TURBIDITY REMOVAL AT TWENTY-ONE SOUTH AFRICAN WATER TREATMENT PLANTS

SJ van Staden, A Amod, AD Ceronio and J Haarhoff

Water Research Group, Rand Afrikaans University, PO Box 524, Auckland Park, 2006.

ABSTRACT

The Water Research Group at the Rand Afrikaans University undertook an ambitious sampling and monitoring programme at twenty-one South African water treatment plants during 2000 and 2001. At some of these plants, there were parallel but different treatment trains due to plant extensions being made at different times. A total of 25 full or partial treatment trains could therefore be monitored. A total of 115 plant visits were made over a period of fifteen months, with samples taken throughout the plant, covering the complete treatment train from raw to final water. Amongst other parameters, the turbidity of each sample was determined on site immediately upon sampling. This paper will summarise and interpret the resulting data set of approximately 1300 turbidity values.

The paper will firstly characterise the raw and final waters respectively. In other words, how does typical raw water vary, and how good is the typical final water produced? The second part will summarise the typical performance of each of the treatment processes. In other words, what reduction in turbidity is typically achieved during settling, dissolved air flotation and filtration?

The paper will make a practical contribution in providing a benchmark to all operators of treatment plants by:

- being able to immediately "position" themselves within a typical range of raw water values.
- judging their final water quality against what is generally achieved, and
- evaluating and troubleshooting their individual process units against what is generally achieved.

1 INTRODUCTION

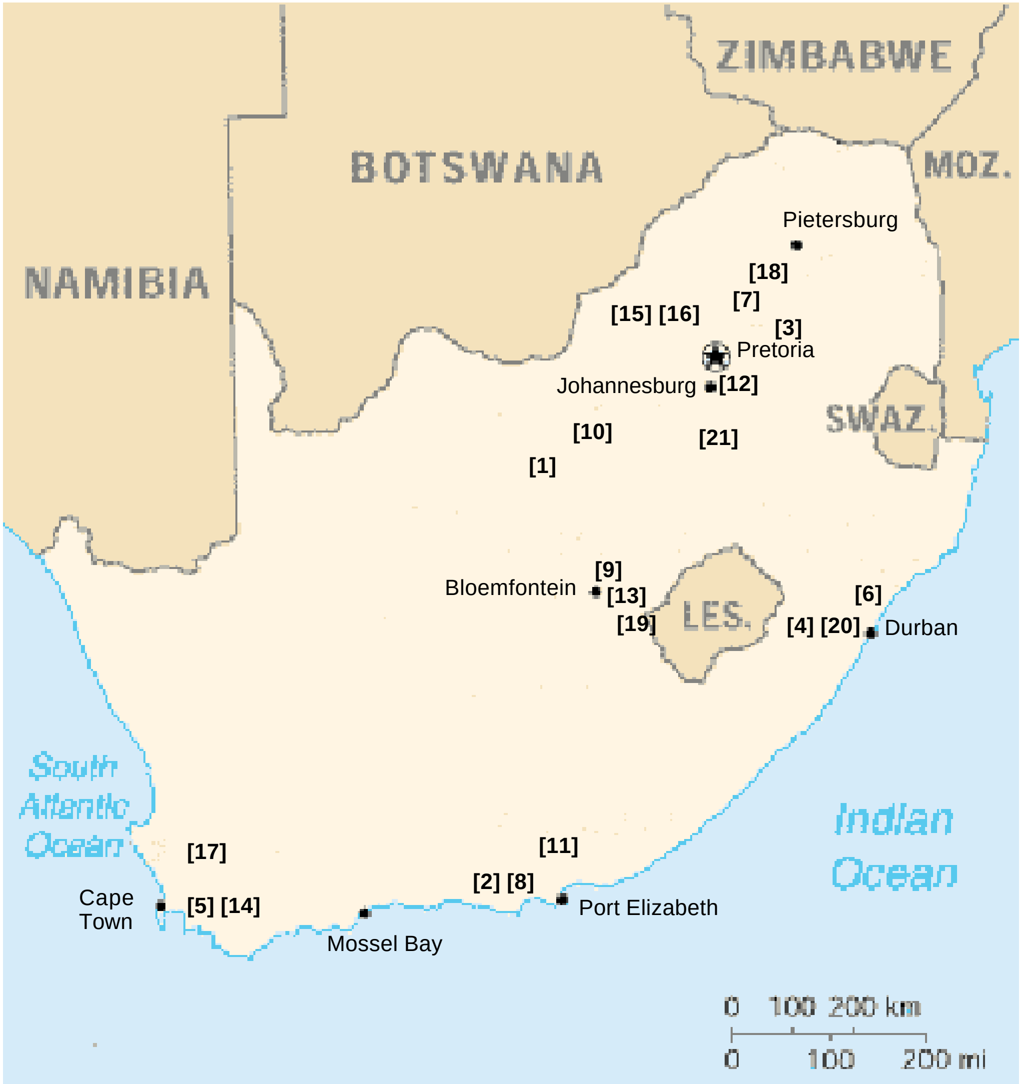
An ambitious sampling and monitoring programme of twenty-one South African water treatment plants was undertaken by the Water Research Group at the Rand Afrikaans University during 2000 and 2001. Some of these plants have parallel but different treatment trains due to plant extensions at different times. Therefore, a total of 25 full or partial treatment trains could be monitored (see Figure 1 below for locations). A total of 115 plant visits were made over a fifteen-month period, with samples taken throughout the plants visited, covering the complete treatment train from raw to final water. The resultant data set consisted of approximately 1300 turbidity values.

