 0,50 | 0,10 | 0,47 |
| **12/21/94** | 14:30 | 472 | 2,60 | 0,93 | 0,26 | 0,31 | 0,28 | 72,04 | 66,67 | 64,23 | 90,00 | 88,08 | 0,50 | 0,10 | 0,47 |
| **12/22/94** | 14:30 | 473 | 3,40 | 1,09 | 0,23 | 0,28 | 0,25 | 78,90 | 74,31 | 67,94 | 93,24 | 91,76 | 0,40 | 0,10 | 0,39 |
| **12/27/94** | 14:45 | 478 | 3,70 | 1,18 | 0,27 | 0,41 | 0,34 | 77,12 | 65,25 | 68,11 | 92,70 | 88,92 | 0,40 | 0,10 | 0,39 |
| **12/29/94** | 14:30 | 480 | 4,60 | 1,90 | 0,25 | 0,25 | 0,25 | 86,84 | 86,84 | 58,70 | 94,57 | 94,57 | 0,40 | 0,10 | 0,39 |
| **01/04/95** | 12:30 | 486 | 2,50 | 1,90 | 0,26 | 0,28 | 0,27 | 86,32 | 85,26 | 24,00 | 89,60 | 88,80 | 0,40 | 0,10 | 0,39 |
| **01/09/95** | 15:30 | 491 | 10,00 | 4,50 | 0,15 | 0,24 | 0,20 | 96,67 | 94,67 | 55,00 | 98,50 | 97,60 | 0,40 | 0,10 | 0,39 |
| **01/12/95** | 15:30 | 494 | 2,50 | 1,95 | 0,21 | 0,21 | 0,21 | 89,23 | 89,23 | 22,00 | 91,60 | 91,60 | 0,40 | 0,10 | 0,39 |
| **01/16/95** | 14:00 | 498 | 2,50 | 1,41 | 0,30 | 0,30 | 0,30 | 78,72 | 78,72 | 43,60 | 88,00 | 88,00 | 0,40 | 0,10 | 0,39 |
| **01/19/95** | 15:00 | 501 | 3,20 | 1,47 | 0,28 | 0,27 | 0,27 | 80,95 | 81,63 | 54,06 | 91,25 | 91,56 | 0,40 | 0,10 | 0,39 |
| **01/24/95** | 14:30 | 506 | 3,60 | 3,30 | 0,20 | 0,18 | 0,19 | 93,94 | 94,55 | 8,33 | 94,44 | 95,00 | 0,40 | 0,10 | 0,39 |
| **01/27/95** | 14:30 | 509 | 2,40 | 1,90 | 0,18 | 0,10 | 0,15 | 90,53 | 94,74 | 20,83 | 92,50 | 95,83 | 0,30 | 0,10 | 0,31 |
| **01/31/95** | 15:00 | 513 | 4,80 | 3,60 | 0,18 | 0,23 | 0,20 | 95,00 | 93,61 | 25,00 | 96,25 | 95,21 | 0,32 | 0,10 | 0,33 |
| **02/08/95** | 15:00 | 521 | 7,10 | 7,00 | 0,18 | 0,21 | 0,19 | 97,43 | 97,00 | 1,41 | 97,46 | 97,04 | 0,30 | 0,08 | 0,30 |
| **02/15/95** | 13:00 | 528 | 10,00 | 6,90 | 0,30 | 0,25 | 0,27 | 95,65 | 96,38 | 31,00 | 97,00 | 97,50 | 0,30 | 0,09 | 0,30 |
| **02/22/95** | 12:30 | 535 | 7,60 | 6,50 | 0,22 | 0,33 | | 96,62 | 94,92 | 14,47 | 97,11 | 95,66 | 0,20 | 0,08 | 0,21 |
| **03/03/95** | 09:30 | 547 | 6,10 | 5,40 | 0,23 | 0,33 | | 95,74 | 93,89 | 11,48 | 96,23 | 94,59 | 0,23 | 0,10 | 0,26 |
| **03/14/95** | 09:30 | 558 | 5,10 | 4,00 | 0,17 | 0,21 | 0,19 | 95,75 | 94,75 | 21,57 | 96,67 | 95,88 | 0,29 | 0,10 | 0,30 |
| **03/23/95** | 10:00 | 567 | 2,00 | 3,00 | 0,18 | 0,23 | 0,20 | 94,00 | 92,33 | -50,00 | 91,00 | 88,50 | 0,29 | 0,10 | 0,30 |
| **03/30/95** | 10:30 | 574 | 2,60 | 2,10 | 0,14 | 0,23 | | 93,33 | 89,05 | 19,23 | 94,62 | 91,15 | 0,30 | 0,10 | 0,31 |
| **05/03/95** | 09:45 | 608 | 3,90 | 1,20 | 0,10 | 0,13 | 0,12 | 91,67 | 89,17 | 69,23 | 97,44 | 96,67 | 0,38 | 0,07 | 0,35 |
| **05/09/95** | 09:15 | 614 | 1,64 | 1,08 | 0,30 | 0,27 | 0,28 | 72,22 | 75,00 | 34,15 | 81,71 | 83,54 | 0,38 | 0,07 | 0,35 |
| **05/17/95** | 09:30 | 622 | 1,52 | 1,30 | 0,09 | 0,16 | 0,12 | 93,08 | 87,69 | 14,47 | 94,08 | 89,47 | 0,15 | 0,05 | 0,16 |
| **05/22/95** | 09:00 | 627 | 1,60 | 1,21 | 0,08 | 0,18 | 0,13 | 93,39 | 85,12 | 24,38 | 95,00 | 88,75 | 0,11 | 0,03 | 0,11 |
| **05/25/95** | 14:00 | 630 | 1,38 | 1,20 | 0,11 | 0,15 | | 90,83 | 87,50 | 13,04 | 92,03 | 89,13 | 0,11 | 0,03 | 0,11 |
| **05/31/95** | 11:00 | 636 | 1,60 | 1,20 | 0,25 | 0,21 | 0,23 | 79,17 | 82,50 | 25,00 | 84,38 | 86,88 | 0,12 | 0,04 | 0,12 |
| **07/17/95** | 11:30 | 683 | 3,50 | 2,70 | 0,23 | 0,30 | | 91,48 | 88,89 | 22,86 | 93,43 | 91,43 | 0,06 | 0,03 | 0,07 |

