ALGAL RUPTURE DURING ABSTRACTION FROM RESERVOIRS AND THE CONSEQUENCES FOR WATER TREATMENT

FINAL REPORT

to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

An investigation has been carried out to establish the occurrence and implications of algal cells being ruptured in the aqueduct between an impoundment and the receiving waterworks. This work was initiated in response to the observation that algal blooms in the main basin and in the abstraction tower at Nagle Dam appeared to severely effect water treatment costs despite the fact that very few of the cells were present in the raw water entering Durban Heights Waterworks (WW).

This raised the question of whether the same situation would arise in the potentially more eutrophic Inanda Dam system where algal numbers are likely to be several times greater than are found in Nagle Dam. Because the Inanda Dam system had not yet been completed when this work was undertaken, the entire aqueduct system had to be simulated to examine possible algal rupture. The techniques developed here have application in any system of water transfer from an impoundment by aqueduct.

This investigation was designed to firmly establish whether algal rupture is indeed occurring in the Nagle to Durban Heights WW system, estimate rupture in the Inanda Dam to Wiggins WW system, and then to look at the implications of this rupture on water treatment as algal cell contents are released into the water. It was also designed to establish the governing principles causing algal rupture in aqueducts.

Historical Evidence for the Occurrence of Algal Rupture Between Nagle Dam and Durban Heights Waterworks

High numbers of *Microcystis* in Nagle Dam did not reflect in algal counts of untreated waters entering Durban Heights WW. Chemical and physical determinands did not give any indication of a deterioration of water quality.

Historical algal and flow data was used in a statistical examination of the effects of the aqueducts between Nagle Dam and Durban Heights WW on algal numbers. Indications from these results are that many algal genera are being lost in their passage from the dam to the WW. This loss in algae appears to be most significant for vacuolate blue-green algae viz. *Microcystis* and *Anabaena.*

The Effect of Algal Rupture on Water Quality

A detailed examination of historical water quality surrounding a significant algal bloom in Nagle Dam in February 1990 was undertaken. This bloom severely impacted on water treatment at Durban Heights WW. Of all the routine water quality determinands examined none, besides the comparisons of algal numbers (and to a lesser degree chlorophyll "a") between the dam and WW, gave a clear indication of a change in water quality due to the presence of the algal bloom or due to the rupture of algal cells in the aqueduct. pH was shown to be slightly elevated at the WW compared to the dam although it is possible that this variable may be co-varying with some other water quality variable. It was also obviously not possible to monitor pH as an indicator of algal blooms as this determinand was variable in its own right and dependent on varying local limnological conditions.

Measuring Algal Rupture in the Nagle Dam - Durban Heights Waterworks System

Due to relatively low algal counts in Nagle Dam, during the project, direct estimation of *in situ* algal loss in the dam to WW aqueduct was not possible. To deal with this problem, and to examine *in situ* algal loss, a novel technique of adding concentrated *Microcystis* algal scums with a lithium marker to the head of the aqueduct was used to accurately show that between 61% and 72% of the *Microcystis* cells were lost during their passage through the aqueduct.

Algal Rupture During Abstraction through the Inanda Dam Abstraction Tower

An algae and lithium tracer technique was employed to examine the extent of algal rupture through the Inanda Dam abstraction tower. Results indicate that there appears to be minimal algal loss after passage through this section of the Inanda to Wiggins WW system.

Aqueduct Simulations and Algal Loss

Algae were subjected to simulated aqueduct pressure and water velocity conditions in an experimental, laboratory scale, chamber. Percentage algal loss for the Nagle system in this chamber (69%) was comparable with *in situ* algal loss (61% to 72%). The simulation chamber therefore provided a reasonable model of *in situ* algal rupture conditions. The simulated Inanda Dam to Wiggins WW system produced negligible algal loss after treatment.

Modelling of Algal Rupture Due to Pressure, Water Velocity and Time

Using data collected after subjecting *Microcystis* algae to a wide range of simulated aqueduct conditions a mathematical response surface model was developed to describe the conditions producing the maximum degree of algal rupture over the range of pressures, water velocities (and hence shear) and times that algae would be exposed to in the respective Nagle and Inanda Dam to WW systems. Pressure was shown to be the most significant factor accounting for algal rupture. The combined values of pressure and velocity that lead to maximum rupture are in the region of 1320 kPa and $\approx 1.6\ ms^{-1}$, respectively. The duration for which these rupture forces are applied was shown to produce very little effect indicating that rupture probably takes place during the initial period of their application.