Paper presented at the Biennial Conference of the Water Institute of Southern Africa (WISA) 19 – 23 May 2002, Durban, South Africa
www.wisa.co.za ISBN Number: 1-86845-844-X
CD-ROM produced by: Water Research Commission (WRC), www.wrc.org.za Organised by: Conference Planners

The turbidity measurements of each process at each plant visited were taken using a turbidimeter and measured in nephelometric turbidity units or NTU. The measurements were taken directly after sampling where possible and, where not possible, the samples were refrigerated and transported to a laboratory where such measurements could be performed.

2 RAW WATER CHARACTERIZATION

The 202 data points available for raw water turbidity were ordered from high too low. It turned out that the highest 5 data points were all measured at the Welbedacht plant – a plant renowned for extreme turbidity peaks. To allow better visualization of the remaining points, the Welbedacht data was therefore omitted from Figure 2, which shows a frequency distribution plot of the raw water turbidity. Figure 2 simply confirms a generally known fact, namely that South African raw water sources are generally fairly turbid due to sporadic, intense rainfall and steep river gradients.



[1]	Balkfontein	[8]	Loerie	[15]	Vaalkop, Plant 2
[2]	Churchill	[9]	Maselpoort	[16]	Vaalkop, Plant 3
[3]	Cullinan	[10]	Midvaal	[17]	Voëlvlei
[4]	Durban Heights	[11]	Nooitgedagt	[18]	Wallmannsthal
[5]	Faure	[12]	Rietvlei	[19]	Welbedacht
[6]	Hazelmere	[13]	Rustfontein	[20]	Wiggins
[7]	Klipdrift	[14]	Steenbras	[21]	Zuikerbosch

Figure 1: Locations of the twenty-one South African water treatment plants included in the sampling and monitoring programme.