Shaded area - filter cleaning and 21d thereafter

Dates in bold - Inanda raw water

# APPENDIX B

## *Results and data manipulations for statistical analysis*

TABLE B1: CUMULATIVE SUM OF RAW WATER TURBIDITY DIFFERENCES WITH RESPECT TO MEAN TURBIDITY

Mean turbidity = 23,2

| Date | Serial time from start (d) | Sample No. | Raw water turbidity (NTU) | Cumulative sum of (turbidity - mean) (NTU) |
|---|---|---|---|---|
| 08/20/93 | | | | |
| 08/23/93 | 0 | 1 | 26,0 | 2,8 |
| 08/24/93 | 3 | 2 | 14,4 | -6,1 |
| 08/25/93 | 4 | 3 | 11,0 | -18,3 |
| 08/26/93 | 5 | 4 | 13,0 | -28,6 |
| 08/27/93 | 6 | 5 | 9,8 | -42,0 |
| 08/30/93 | 7 | 6 | 13,1 | -52,2 |
| 08/31/93 | 10 | 7 | 10,0 | -65,4 |
| 09/01/93 | 11 | 8 | 14,4 | -74,3 |
| 09/02/93 | 12 | 9 | 10,7 | -86,8 |
| 09/03/93 | 13 | 10 | 19,7 | -90,4 |
| 09/06/93 | 14 | 11 | 10,4 | -103,2 |
| 09/07/93 | 17 | 12 | 8,1 | -118,3 |
| 09/08/93 | 18 | 13 | 9,1 | -132,5 |
| 09/09/93 | 19 | 14 | 11,0 | -144,7 |
| 09/10/93 | 20 | 15 | 9,9 | -158,1 |
| 09/13/93 | 21 | 16 | 7,5 | -173,8 |
| 09/14/93 | 24 | 17 | 12,0 | -185,1 |
| 09/15/93 | 25 | 18 | 8,7 | -199,6 |
| 09/16/93 | 26 | 19 | 9,3 | -213,6 |
| 09/17/93 | 27 | 20 | 9,8 | -227,0 |
| 09/20/93 | 28 | 21 | 7,4 | -242,9 |
| 09/21/93 | 31 | 22 | 9,9 | -256,2 |
| 09/22/93 | 32 | 23 | 11,0 | -268,4 |
| 09/23/93 | 33 | 24 | 13,2 | -278,5 |
| 09/27/93 | 34 | 25 | 35,0 | -266,7 |
| 09/28/93 | 35 | 26 | 73,0 | -217,0 |
| 09/29/93 | 36 | 27 | 62,0 | -178,2 |
| 09/29/93 | 37 | 28 | 31,0 | -170,5 |
| 09/30/93 | 37 | 29 | 34,0 | -159,7 |
| 10/01/93 | 38 | 30 | 47,0 | -136,0 |
| 10/04/93 | 39 | 31 | 32,0 | -127,2 |
| 10/05/93 | 44 | 32 | 31,0 | -119,5 |
| 10/06/93 | 45 | 33 | 30,0 | -112,7 |
| 10/07/93 | 46 | 34 | 46,0 | -89,9 |
| 10/08/93 | 47 | 35 | 77,0 | -36,2 |
| 10/11/93 | 48 | 36 | 48,0 | -11,4 |
| 10/12/93 | 51 | 37 | 39,0 | 4,3 |
| 10/13/93 | 52 | 38 | 19,0 | 0,1 |
| 10/14/93 | 53 | 39 | 25,0 | 1,8 |
| 10/15/93 | 54 | 40 | 21,0 | -0,4 |
| 10/18/93 | 55 | 41 | 17,8 | -5,9 |
| 10/19/93 | 58 | 42 | 20,0 | -9,1 |
| 10/20/93 | 59 | 43 | 16,2 | -16,2 |
| 10/21/93 | 60 | 44 | 16,8 | -22,6 |
| 10/22/93 | 61 | 45 | 19,3 | -26,5 |
| 10/25/93 | 62 | 46 | 23,0 | -26,8 |
| 10/26/93 | 65 | 47 | 18,7 | -31,3 |
| 10/27/93 | 66 | 48 | 17,1 | -37,5 |
| 10/28/93 | 67 | 49 | 19,8 | -40,9 |

summed in sample order

TABLE B1: CUMULATIVE SUM OF RAW WATER TURBIDITY DIFFERENCES WITH RESPECT TO MEAN TURBIDITY (CONTINUED)

| Date | Serial time from start (d) | Sample No. | Raw water turbidity (NTU) | Cumulative sum of (turbidity - mean) (NTU) |
|---|---|---|---|---|
| | | | Mean turbidity = | 23,2 |
| 10/29/93 | 68 | 50 | 19,1 | -45,1 |
| 11/01/93 | 69 | 51 | 31,0 | -37,3 |
| 11/02/93 | 72 | 52 | 17,2 | -43,4 |
| 11/03/93 | 73 | 53 | 17,9 | -48,7 |
| 11/04/93 | 74 | 54 | 19,1 | -52,9 |
| 11/05/93 | 75 | 55 | 19,1 | -57,0 |
| 11/08/93 | 76 | 56 | 78,0 | -2,2 |
| 11/09/93 | 79 | 57 | 19,9 | -5,6 |
| 11/10/93 | 80 | 58 | 22,0 | -6,8 |
| 11/11/93 | 81 | 59 | 19.2 | -30,1 |
| 11/12/93 | 82 | 60 | 21,0 | -32,3 |
| 11/15/93 | 83 | 61 | 24,0 | -31,6 |
| 11/16/93 | 86 | 62 | 23,0 | -31,8 |
| 11/17/93 | 87 | 63 | 65,0 | 9,9 |
| 11/18/93 | 88 | 64 | 34,0 | 20,7 |
| 11/19/93 | 89 | 65 | 45,0 | 42,4 |
| 11/22/93 | 90 | 66 | 66,0 | 85,2 |
| 11/23/93 | 93 | 67 | 69,0 | 131,0 |
| 11/24/93 | 94 | 68 | 48,0 | 155,7 |
| 11/25/93 | 95 | 69 | 37,0 | 169,5 |
| 11/26/93 | 96 | 70 | 24,0 | 170,2 |
| 11/29/93 | 97 | 71 | 114,0 | 261,0 |
| 11/30/93 | 100 | 72 | 22,0 | 259,7 |
| 12/01/93 | 101 | 73 | 41,0 | 277,5 |
| 12/02/93 | 102 | 74 | 21,0 | 275,2 |
| 12/03/93 | 103 | 75 | 46,0 | 298,0 |
| 12/06/93 | 104 | 76 | 308,0 | 582,7 |
| 12/07/93 | 107 | 77 | 56,0 | 615,5 |
| 12/10/93 | 108 | 78 | 40,0 | 632,3 |
| 12/13/93 | 109 | 79 | 123,0 | 732,0 |
| 12/14/93 | 112 | 80 | 29,0 | 737,8 |
| 12/15/93 | 113 | 81 | 24,0 | 738,5 |
| 12/17/93 | 114 | 82 | 52,0 | 767,3 |
| 12/20/93 | 116 | 83 | 69,0 | 813,0 |
| 12/21/93 | 119 | 84 | 27,0 | 816,8 |
| 12/22/93 | 120 | 85 | 61,0 | 854,5 |
| 12/23/93 | 121 | 86 | 26,0 | 857,3 |
| 12/24/93 | 122 | 87 | 28,0 | 862,0 |
| 12/27/93 | 123 | 88 | 24,0 | 862,8 |
| 12/28/93 | 126 | 89 | 25,0 | 864,6 |
| 12/30/93 | 127 | 90 | 119,0 | 960,3 |
| -12/31/93 | 129 | 91 | 55,0 | 992,1 |
| 01/03/94 | 130 | 92 | 30,0 | 998,8 |
| 01/04/94 | 133 | 93 | 35,0 | 1010,6 |
| 01/05/94 | 134 | 94 | 41,0 | 1028,3 |
| 01/06/94 | 135 | 95 | 30,0 | 1035,1 |
| 01/07/94 | 136 | 96 | 31,0 | 1042,8 |
| 01/13/94 | 137 | 97 | 48,0 | 1067,6 |
| 01/14/94 | 143 | 98 | 60,0 | 1104,3 |
| 01/17/94 | 144 | 99 | 27,0 | 1108,1 |