Visual Appearance of Algal Cells Treated to Simulated Aqueduct Conditions

Light and electron microscopy showed simulated aqueduct treated algal cells with a deflated appearance although no sub-cellular fragments were ever positively identified as coming from ruptured algal cells. This lack of positive identification of fragments may have been a limitation in preparation techniques however. The deflated appearance of pressure treated cells confirmed the work of other authors in showing the effects of pressure on gas vacuolate algal cells.

Consequences of Algal Rupture for Water Treatment

Associated with historical algal blooms in Nagle Dam there was a corresponding increase in treatment costs at Durban Heights WW. This was out of proportion to the number of algae entering the WW and could only be anticipated by monitoring algal numbers in the Dam.

Investigations into the treatment consequences of algal rupture have shown that coagulant demand increased by up to 700% if cells were ruptured. This effect was more significant at higher cell numbers (around 1 million cells/mℓ). At a more reasonable cell number (100 000 cells/mℓ) the increase in coagulant demand was up to 240%. The same trend, with differing efficiencies, was observed with the four coagulation chemicals investigated in this research.

The pre-chlorination demand of untreated samples increased with cell concentration irrespective of whether the algae were ruptured or unruptured. This was expected as chlorine breaks up intact cells. Where samples were first treated with coagulant sufficient to obtain a turbidity of <0,5 NTU, and then filtered, there was a significant increase in the chlorine demand of ruptured over unruptured samples particularly when algal numbers were 1 million cells/mℓ.

The release of geosmin into the water was found to be several fold greater if cells were ruptured. It was not possible during the time of this investigation to more clearly assess the impact of taste and odours on water treatment as these were present in extremely low concentrations in the *Microcystis* scums that were collected from Inanda Dam. It appears that the production of these compounds is erratic and unrelated to cell number.

Dissolved organic carbon concentrations and turbidities also increased as a result of cell rupture but this was only clearly noticeable at very high cell concentrations.

Treatment Cost Implications

Coagulant costs were shown to increase significantly with the percentage of ruptured algae in the water. Therefore in the case of there being 100 000 cells/mℓ, subjected to 67% rupture (as in the Nagle-Durban Heights system), the increase in coagulant cost would be between 35% and 85%. Of those tested a polyamine-polyaluminium chloride (PA-PACℓ) blend was found to be the least influenced by algal rupture although it was the most expensive. $FeC\ell_3$ was the most cost efficient at lower cell concentrations but was slightly less efficient than alum at higher cell concentrations. The cost merits of $FeC\ell_3$ and alum were balanced by higher sludge production when compared to PA-PACℓ.

The impact on treatment cost of the release of taste and odours causing chemicals, such as geosmin, is likely to be far more significant than that attributable to coagulant demand.

In early 1994 a severe bloom of *Anabaena* in Nagle Dam, with geosmin concentrations of up to 1970 ng/ℓ, necessitated dosing powdered activated carbon (PAC) at up to 15 mg/ℓ to remove the taste and odours produced by up to 30 000 cells/mℓ of *Anabaena*. These figures were the extremes experienced for this period but on an average dosage of 10mg/ℓ PAC, over the two month incident, costs for PAC alone were in the region of R950 000. If one included laboratory tests and personnel costs for this incident then the real costs would probably be in the region of R1 million. It is likely that the problem is being exacerbated by the rupture of a high percentage of the *Anabaena* cells. It is predicted that treatment costs would be much lower if cell rupture

did not occur. This was obviously a particularly "productive" taste and odour scum as algae collected during other phases of this investigation contained little geosmin although algal numbers were orders of magnitude higher.

Summary of Research Work and Design Considerations

There is a large body of evidence in this study which suggests that algal rupture is taking place in the aqueducts between Nagle Dam and Durban Heights WW. This has significant implications for the treatment of water abstracted from this dam particularly when the algal compliment of this water is dominated by blue-green algae such as *Microcystis* and or *Anabaena*.

Simulation work suggests that for the Inanda to Wiggins WW system there will be little to no loss of algae in water abstracted from this dam. This is because, in terms of potential rupture forces (pressure and water velocity), this abstraction and aqueduct system is relatively mild.

The implications of this work on the Nagle Dam system suggest that future water abstraction and aqueduct systems should attempt, as far as possible, to minimise the pressure and water velocity conditions in aqueducts, keeping these well below 1320 kPa and 1.6ms^{-1} respectively. Alternatively, algae should be removed from the water prior to passing through an energetic (high rupture potential) system. These recommendations are made so that excessive water treatment costs are not incurred through the necessity of using advanced treatment processes to deal with ruptured algae and associated taste and odours and other cell contents.

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TERMS OF REFERENCE

The following is the final report on research conducted at Umgeni Water for the Water Research Commission on the problems of algal rupture in water abstracted from impoundments. This research expanded rapidly from the original investigation begun by Umgeni Water in 1991 and which was granted WRC funding in 1992 and 1993.