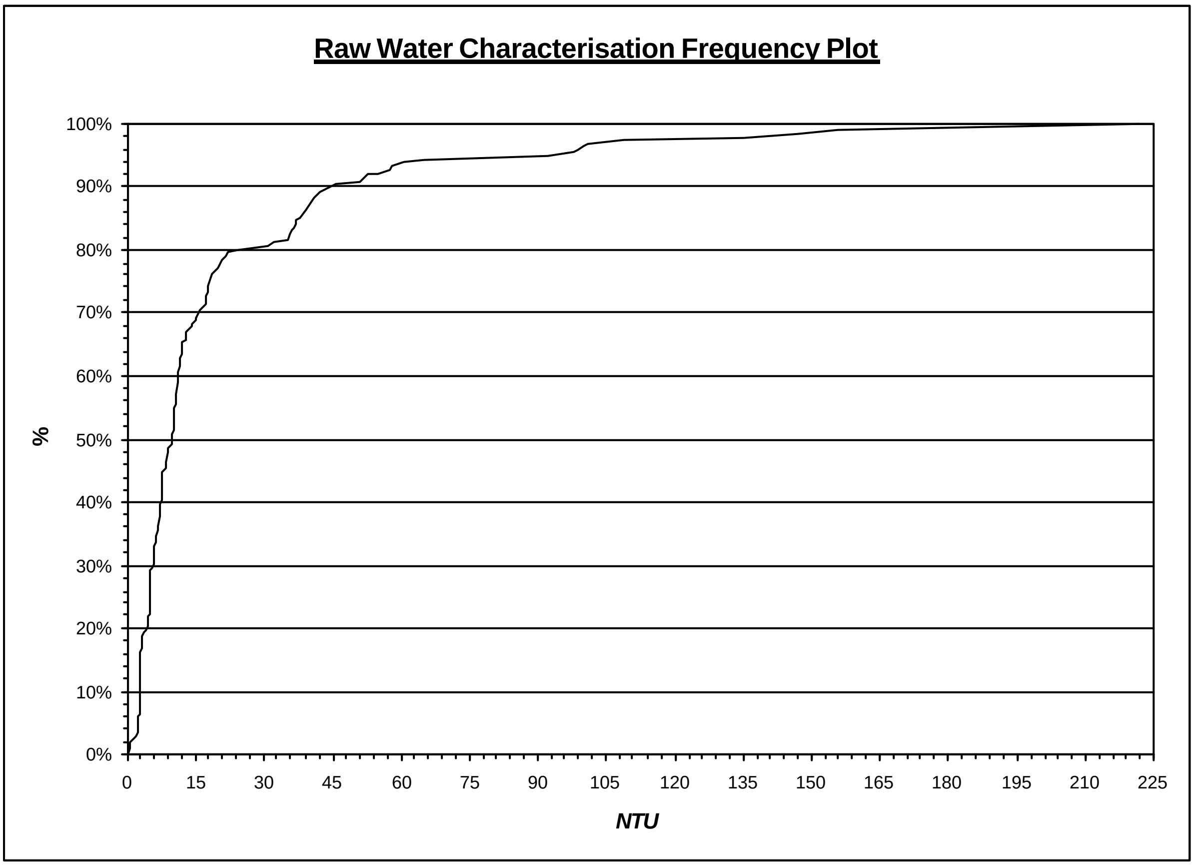


Figure 2: Frequency distribution plot for raw water turbidity at twenty-one South African water treatment plants.

3 FINAL WATER CHARACTERIZATION

The 196 data points available for filtered water turbidity were ordered from high to low. The highest data point was measured at Welbedacht and was suspect, as it was much higher than other final water data points from the same plant during the same visit. This indicated either an experimental error, or an unusual breakdown in operational efficiency, as the values during the other visits were quite normal. This value was therefore stripped from the final water data set. Figure 3 shows a frequency distribution plot of the final water turbidity.

The plant performance indicated by Figure 3 shows a surprisingly wide performance range.