summed in sample order

TABLE B1: CUMULATIVE SUM OF RAW WATER TURBIDITY DIFFERENCES
WITH RESPECT TO MEAN TURBIDITY (CONTINUED)

| | | | Mean turbidity = | 23,2 |
|---|---|---|---|---|
| Date | Serial time from start (d) | Sample No. | Raw water turbidity (NTU) | Cumulative sum of (turbidity - mean) (NTU) |
| 01/18/94 | 147 | 100 | 27,0 | 1111,8 |
| 01/19/94 | 148 | 101 | 56,0 | 1144,6 |
| 01/20/94 | 149 | 102 | 23,0 | 1144,4 |
| 01/21/94 | 150 | 103 | 26,0 | 1147,1 |
| 01/24/94 | 151 | 104 | 23,0 | 1146,9 |
| 01/25/94 | 154 | 105 | 24,0 | 1147,6 |
| 01/26/94 | 155 | 106 | 26,0 | 1150,4 |
| 01/27/94 | 156 | 107 | 21,0 | 1148,1 |
| 01/31/94 | 157 | 108 | 26,0 | 1150,9 |
| 02/01/94 | 161 | 109 | 28,0 | 1155,6 |
| 02/02/94 | 162 | 110 | 17,0 | 1149,4 |
| 02/03/94 | 163 | 111 | 27,0 | 1153,1 |
| 02/04/94 | 164 | 112 | 25,0 | 1154,9 |
| 02/07/94 | 165 | 113 | 17,0 | 1148,7 |
| 02/08/94 | 168 | 114 | 37,0 | 1162,4 |
| 02/09/94 | 169 | 115 | 71,0 | 1210,2 |
| 02/10/94 | 170 | 116 | 28,0 | 1214,9 |
| 02/11/94 | 171 | 117 | 48,0 | 1239,7 |
| 02/14/94 | 172 | 118 | 21,0 | 1237,4 |
| 02/15/94 | 173 | 119 | 14,2 | 1228,4 |
| 02/16/94 | 174 | 120 | 13,1 | 1218,2 |
| 02/17/94 | 175 | 121 | 19,2 | 1214,2 |
| 02/18/94 | 176 | 122 | 23,0 | 1213,9 |
| 02/21/94 | 177 | 123 | 7,0 | 1197,7 |
| 02/22/94 | 180 | 124 | 22,0 | 1196,5 |
| 02/23/94 | 181 | 125 | 29,0 | 1202,2 |
| 02/24/94 | 182 | 126 | 42,0 | 1221,0 |
| 02/25/94 | 183 | 127 | 17,5 | 1215,2 |
| 02/28/94 | 184 | 128 | 31,0 | 1223,0 |
| 03/01/94 | 187 | 129 | 14,0 | 1213,7 |
| 03/02/94 | 188 | 130 | 23,0 | 1213,5 |
| 03/03/94 | 189 | 131 | 36,0 | 1226,2 |
| 03/04/94 | 190 | 132 | 0,0 | 1203,0 |
| 03/07/94 | 191 | 133 | 39,0 | 1218,7 |
| 03/08/94 | 191 | 134 | 106,0 | 1301,5 |
| 03/09/94 | 192 | 135 | 33,0 | 1311,3 |
| 03/10/94 | 193 | 136 | 132,0 | 1420,0 |
| 03/11/94 | 194 | 137 | 44,0 | 1440,8 |
| 03/14/94 | 195 | 138 | 35,0 | 1452,5 |
| 03/16/94 | 198 | 139 | 28,0 | 1457,3 |
| 03/17/94 | 200 | 140 | 33,0 | 1467,0 |
| -03/18/94 | 201 | 141 | 30,0 | 1473,8 |
| 03/28/94 | 206 | 142 | 28,0 | 1478,5 |
| 03/29/94 | 206 | 143 | 35,0 | 1490,3 |
| 03/31/94 | 207 | 144 | 52,0 | 1519,0 |
| 04/07/94 | 208 | 145 | 31,0 | 1526,8 |
| 04/08/94 | 215 | 146 | 36,0 | 1539,6 |
| 04/11/94 | 216 | 147 | 35,0 | 1551,3 |
| 04/12/94 | 219 | 148 | 39,0 | 1567,1 |
| 04/13/94 | 220 | 149 | 77,0 | 1620,8 |

summed in sample order

TABLE B1: CUMULATIVE SUM OF RAW WATER TURBIDITY DIFFERENCES WITH RESPECT TO MEAN TURBIDITY (CONTINUED)

| Date | Serial time from start (d) | Sample No. | Raw water turbidity (NTU) | Cumulative sum of (turbidity - mean) (NTU) |
|---|---|---|---|---|
| | | | Mean turbidity = | 23,2 |
| 04/14/94 | 221 | 150 | 46,0 | 1643,6 |
| 04/15/94 | 222 | 151 | 52,0 | 1672,3 |
| 04/18/94 | 223 | 152 | 40,0 | 1689,1 |
| 04/20/94 | 226 | 153 | 82,0 | 1747,8 |
| 04/25/94 | 228 | 154 | 45,0 | 1769,6 |
| 04/26/94 | 233 | 155 | 37,0 | 1783,3 |
| 04/29/94 | 234 | 156 | 24,0 | 1784,1 |
| 05/02/94 | 237 | 157 | 35,0 | 1795,9 |
| 05/03/94 | 240 | 158 | 29,0 | 1801,6 |
| 05/04/94 | 241 | 159 | 28,0 | 1806,4 |
| 05/05/94 | 242 | 160 | 28,0 | 1811,1 |
| 05/06/94 | 243 | 161 | 30,0 | 1817,9 |
| 05/09/94 | 244 | 162 | 40,0 | 1834,6 |
| 05/11/94 | 247 | 163 | 25,0 | 1836,4 |
| 05/17/94 | 249 | 164 | 41,0 | 1854,1 |
| 05/23/94 | 255 | 165 | 18,7 | 1849,6 |
| 05/24/94 | 261 | 166 | 16,1 | 1842,4 |
| 05/25/94 | 262 | 167 | 18,6 | 1837,8 |
| 05/26/94 | 263 | 168 | 12,0 | 1826,6 |
| 06/03/94 | 264 | 169 | 15,0 | 1818,3 |
| 06/08/94 | 272 | 170 | 10,5 | 1805,6 |
| 06/09/94 | 277 | 171 | 8,5 | 1790,8 |
| 06/10/94 | 278 | 172 | 13,4 | 1781,0 |
| 06/13/94 | 279 | 173 | 8,3 | 1766,0 |
| 06/15/94 | 282 | 174 | 10,4 | 1753,2 |
| 06/16/94 | 284 | 175 | 8,8 | 1738,7 |
| 06/17/94 | 285 | 176 | 9,5 | 1725,0 |
| 06/20/94 | 286 | 177 | 14,0 | 1715,7 |
| 06/21/94 | 289 | 178 | 8,3 | 1700,8 |
| 06/23/94 | 290 | 179 | 10,1 | 1687,7 |
| 06/24/94 | 292 | 180 | 14,7 | 1679,1 |
| 06/27/94 | 293 | 181 | 11,6 | 1667,5 |
| 06/28/94 | 296 | 182 | 12,4 | 1656,6 |
| 06/29/94 | 297 | 183 | 8,2 | 1641,6 |
| 06/30/94 | 298 | 184 | 7,4 | 1625,7 |
| 07/01/94 | 299 | 185 | 6,8 | 1609,3 |
| 07/04/94 | 300 | 186 | 6,5 | 1592,5 |
| 07/05/94 | 303 | 187 | 7,6 | 1576,9 |
| 07/06/94 | 304 | 188 | 6,8 | 1560,4 |
| 07/07/94 | 305 | 189 | 9,1 | 1546,3 |
| 07/08/94 | 306 | 190 | 7,1 | 1530,2 |
| 07/11/94 | 307 | 191 | 8,0 | 1514,9 |
| 07/12/94 | 309 | 192 | 9,6 | 1501,3 |
| 07/13/94 | 310 | 193 | 6,5 | 1484,5 |
| 07/14/94 | 311 | 194 | 26,0 | 1487,3 |
| 07/15/94 | 312 | 195 | 62,0 | 1526,0 |
| 07/19/94 | 312 | 196 | 69,0 | 1571,8 |
| 07/21/94 | 317 | 197 | 8,9 | 1557,4 |
| 07/22/94 | 319 | 198 | 4,8 | 1539,0 |
| 07/29/94 | 320 | 199 | 5,6 | 1521,3 |