Research Objectives

The research objectives of this project were principally to establish whether algal cells were rupturing in the Nagle Dam to Durban Heights Waterworks system and if so to then establish the probable scenario for the (then unfinished) Inanda Dam to Wiggins Waterworks system. The impact and implications of this algal rupture on water treatment processes were also examined.

The specific objectives of the project were as follows:

- to investigate the historical evidence indicating algal rupture was occuring in the Nagle Dam to Durban Heights Waterworks system;
- to establish the effect of this algal rupture on water quality;
- to accurately measure the degree of algal rupture in the Nagle Dam to Durban Heights Waterworks system;
- to develop a laboratory simulation of algal rupture in the Nagle Dam to Durban Heights Waterworks system;
- to simulate and then predict the degree of algal rupture in the then unfinished Inanda Dam to Wiggins Waterworks system;
- to establish the causes of algal rupture in aqueducts; and finally
- to examine the consequences of algal rupture for water treatment processes and the cost implications of this phenomenon.

CHAPTER 1

INTRODUCTION

Historical data collected by Umgeni Water has indicated that a large proportion of the algae contained in water abstracted from Nagle Dam disappears during transport from the dam to the treatment plant at Durban Heights. It is likely that the bulk of these cells, predominantly the vacuolate genus *Microcystis*, rupture in the water due to changes in water pressure and turbulent shear forces experienced in the aqueduct. This situation is likely to contribute to problems in the treatment of the water as the bulk of the cell contents will be dissolved in the water and will require added and expensive treatment to effect their removal.

It is well known that the presence of blue-green algae in raw water supplies creates problems for water treatment. It is also known that the chlorination of raw water entering a WW is an undesirable practise if algal numbers are high (Ando *et al.* 1992). This is due mainly to the liberation of taste and odour forming chemicals from lysing cells (Ashitani *et al.*, 1988; Utkilen & Froshaug, 1992) and the formation of trihalomethanes (van Steenderen *et al.*, 1988) from the released organic compounds. What has not been clearly established is whether cell lysis occurs by physical processes during the abstraction of raw water. If this is the case, then taste and odour and other organic compounds would be released prior to treatment which would rule out the management option of pre-treatment algal removal. This would have important implications for the design of abstraction and treatment systems as the potential exists to remove algae prior to their entering the aqueduct.

A recent, comprehensive review of the literature by the authors, as well as the CSIR, failed to return any mention of algal rupture or loss due to either pressure or shear (associated with water velocity in aqueducts). This indicates the paucity of information available on the subject of algal rupture and loss from an impoundment to WW.

There was however allegorical mention of this phenomenon by Oksiyuk (1971) who recorded reductions in algae in water supply canals in the former Soviet Union due to "unfavourable conditions." These he lists as high turbidity, lack of biogenic substances, *high current velocities* (our emphasis) and low water temperatures. Typically the algae decrease in abundance in their passage down canals where current velocities exceed 0.9 m/sec. In addition, in all canals he examined, the abundance of phytoplankton was adversely affected by pumping stations and the high-pressure pipelines attached to them. He attributes this phenomenon to a number of factors, namely the mechanical effect of increased mixing pressure and better aeration of the water.

Oksiyuk (*op. cit.*) identifies blue-green bloom-forming algal species in particular as only poorly tolerating these conditions. *Aphanizomenon flos-aquae* and *Anabaena flos-aquae* are typical in this regard. *Microcystis* forms appear to tolerate conditions much better however, although they too are sensitive to current velocities greater than 0.5 m/sec. *M. aeruginosa* was shown "to diminish sharply in canals with pumping stations where the current velocity in the open expanses is 0.15 to 0.65 m/sec." He attributes the unfavourable factors here as

being the pumping stations themselves, and the presence of high-pressure conduits and inverted siphons where the current velocities are 1.0 to 1.5 m/sec. He notes that despite these conditions *M. aeruginosa* often reaches the terminal sections of even very long canals (over 100 km) sometimes in fairly large quantities.

Other than this there were no references found specific to algal loss during abstraction from impoundments to WW. Several authors do report however on the ability of gas vacuoles of blue-green algae to be *collapsed* by the application of hydrostatic pressure (e.g. Walsby 1969, 1971, 1972; Jost & Jones 1970). Walsby (1971) in particular has found that there is little change in the appearance of gas vacuoles up to pressures of 150 kPa. Above this pressure the vacuoles show a progressive decrease in size and brightness when examined under a light microscope with no vacuoles being detectable in cells exposed to pressures above 400 kPa. It is important to note that this does not appear to effect the integrity of the cell as a whole and therefore cannot be equated with cell rupture.