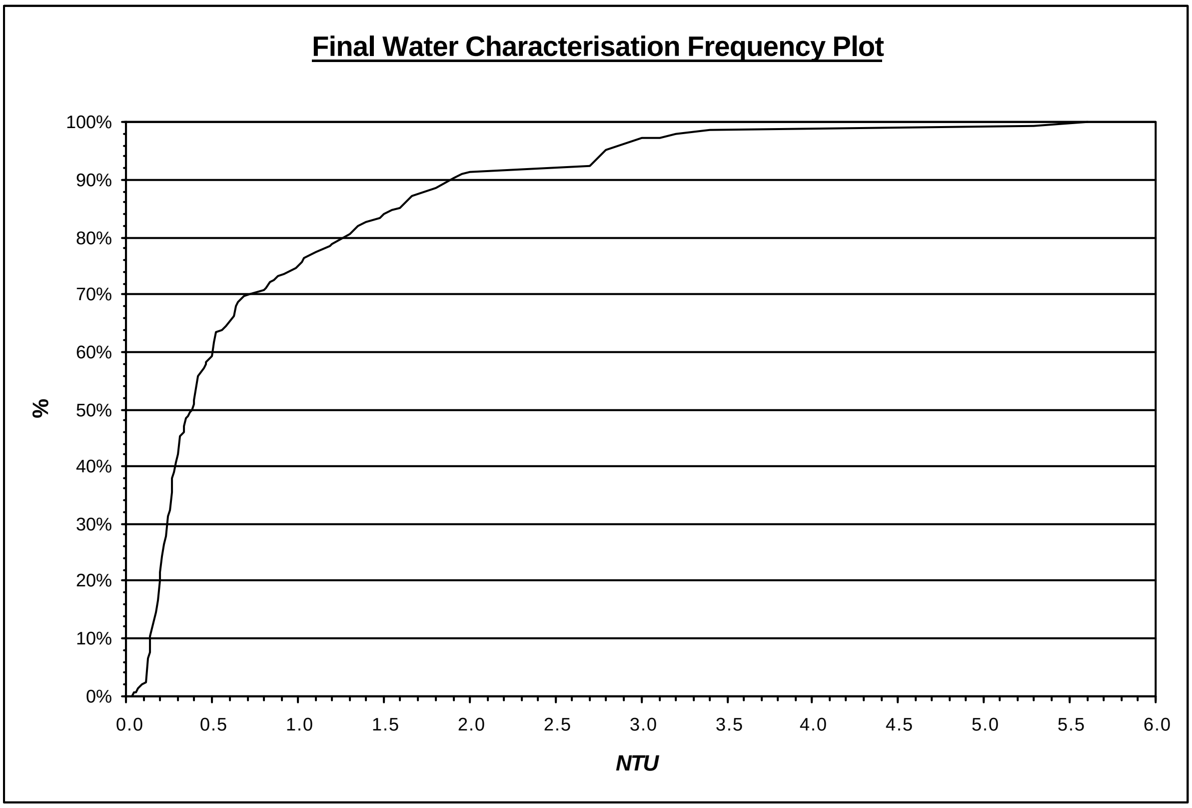


Figure 3: Frequency distribution plot for final water turbidity at twenty-one South African water treatment plants.

4 OVERALL TREATMENT PLANT PERFORMANCE

A paired comparison was next made to determine whether final turbidity is affected in a systematic way by the turbidity of the raw water. The 191 available data pairs were grouped into five raw water categories in such a way that approximately an equal number of data pairs fell into each category. Figure 4 illustrates the average final water turbidity per category and disproves the popular thinking that “it is easier to clean dirty water than clean water”.