summed in sample order

TABLE B1: CUMULATIVE SUM OF RAW WATER TURBIDITY DIFFERENCES WITH RESPECT TO MEAN TURBIDITY (CONTINUED)

| | | | Mean turbidity = | 23,2 |
|---|---|---|---|---|
| Date | Serial time from start (d) | Sample No. | Raw water turbidity (NTU) | Cumulative sum of (turbidity - mean) (NTU) |
| 08/03/94 | 324 | 200 | 5,0 | 1503,1 |
| 08/10/94 | 329 | 201 | 3,0 | 1482,9 |
| 08/11/94 | 336 | 202 | 4,2 | 1463,8 |
| 08/16/94 | 337 | 203 | 2,7 | 1443,3 |
| 08/22/94 | 342 | 204 | 3,4 | 1423,4 |
| 08/23/94 | 348 | 205 | 2,5 | 1402,7 |
| 09/02/94 | 349 | 206 | 2,2 | 1381,6 |
| 09/05/94 | 359 | 207 | 3,2 | 1361,6 |
| 09/06/94 | 362 | 208 | 3,4 | 1341,7 |
| 09/07/94 | 363 | 209 | 4,0 | 1322,5 |
| 09/12/94 | 364 | 210 | 5,1 | 1304,3 |
| 09/15/94 | 369 | 211 | 3,9 | 1285,0 |
| 09/21/94 | 372 | 212 | 9,0 | 1270,8 |
| 09/23/94 | 378 | 213 | 4,4 | 1251,9 |
| 09/26/94 | 380 | 214 | 6,9 | 1235,6 |
| 09/28/94 | 382 | 215 | 4,5 | 1216,8 |
| 09/29/94 | 385 | 216 | 4,1 | 1197,7 |
| 09/30/94 | 385 | 217 | 6,6 | 1181,0 |
| 10/03/94 | 386 | 218 | 4,0 | 1161,8 |
| 10/07/94 | 390 | 219 | 3,9 | 1142,4 |
| 10/11/94 | 392 | 220 | 10,6 | 1129,8 |
| 10/12/94 | 396 | 221 | 2,9 | 1109,4 |
| 10/13/94 | 398 | 222 | 5,6 | 1091,8 |
| 10/18/94 | 399 | 223 | 5,7 | 1074,3 |
| 10/19/94 | 403 | 224 | 11,6 | 1062,6 |
| 10/20/94 | 405 | 225 | 3,0 | 1042,4 |
| 10/21/94 | 405 | 226 | 4,2 | 1023,3 |
| 10/24/94 | 406 | 227 | 4,1 | 1004,2 |
| 10/25/94 | 407 | 228 | 3,3 | 984,2 |
| 10/26/94 | 408 | 229 | 5,1 | 966,1 |
| 10/31/94 | 409 | 230 | 2,7 | 945,5 |
| 11/01/94 | 415 | 231 | 6,9 | 929,2 |
| 11/02/94 | 415 | 232 | 2,9 | 908,8 |
| 11/04/94 | 416 | 233 | 5,7 | 891,3 |
| 11/08/94 | 418 | 234 | 3,8 | 871,9 |
| 11/09/94 | 422 | 235 | 5,7 | 854,3 |
| 11/11/94 | 423 | 236 | 6,4 | 837,5 |
| 11/14/94 | 425 | 237 | 5,7 | 819,9 |
| 11/16/94 | 428 | 238 | 5,8 | 802,5 |
| 11/17/94 | 430 | 239 | 3,8 | 783,0 |
| 11/18/94 | 431 | 240 | 4,8 | 764,6 |
| 11/21/94 | 432 | 241 | 6,1 | 747,4 |
| 11/23/94 | 435 | 242 | 5,6 | 729,8 |
| 11/25/94 | 437 | 243 | 3,3 | 709,8 |
| 11/28/94 | 439 | 244 | 3,4 | 690,0 |
| 11/30/94 | 442 | 245 | 3,3 | 670,1 |
| 12/02/94 | 444 | 246 | 4,2 | 651,0 |
| 12/05/94 | 447 | 247 | 3,9 | 631,7 |
| 12/07/94 | 450 | 248 | 6,5 | 614,9 |
| 12/12/94 | 452 | 249 | 7,9 | 599,6 |

summed in sample order

TABLE B1: CUMULATIVE SUM OF RAW WATER TURBIDITY DIFFERENCES WITH RESPECT TO MEAN TURBIDITY (CONTINUED)