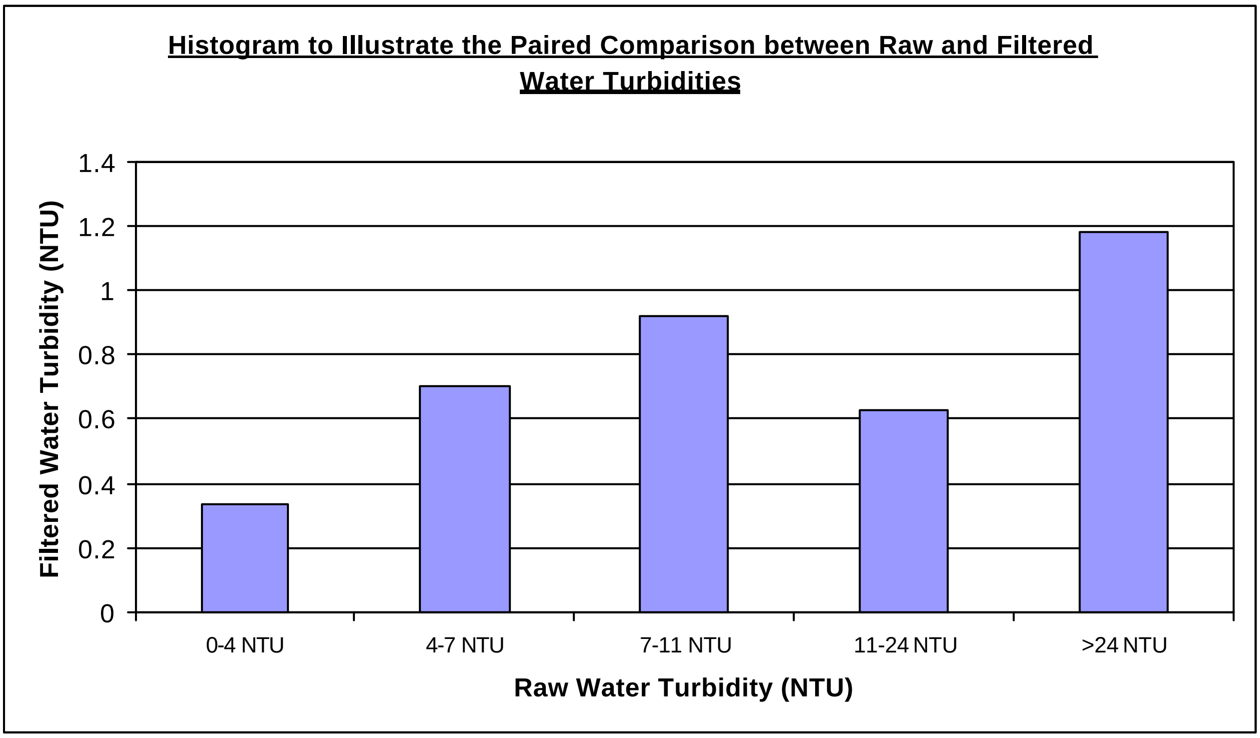


Figure 4: Histogram to illustrate average final water turbidity per raw water turbidity category at twenty-one South African water treatment plants.

5 MATHEMATICAL MODEL FOR TURBIDITY REMOVAL

To systematically quantify the performance (in terms of turbidity removal) of different processes, it was necessary to construct a mathematical model. The following general exponential function was used:

$$NTU_{FR} = \frac{NTU_{out}}{NTU_{in}} = A.e^{-kNTU_{in}} \qquad (1)$$

where:
NTU_{FR} = *fraction turbidity remaining*
NTU_{out} = *turbidity of the water leaving the process*
NTU_{in} = *turbidity of the water entering the process*
A = *boundary condition constant*
k = *process performance parameter*

However, there exists a residual turbidity (X), which the process is unable to remove from the water. Therefore, the k value for the process has to be calculated after X has been accounted for, i.e. subtracted from both NTU_{in} and NTU_{out}. In addition, the constant A can be determined by considering the boundary condition of $NTU_{FR} = 1$ if $NTU_{in} = X$. From this, the constant A is found to be 1. The final equation used was:

$$NTU_{FR} = \frac{NTU_{out} - X}{NTU_{in} - X} = e^{-k(NTU_{in} - X)} \qquad (2)$$

This equation can be altered to solve for the k value as follows:

$$\ln(NTU_{in} - X) - k(NTU_{in} - X) = \ln(NTU_{out} - X)$$

$$\therefore k = \frac{\ln(NTU_{in} - X) - \ln(NTU_{out} - X)}{(NTU_{in} - X)} \qquad (3)$$

Therefore, for every data point a k value can be calculated and, from this set of k values percentile k values (denoted as k_x) can be determined. With k_x values chosen, the estimated NTU_{out} can now be written in terms of NTU_{in} as follows:

$$NTU_{out} = X + (NTU_{in} - X)\left(e^{-k_x(NTU_{in} - X)}\right) \qquad (4)$$

The turbidity removal ability of each process can thus be described by the two parameters k_x and X, or a practical range for each.

5 INDIVIDUAL PROCESS PERFORMANCE

Initial analysis of the data consisted of simple plots of the data for nine identified processes:

- Pre-oxidation
- Coagulation
- Flocculation
- Horizontal settling
- Vertical settling
- Clariflocculation
- Flotation
- Combined flotation and filtration, and
- Filtration

The first three of these nine processes were identified as having no effect on turbidity, since the general slope of each plot was approximately equal to one, i.e. $NTU_{in} = NTU_{out}$.

The next step in calibrating the mathematical model was to determine the X value for each of the remaining six processes. This value was obtained from a turbidity data plot of NTU_{in} versus $NTU_{\%}$ (percentage turbidity removed) for each process, where $NTU_{\%}$ is calculated as follows:

$$NTU_{\%} = \frac{NTU_{in} - NTU_{out}}{NTU_{in}} \qquad (5)$$

The X value was read off the x–axis (NTU_{in}) of each graph as that point where $NTU_{\%}$ is approximately zero. As an example of this step, Figure 5 shows how X = 0 was determined for the filtration process.

Once the X value for each process was determined, it was substituted into equation 1 to solve for the k value for each data point. These k values were then used to determine the k_x values for each process.

The X value and five selected k_x values for each process were then used to generate five separate equations for each process, enabling one to predict NTU_{FR} and NTU_{out} for each process, based on expected process performance, i.e.:

- k_{10} value substituted for very poor performance
- k_{25} value substituted for below average performance
- k_{50} value substituted for average performance
- k_{75} value substituted for above average performance
- k_{90} value substituted for very good performance

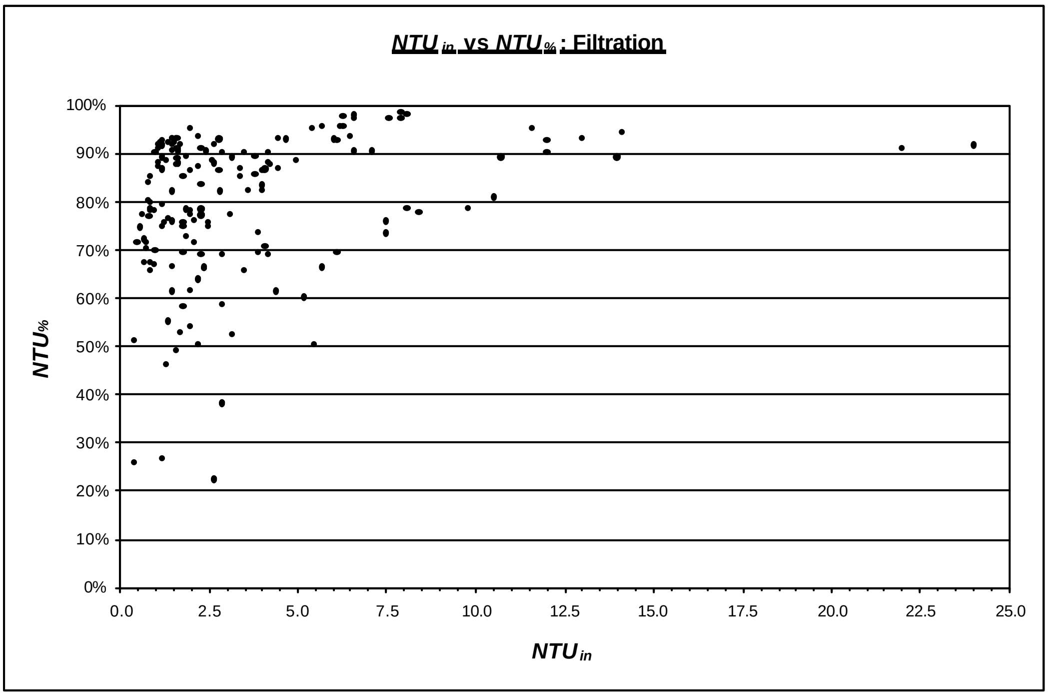


Figure 5: Plot of NTU_{in} against $NTU_{\%}$ for the filtration process, indicating a residual turbidity value = 0.

The equations obtained for the various processes are represented in Table 1 below.

Table 1: Values used to predict NTU_{FR} and NTU_{out} for six treatment processes.

Process	X	k_{10}	k_{25}	k_{50}	k_{75}	k_{90}
Horizontal Settling	1.00	0.044	0.066	0.161	0.253	0.367
Vertical Settling	1.00	0.031	0.076	0.288	0.381	0.954
Clariflocculation	1.00	0.023	0.030	0.073	0.147	0.299
Flotation	1.00	0.224	0.269	0.388	0.896	1.556
Combined Flotation and Filtration	0.00	0.274	0.462	0.538	0.708	1.115
Filtration	0.00	0.191	0.429	0.602	1.303	1.817

The constants in Table 1 allow the construction of hypothetical turbidity removal curves. These curves, together with the original data points, are illustrated in Figure 6 for the filtration process.