| | | | Mean turbidity = | 23,2 |
|---|---|---|---|---|
| Date | Serial time from start (d) | Sample No. | Raw water turbidity (NTU) | Cumulative sum of (turbidity - mean) (NTU) |
| 12/13/94 | 457 | 250 | 6,0 | 582,3 |
| 12/14/94 | 458 | 251 | 4,5 | 563,6 |
| 12/15/94 | 459 | 252 | 2,6 | 542,9 |
| 12/19/94 | 460 | 253 | 3,1 | 522,8 |
| 12/20/94 | 464 | 254 | 3,4 | 502,9 |
| 12/21/94 | 465 | 255 | 2,6 | 482,3 |
| 12/22/94 | 466 | 256 | 3,4 | 462,5 |
| 12/27/94 | 467 | 257 | 3,7 | 442,9 |
| 12/29/94 | 472 | 258 | 4,6 | 424,3 |
| 01/04/95 | 474 | 259 | 2,5 | 403,5 |
| 01/09/95 | 480 | 260 | 10,0 | 390,3 |
| 01/12/95 | 485 | 261 | 2,5 | 369,5 |
| 01/16/95 | 488 | 262 | 2,5 | 348,8 |
| 01/19/95 | 492 | 263 | 3,2 | 328,7 |
| 01/24/95 | 495 | 264 | 3,6 | 309,1 |
| 01/27/95 | 500 | 265 | 2,4 | 288,2 |
| 01/31/95 | 503 | 266 | 4,8 | 269,8 |
| 02/08/95 | 507 | 267 | 7,1 | 253,7 |
| 02/15/95 | 515 | 268 | 10,0 | 240,4 |
| 02/22/95 | 522 | 269 | 7,6 | 224,8 |
| 03/03/95 | 529 | 270 | 6,1 | 207,6 |
| 03/14/95 | 541 | 271 | 5,1 | 189,5 |
| 03/23/95 | 552 | 272 | 2,0 | 168,2 |
| 03/30/95 | 561 | 273 | 2,6 | 147,6 |
| 05/03/95 | 568 | 274 | 3,9 | 128,2 |
| 05/09/95 | 602 | 275 | 1,6 | 106,6 |
| 05/17/95 | 608 | 276 | 1,5 | 84,9 |
| 05/22/95 | 616 | 277 | 1,6 | 63,3 |
| 05/25/95 | 621 | 278 | 1,4 | 41,4 |
| 05/31/95 | 624 | 279 | 1,6 | 19,7 |
| 07/17/95 | 630 | 280 | 3,5 | -0,0 |

summed in sample order

TABLE B2 : TURBIDITY AND MICROBIOLOGICAL SAMPLE FREQUENCY

| | Time (d) | | | Set 1 | | Set 2 | |
|---|---|---|---|---|---|---|---|
| | Lower | Upper | | Sample | Relative | Sample | Relative |
| Class | limit | limit | Midpoint | frequency | frequency | frequency | frequency |
| at or below | | 0 | -15 | 0 | 0,00 | 0 | 0,00 |
| 1 | 0 | 30 | 15 | 20 | 7,09 | 2 | 4,26 |
| 2 | 30 | 60 | 45 | 25 | 8,87 | 3 | 6,38 |
| 3 | 60 | 90 | 75 | 21 | 7,45 | 4 | 8,51 |
| 4 | 90 | 120 | 105 | 20 | 7,09 | 2 | 4,26 |
| 5 | 120 | 150 | 135 | 19 | 6,74 | 2 | 4,26 |
| 6 | 150 | 180 | 165 | 22 | 7,80 | 2 | 4,26 |
| 7 | 180 | 210 | 195 | 19 | 6,74 | 3 | 6,38 |
| 8 | 210 | 240 | 225 | 14 | 4,96 | 2 | 4,26 |
| 9 | 240 | 270 | 255 | 10 | 3,55 | 3 | 6,38 |
| 10 | 270 | 300 | 285 | 17 | 6,03 | 2 | 4,26 |
| 11 | 300 | 330 | 315 | 15 | 5,32 | 3 | 6,38 |
| 12 | 330 | 360 | 345 | 7 | 2,48 | 3 | 6,38 |
| 13 | 360 | 390 | 375 | 11 | 3,90 | 5 | 10,64 |
| 14 | 390 | 420 | 405 | 15 | 5,32 | 4 | 8,51 |
| 15 | 420 | 450 | 435 | 14 | 4,96 | 1 | 2,13 |
| 16 | 450 | 480 | 465 | 12 | 4,26 | 2 | 4,26 |
| 17 | 480 | 510 | 495 | 7 | 2,48 | 2 | 4,26 |
| 18 | 510 | 540 | 525 | 4 | 1,42 | 1 | 2,13 |
| 19 | 540 | 570 | 555 | 3 | 1,06 | 0 | 0,00 |
| 20 | 570 | 600 | 585 | 0 | 0,00 | 0 | 0,00 |
| 21 | 600 | 630 | 615 | 6 | 2,13 | 1 | 2,13 |
| 22 | 630 | 660 | 645 | 0 | 0,00 | 0 | 0,00 |
| 23 | 660 | 690 | 675 | 1 | 0,35 | 0 | 0,00 |
| above | 690 | | 705 | 0 | 0,00 | 0 | 0,00 |
| | | | Total = | 282 | Total = | 47 | |
| | | | | | | | |

Mean = 269,54 Standard deviation = 155,25

SET 1 = TURBIDITY SET 2 = MICROBIOLOGY

TABLE B3 : CUMULATIVE FREQUENCY OF RAW WATER TURBIDITY

| Set 1 | | | Set 2 | | |
|---|---|---|---|---|---|
| Turbidity (NTU) | Frequency | Cumulative frequency (%) | Turbidity (NTU) | Frequency | Cumulative frequency (%) |
| 1,52 | 3 | 1,0752688172 | 1,52 | 1 | 1,96078431373 |
| 2,6 | 13 | 5,73476702509 | 2,5 | 3 | 7,8431372549 |
| 3,4 | 17 | 11,8279569892 | 3,2 | 4 | 15,6862745098 |
| 6,1 | 38 | 25,4480286738 | 4,1 | 6 | 27,4509803922 |
| 17 | 71 | 50,8960573477 | 10 | 14 | 54,9019607843 |
| 31 | 73 | 77,0609318996 | 28 | 14 | 82,3529411765 |
| 48 | 37 | 90,3225806452 | 41 | 5 | 92,1568627451 |
| 69 | 15 | 95,6989247312 | 46 | 3 | 98,0392156863 |
| 73 | 2 | 96,4157706093 | 62 | 0 | 98,0392156863 |
| 200 | 9 | 99,6415770609 | 73 | 1 | 100 |
| 536 | 1 | 100 | | 0 | |
| | 0 | | | | |
| Total | 279 | | Total | 51 | |

SET 1 = TURBIDITY RESULTS

SET 2 = TURBIDITY RESULTS CORRESPONDING TO MICROBIOLOGICAL SAMPLING

**Test for randomness of raw water turbidity sampling**

Null hypothesis: Ho = No pattern
Alternate hypothesis: Ha1 = evidence of patterns above/below median
Alternate hypothesis: Ha2 = evidence of patterns up/down

Median = 17 based on 282 observations
Number of runs above and below median = 22
Expected number = 141.993
Large sample test statistic Z = -14,2575
Two-tailed probability of equaling or exceeding Z = 0
Therefore reject null hypothesis, i.e. there are patterns above and below median turbidity.

Number of runs up and down = 184
Expected number = 185
Large sample test statistic Z = -0,0713558
Two-tailed probability of equaling or exceeding Z = 0,943109
Therefore do not reject null hypothesis, i.e. there are no patterns up and dc
i.e. the turbidity fluctuates up and down.

Note: '4 adjacent values ignored

# APPENDIX C

*Experimental results for microbiology*

TABLE C1 MICROBIOLOGICAL RESULTS - RAW DATA

| Date | Serial time from start (d) | Turbidity Raw (NTU) | Turbidity Filtered 2 (NTU) | Turbidity Pre-treated (NTU) | Coliforms Raw (/100 ml) | Coliforms Pre-treated (/100 ml) | Coliforms Filtered 1 (/100 ml) | Coliforms Filtered 2 (/100 ml) | SSF2 Coliforms Removal (%) | E Coli Raw (/100 ml) | E Coli Pre-treated (/100 ml) | E Coli Filtered 1 (/100 ml) | E Coli Filtered 2 (/100 ml) | SSF2 E Coli Removal (%) | F Strep Raw (/100 ml) | F Strep Pre-treated (/100 ml) | F Strep Filtered 1 (/100 ml) | F Strep Filtered 2 (/100 ml) | SSF2 F Strep Removal (%) | SPC at 22 °C Raw (/ml) | SPC at 22 °C Pre treated (/ml) | SPC at 22 °C Filtered 1 (/ml) | SPC at 22 °C Filtered 2 (/ml) | SSF2 SPC at 22 °C Removal (%) | SPC at 37 °C Raw (/ml) | SPC at 37 °C Pre treated (/ml) | SPC at 37 °C Filtered 1 (/ml) | SPC at 37 °C Filtered 2 (/ml) | SSF2 SPC at 37 °C Removal (%) | SSF1 Filtration Rate (m/h) | SSF2 Filtration Rate (m/h) | Sedimentation Upflow rate (m/h) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 08/31/93 | 11 | 13.10 | 2.60 | 7.70 | 81.00 | | 7.00 | 7.00 | 91.36 | 33.00 | | 2.00 | 1.00 | 96.97 | 17.00 | | 0.00 | 1.00 | 94.12 | 392.00 | | 268.00 | 276.00 | 29.59 | 17.00 | | 0.00 | 0.00 | 100.00 | 0.10 | 0.10 | 0.20 |
| 09/17/93 | 23 | 9.30 | 3.80 | 7.70 | 294.00 | | 9.00 | 7.00 | 97.62 | 147.00 | | 4.00 | 6.00 | 95.92 | 23.00 | | 0.00 | 0.00 | 100.00 | 294.00 | | 576.00 | 572.00 | -94.56 | 135.00 | | 1.00 | 0.00 | 100.00 | 0.20 | 0.20 | 0.41 |
| 09/22/93 | 33 | 9.90 | 2.80 | 8.30 | 94.00 | | 2.00 | 3.00 | 96.81 | 91.00 | | 2.00 | 0.00 | 100.00 | 25.00 | | 0.00 | 0.00 | 100.00 | 749.00 | | 670.00 | 256.00 | 65.82 | 120.00 | | 0.00 | 0.00 | 100.00 | 0.20 | 0.20 | 0.41 |
| 09/29/93 | 37 | 73.00 | 11.60 | 45.00 | 690.00 | | 300.00 | 320.00 | 53.62 | 420.00 | | 98.00 | 73.00 | 82.62 | 28.00 | | 34.00 | 31.00 | -10.71 | 112.00 | | 366.00 | 346.00 | -203.93 | 952.00 | | 90.00 | 94.00 | 90.13 | 0.20 | 0.20 | 0.41 |
| 10/06/94 | 48 | 46.00 | 22.00 | 44.00 | 202.00 | | 61.00 | 66.00 | 67.33 | 202.00 | | 31.00 | 40.00 | 80.20 | 176.00 | | 53.00 | 42.00 | 76.14 | 57.00 | | 13.00 | 7.00 | 87.72 | 320.00 | | 90.00 | 112.00 | 65.00 | 0.20 | 0.20 | 0.41 |
| 10/29/93 | 69 | 19.90 | 3.50 | 13.90 | 47.00 | | 1.00 | 0.00 | 100.00 | 31.00 | | 0.00 | 0.00 | 100.00 | 3.00 | | 0.00 | 0.00 | 100.00 | 145.00 | | 92.00 | 90.00 | 37.93 | 23.00 | | 5.00 | 6.00 | 73.91 | 0.20 | 0.10 | 0.31 |
| 11/03/93 | 74 | 17.20 | 4.90 | 14.90 | 236.00 | | 2.00 | 4.00 | 98.31 | 140.00 | | 0.00 | 0.00 | 100.00 | 8.00 | | 0.00 | 0.00 | 100.00 | 230.00 | | 125.00 | 315.00 | -36.96 | 130.00 | | 19.00 | 29.00 | 77.69 | 0.20 | 0.10 | 0.31 |
| 11/11/93 | 82 | 22.00 | 2.40 | 14.10 | 137.00 | | 2.00 | 1.00 | 99.27 | 86.00 | | 0.00 | 0.00 | 100.00 | 7.00 | | 0.00 | 0.00 | 100.00 | 392.00 | | 264.00 | 352.00 | 10.20 | 284.00 | | 25.00 | 23.00 | 91.90 | 0.20 | 0.10 | 0.31 |
| 11/20/93 | 91 | 45.00 | 2.00 | 19.10 | 152.00 | | 1.00 | 1.00 | 99.34 | 66.00 | | 0.00 | 1.00 | 98.48 | 4.00 | | 0.00 | 0.00 | 100.00 | 3240.00 | | 128.00 | 76.00 | 97.65 | 122.00 | | 29.00 | 36.00 | 70.49 | 0.20 | 0.10 | 0.31 |
| 12/01/93 | 102 | 22.00 | 2.10 | 17.00 | 56.00 | | 1.00 | 0.00 | 100.00 | 38.00 | | 0.00 | 0.00 | 100.00 | 6.00 | | 0.00 | 0.00 | 100.00 | 896.00 | | 190.00 | 344.00 | 61.61 | 640.00 | | 64.00 | 141.00 | 77.97 | 0.20 | 0.10 | 0.31 |
| 12/15/93 | 114 | 29.00 | 3.00 | 17.90 | 214.00 | | 11.00 | 20.00 | 90.65 | 144.00 | | 3.00 | 4.00 | 97.22 | 25.00 | | 0.00 | 0.00 | 100.00 | 876.00 | | 152.00 | 350.00 | 60.05 | 352.00 | | 100.00 | 232.00 | 34.09 | 0.20 | 0.10 | 0.31 |
| 01/05/94 | 135 | 35.00 | 6.50 | 27.00 | 640.00 | | 1.00 | 3.00 | 99.53 | 335.00 | | 0.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 303.00 | | 78.00 | 115.00 | 62.05 | 376.00 | | 59.00 | 42.00 | 88.83 | 0.20 | 0.10 | 0.31 |
| 01/19/94 | 149 | 27.00 | 5.10 | 21.00 | 414.00 | | 0.00 | 3.00 | 99.28 | 174.00 | | 0.00 | 0.00 | 100.00 | 15.00 | | 0.00 | 0.00 | 100.00 | 1520.00 | | 328.00 | 146.00 | 90.39 | 115.00 | | 13.00 | 13.00 | 88.70 | 0.20 | 0.10 | 0.31 |
| 02/07/94 | 168 | 17.00 | 1.80 | 13.30 | 272.00 | | 0.00 | 0.00 | 100.00 | 238.00 | | 0.00 | 0.00 | 100.00 | 17.00 | | 0.00 | 0.00 | 100.00 | 478.00 | | 17.00 | 5.00 | 98.95 | 688.00 | | 15.00 | 2.00 | 99.71 | 0.10 | 0.10 | 0.20 |