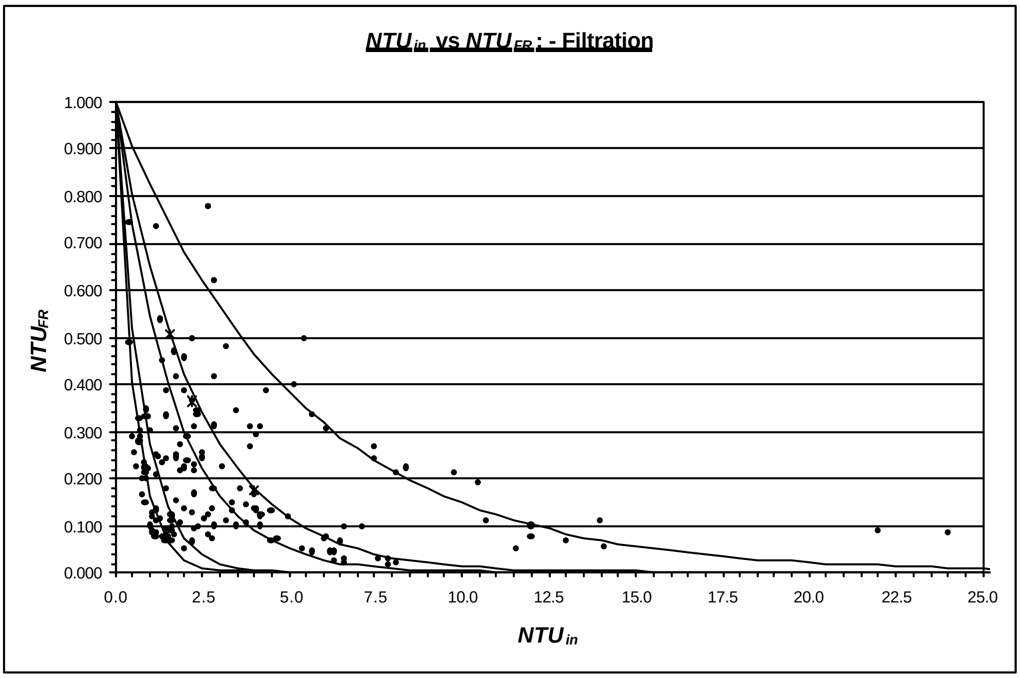


Figure 6: Plot of NTU_{in} against NTU_{FR} for the filtration process, indicating the five hypothetical removal curves.

5 CONCLUSIONS

This study provides valuable data relating to South African water treatment plants. This study could have included evaluations of more water treatment plants in South Africa, and could also have extended over a longer period and more plant visits. Within the practical limits of time and budget, however, the authors feel confident that the models generated by this undertaking portrays the current situation with reasonable accuracy.

The main conclusions drawn from this analysis are:

- The raw water turbidity spectrum is very broad, posing special challenges to operational personnel to treat water consistently and effectively.
- Perhaps as a result, the turbidity spectrum of the filtered water regularly exceeds commonly accepted limits for potable water.
- There is a much higher than expected variation in individual process performance, when data from different days at the same plant are compared. This emphasizes that more emphasis should be placed on operational quality control systems, rather than the conventional emphasis which is almost exclusively placed on design issues.

Similar studies could (and should) be performed for other water quality parameters, such as dissolved organic carbon (*DOC*), chlorophyll *a* and dissolved solids, allowing the prediction of a full spectrum of water quality parameters from a specified raw water sample.

6 ACKNOWLEDGEMENTS

Many thanks must go to the combined efforts of the Water Research Group at the Rand Afrikaans University, as well as those people who gave permission for the various samples to be taken that made this undertaking what it is. There were also various other people behind the scenes that offered their time and support, and whose contribution to this project was invaluable.