| 02/17/94 | 176 | 13.10 | 2.40 | 7.40 | 88.00 | | 0.00 | 0.00 | 100.00 | 73.00 | | 0.00 | 0.00 | 100.00 | 8.00 | | 0.00 | 0.00 | 100.00 | 117.00 | | 124.00 | 88.00 | 24.79 | 877.00 | | 14.00 | 5.00 | 99.43 | 0.10 | 0.10 | 0.20 |
| 03/03/94 | 190 | 23.00 | 2.40 | 17.10 | 700.00 | | 3.00 | 0.00 | 100.00 | 275.00 | | 0.00 | 0.00 | 100.00 | 39.00 | | 0.00 | 0.00 | 100.00 | 2732.00 | | 47.00 | 80.00 | 97.07 | 585.00 | | 12.00 | 2.00 | 99.66 | 0.20 | 0.10 | 0.31 |
| 03/28/94 | 206 | 28.00 | 10.70 | 25.00 | 156.00 | | 36.00 | 2.00 | 98.72 | 153.00 | | 30.00 | 2.00 | 98.69 | 74.00 | | 0.00 | 0.00 | 100.00 | 96.00 | | 165.00 | 88.00 | 8.33 | 335.00 | | 500.00 | 854.00 | -154.93 | 0.20 | 0.10 | 0.31 |
| 03/29/94 | 207 | 28.00 | 8.90 | 25.00 | 182.00 | | 36.00 | 34.00 | 81.32 | 180.00 | | 16.00 | 21.00 | 88.33 | 24.00 | | 4.00 | 0.00 | 100.00 | 520.00 | | 308.00 | 430.00 | 17.31 | 443.00 | | 556.00 | 723.00 | -63.21 | 0.20 | 0.10 | 0.31 |
| 04/07/94 | 215 | 31.00 | 8.70 | 23.00 | 1480.00 | | 36.00 | 52.00 | 96.49 | 1080.00 | | 30.00 | 19.00 | 96.24 | 13.00 | | 1.00 | 0.00 | 100.00 | 28.00 | | 32.00 | 33.00 | -17.86 | 20.00 | | 27.00 | 44.00 | -120.00 | 0.20 | 0.10 | 0.31 |
| 04/26/94 | 234 | 45.00 | 4.30 | 46.00 | 540.00 | | 8.00 | missing | 100.00 | 189.00 | | 1.00 | missing | 100.00 | 92.00 | | 0.00 | missing | 100.00 | 1283.00 | | 46.00 | missing | 100.00 | 822.00 | | 27.00 | missing | 100.00 | 0.20 | 0.10 | 0.31 |
| 05/04/94 | 242 | 29.00 | 3.10 | 28.00 | 174.00 | | 76.00 | 3.00 | 98.28 | 59.00 | | 68.00 | 1.00 | 98.31 | 21.00 | | 0.00 | 0.00 | 100.00 | 153.00 | | 381.00 | 489.00 | -219.61 | 461.00 | | 2000.00 | 528.00 | -14.53 | 0.20 | 0.10 | 0.31 |
| 05/17/94 | 255 | 41.00 | 2.50 | 31.00 | 199.00 | | 122.00 | 1.00 | 99.50 | 67.00 | | 4.00 | 1.00 | 98.51 | 33.00 | | 0.00 | 0.00 | 100.00 | 212.00 | | 1818.00 | 32.00 | 84.91 | 202.00 | | 1640.00 | 9.00 | 95.54 | 0.20 | 0.10 | 0.31 |
| 05/25/94 | 263 | 16.10 | 1.80 | 14.20 | 104.00 | | 0.00 | 0.00 | 100.00 | 56.00 | | 0.00 | 0.00 | 100.00 | 46.00 | | 0.00 | 0.00 | 100.00 | 106.00 | | 40.00 | 43.00 | 59.43 | 176.00 | | 32.00 | 18.00 | 89.77 | 0.20 | 0.10 | 0.31 |
| 06/22/94 | 291 | 8.30 | 0.70 | 7.90 | 62.00 | | 0.00 | 0.00 | 100.00 | 26.00 | | 0.00 | 0.00 | 100.00 | 12.00 | | 0.00 | 0.00 | 100.00 | 190.00 | | 5.00 | 2.00 | 98.95 | 284.00 | | 16.00 | 10.00 | 96.48 | 0.10 | 0.05 | 0.15 |
| 06/27/94 | 296 | 11.60 | 1.60 | 8.20 | 386.00 | | 2.00 | 4.00 | 98.96 | 360.00 | | 1.00 | 1.00 | 99.72 | 68.00 | | 0.00 | 0.00 | 100.00 | 352.00 | | 8.00 | 34.00 | 90.34 | 1000.00 | | 12.00 | 123.00 | 87.70 | 0.10 | 0.10 | 0.20 |
| 07/14/94 | 312 | 6.50 | 0.76 | 6.30 | 360.00 | | 5.00 | 0.00 | 100.00 | 188.00 | | 4.00 | 0.00 | 100.00 | 42.00 | | 0.00 | 0.00 | 100.00 | 108.00 | | 8.00 | 1.00 | 99.07 | 880.00 | | 13.00 | 5.00 | 99.43 | 0.20 | 0.10 | 0.31 |
| **07/29/94** | 324 | 5.60 | 1.89 | 4.50 | 28.00 | | 0.00 | missing | 100.00 | 0.00 | | 0.00 | missing | ERR | 0.00 | | 0.00 | missing | ERR | 160.00 | | 36.00 | missing | 100.00 | 376.00 | | 104.00 | missing | 100.00 | 0.20 | 0.10 | 0.31 |
| **08/03/94** | 329 | 5.00 | 1.30 | 3.30 | 12.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 174.00 | | 4.00 | 10.00 | 94.25 | 139.00 | | 14.00 | 98.00 | 29.50 | 0.20 | 0.10 | 0.31 |
| **08/11/94** | 337 | 3.00 | 0.93 | 4.00 | 44.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 2000.00 | | 17.00 | 3.00 | 99.85 | 752.00 | | 5.00 | 11.00 | 98.54 | 0.10 | 0.10 | 0.20 |
| **09/02/94** | 359 | 2.20 | 0.77 | 2.40 | missing | | 24.00 | 0.00 | ERR | missing | | 24.00 | 0.00 | ERR | missing | | 17.00 | 0.00 | ERR | missing | | 1284.00 | 9.00 | ERR | missing | | 291.00 | 7.00 | ERR | 0.10 | 0.10 | 0.20 |
| **09/05/94** | 362 | 3.20 | 0.71 | 1.75 | 26.00 | | 2.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 10.00 | 0.00 | ERR | 880.00 | | 616.00 | 35.00 | 96.02 | 29.00 | | 500.00 | 2.00 | 93.10 | 0.10 | 0.10 | 0.20 |
| **09/08/94** | 365 | 4.00 | 0.80 | 1.80 | 0.00 | | 3.00 | 9.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 484.00 | | 412.00 | 568.00 | -17.36 | 70.00 | | 121.00 | 45.00 | 35.71 | 0.10 | 0.10 | 0.20 |
| **09/09/94** | 366 | 4.00 | 0.80 | 1.70 | 2.00 | | 1.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 2.00 | | 1.00 | 0.00 | 100.00 | 856.00 | | 666.00 | 476.00 | 44.39 | 106.00 | | 119.00 | 92.00 | 13.21 | 0.10 | 0.10 | 0.20 |
| **09/14/94** | 371 | 4.00 | 0.45 | 1.60 | 4.00 | | 2.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 2000.00 | | 440.00 | 72.00 | 96.40 | 302.00 | | 388.00 | 10.00 | 96.69 | 0.10 | 0.10 | 0.20 |
| **09/19/94** | 376 | 8.00 | 0.50 | 1.70 | 8.00 | | 0.00 | 0.00 | 100.00 | 4.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 392.00 | | 12.00 | 1.00 | 99.74 | 110.00 | | 62.00 | 0.00 | 100.00 | 0.10 | 0.10 | 0.20 |
| **09/26/94** | 382 | 6.90 | 0.52 | 1.80 | 8.00 | | 0.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 25.00 | | 31.00 | 1.00 | 96.00 | 24.00 | | 42.00 | 2.00 | 91.67 | 0.10 | 0.10 | 0.20 |
| **09/29/94** | 385 | 4.50 | 0.41 | 2.20 | 4.00 | | 3.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 6.00 | | 0.00 | 0.00 | 100.00 | 444.00 | | 31.00 | 8.00 | 98.20 | 39.00 | | 24.00 | 3.00 | 92.31 | 0.10 | 0.10 | 0.20 |
| **10/03/94** | 390 | 4.00 | 0.41 | 1.40 | 6.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 70.00 | | 38.00 | 5.00 | 92.86 | 16.00 | | 44.00 | 4.00 | 75.00 | 0.10 | 0.10 | 0.20 |
| **10/12/94** | 398 | 10.60 | 0.40 | 1.50 | 2.00 | | 0.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 608.00 | | 9.00 | 10.00 | 98.36 | 568.00 | | 17.00 | 1.00 | 99.82 | 0.10 | 0.10 | 0.20 |
| **10/18/94** | 403 | 5.70 | 0.56 | 1.60 | 4.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 74.00 | | 10.00 | 16.00 | 78.38 | 332.00 | | 27.00 | 7.00 | 97.89 | 0.10 | 0.10 | 0.20 |
| **10/25/94** | 408 | 4.10 | 0.35 | 1.64 | 6.00 | | 0.00 | 1.00 | 83.33 | 0.00 | | 0.00 | 0.00 | ERR | missing | | missing | missing | ERR | missing | | missing | missing | ERR | 498.00 | | 15.00 | 5.00 | 99.00 | 0.10 | 0.10 | 0.20 |
| **11/01/94** | 415 | 2.70 | 0.45 | 1.80 | 2.00 | | 0.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 2.00 | | 0.00 | 0.00 | 100.00 | 218.00 | | 23.00 | 14.00 | 93.58 | 400.00 | | 14.00 | 0.00 | 100.00 | 0.10 | 0.10 | 0.20 |
| **11/08/94** | 422 | 3.80 | 0.41 | 1.10 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 19.00 | | 65.00 | 18.00 | 5.26 | 102.00 | | 52.00 | 20.00 | 80.39 | 0.10 | 0.10 | 0.20 |
| **12/14/94** | 459 | 6.00 | 0.31 | 1.91 | 2.00 | | 0.00 | 0.00 | 100.00 | 0.00 | | 0.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 2216.00 | | 34.00 | 29.00 | 98.69 | 2176.00 | | 7.00 | 13.00 | 99.40 | 0.40 | 0.10 | 0.51 |
| **01/06/95** | 482 | 2.50 | 0.28 | 3.00 | 0.00 | | 5.00 | 0.00 | ERR | 0.00 | | 3.00 | 0.00 | ERR | 0.00 | | 0.00 | 0.00 | ERR | 16.00 | | 21.00 | 0.00 | 100.00 | 94.00 | | 5.00 | 0.00 | 100.00 | 0.40 | 0.10 | 0.51 |
| **01/26/95** | 502 | 3.00 | 0.10 | 2.00 | 2.00 | 1.00 | | | 100.00 | 2.00 | 1.00 | | | 100.00 | 0.00 | 0.00 | | | ERR | 872.00 | 904.00 | | | 100.00 | 1300.00 | 968.00 | | | 100.00 | 0.40 | 0.10 | 0.51 |
| **01/31/95** | 507 | 4.80 | 0.23 | 3.60 | 6.00 | 37.00 | | | 100.00 | 2.00 | 24.00 | | | 100.00 | 0.00 | 0.00 | | | ERR | 488.00 | 1000.00 | | | 100.00 | 1208.00 | 380.00 | | | 100.00 | 0.40 | 0.10 | 0.51 |
| **02/06/95** | 513 | 7.00 | 0.21 | 4.00 | 4.00 | 4.00 | 0.00 | 0.00 | 100.00 | 4.00 | 4.00 | 0.00 | 0.00 | 100.00 | 0.00 | 0.00 | 0.00 | 0.00 | ERR | 2048.00 | 2900.00 | 3.00 | 25.00 | 93.78 | 1208.00 | 2240.00 | 8.00 | 1.00 | 99.92 | 0.32 | 0.10 | 0.43 |
| **02/09/95** | 516 | 7.10 | 0.21 | 7.00 | 6.00 | 6.00 | | | 100.00 | 5.00 | 1.00 | | | 100.00 | 1.00 | 0.00 | | | 100.00 | 704.00 | 1392.00 | | | 100.00 | 344.00 | 1792.00 | | | 100.00 | 0.30 | 0.08 | 0.39 |
| **05/16/95** | 615 | 1.52 | 0.16 | 1.30 | 0.00 | 0.00 | 0.00 | 0.00 | ERR | 0.00 | 0.00 | 0.00 | 0.00 | ERR | 0.00 | 0.00 | 0.00 | 0.00 | ERR | 384.00 | 1296.00 | 54.00 | 172.00 | 55.21 | 228.00 | 1032.00 | 9.00 | 39.00 | 82.89 | 0.30 | 0.09 | 0.40 |
| **06/29/95** | 659 | 2.50 | 0.20 | 2.00 | 46.00 | 3.00 | 0.00 | | 100.00 | 2.00 | 2.00 | 0.00 | | 100.00 | 0.00 | 0.00 | 0.00 | | ERR | 1350.00 | 122.00 | 124.00 | | 100.00 | 640.00 | 74.00 | 9.00 | | 100.00 | 0.15 | 0.05 | 0.20 |
| **07/12/95** | 672 | 3.50 | 0.30 | 2.70 | 12.00 | 2.00 | 0.00 | | 100.00 | 4.00 | 1.00 | 0.00 | | 100.00 | 0.00 | 0.00 | 0.00 | | ERR | 292.00 | 42.00 | 244.00 | | 100.00 | 99.00 | 352.00 | 0.00 | | 100.00 | 0.10 | 0.04 | 0.14 |

Blank cells = no samples or missing results
ERR = divide by 0 or calculation of blank cell
Shaded area = Filter clean and about 21 d thereafter
**Dates in bold = Inanda raw water**

APPENDIX C