Hemmingsen and Hemmingsen (1980) have found that in gas vacuolate bacteria that were saturated with inert gasses under pressure and then rapidly decompressed the gas vesicles expanded and ruptured the cells. The minimum gas saturation pressures required to achieve this were of the order of 2 500 to 5 000 kPa although the majority of the cell envelopes were ruptured at pressures between 5 000 and 10 000 kPa. Interestingly these authors found that in bacteria which do not normally possess gas vesicles there was no destruction of cells following decompression from gas saturation pressures of up to 30 000 kPa.

Although little can be done to change the *status quo* at Nagle Dam and Durban Heights these results were important for developments at Inanda Dam and Wiggins WW. An algal removal plant is being planned for the treatment of water coming from Inanda as this is likely to be eutrophic and algal rich. The siting of this plant and its functional design could depend on the degree of algal rupture that would occur in this aqueduct. This would also be of interest and relevance to other water operations.

This report set out to establish that algal rupture takes place during the abstraction of water from an impoundment and the subsequent transport through the aqueduct. Historical data from Durban Heights WW was available to give an indication of what the consequences of algal rupture on water treatment costs were. In order to define the link between algal rupture and treatment costs treatability tests were performed in the laboratory using dam water spiked with known amounts of either ruptured or unruptured *Microcystis* algae to simulate possible rupture scenarios.

This investigation was broken into several parts. Briefly these were as follows.

- An investigation of the historical data surrounding this algal loss phenomena from both an algal number and water quality point of view (Chapters 4 & 5).

- An accurate measurement of algal loss in the current Nagle Dam : Durban Heights WW system and then a brief look at the Inanda Dam abstraction tower and potential algal loss there (Chapters 6 & 7).

- Aqueduct conditions in the respective systems (Nagle Dam to Durban Heights WW and Inanda Dam to Wiggins WW) were simulated in the laboratory (Chapter 8).

- A mathematical model was developed to find the pressure and current velocity conditions producing the maximum degree of algal rupture over the range of conditions experienced in the respective systems (Chapter 9).

- The visual effect of simulated aqueduct conditions on algal cells was investigated (Chapter 10).

- Consideration was also given to the treatment (and relative costs associated with the treatment) of water containing ruptured algae from both an *in situ* and projected algal rupture point of view (Chapter 11).

The experimental procedures followed in this study are detailed separately from the results and conclusions with the principal conclusions summarised in a final discussion (Chapter 12).

For brevity the term "shear" (as the force acting on algae) was used as a measure of current velocity in aqueducts (see section 3.4.1 which details the conversion of current velocity in an aqueduct to a radial velocity (or stirrer speed) in a chamber for aqueduct simulation work).

CHAPTER 2

LOCATION

The general location of the study area is indicated on Figure 1. Both Nagle (29°35′31″E, 30°37′41″S) and Inanda (29°42′29″E, 30°52′04″S) Dams lie on the Umgeni River system approximately 45 km and 30 km respectively inland of the coastal city of Durban, KwaZulu-Natal, South Africa. Rainfall, and thus highest river flow, is greatest in mid summer (December). Nagle Dam is a moderately small reservoir (24.6 Mm^3) receiving water from a much larger reservoir (Albert Falls Dam) some 25 km upstream. Inanda Dam, on the other hand, is a much larger reservoir, (251.7 Mm^3) which receives some water from the outflow of Nagle Dam upstream and the Umsunduzi River, which has it's confluence with the Umgeni River between Nagle and Inanda Dams.

Nagle Dam has two abstraction points, one at the dam wall and the other half way along the reservoir. The abstraction towers both pass into two aqueducts, 1 & 2 and 3 & 4 respectively, which connect the Dam to the city's principal Waterworks, Durban Heights. These pass through steeply undulating countryside as a system of siphons and tunnels (Figure 2). The physical data of aqueducts 3 & 4, that were used in this study, are shown in Table 1 (page 16). Water in the two aqueducts (3 & 4) mix together when passing through tunnels but remain separate when passing in siphons beneath rivers. At full bore water takes just over 5 hours to travel the ≈36km from the Dam to the WW, whilst at lower flows the time increases to over 8 hours.

Inanda Dam on the other hand has a multi-level offtake at the main wall which passes into a series of tunnels and siphons which connect to Durban's new WW, Wiggins (Figure 3). Again, the physical aqueduct and siphon data used to simulate this system are shown in Table 2 (page 16). There is no separation of siphons or tunnels in this system and water is estimated to take approximately 10 hours to travel the ≈20km between Dam and WW.

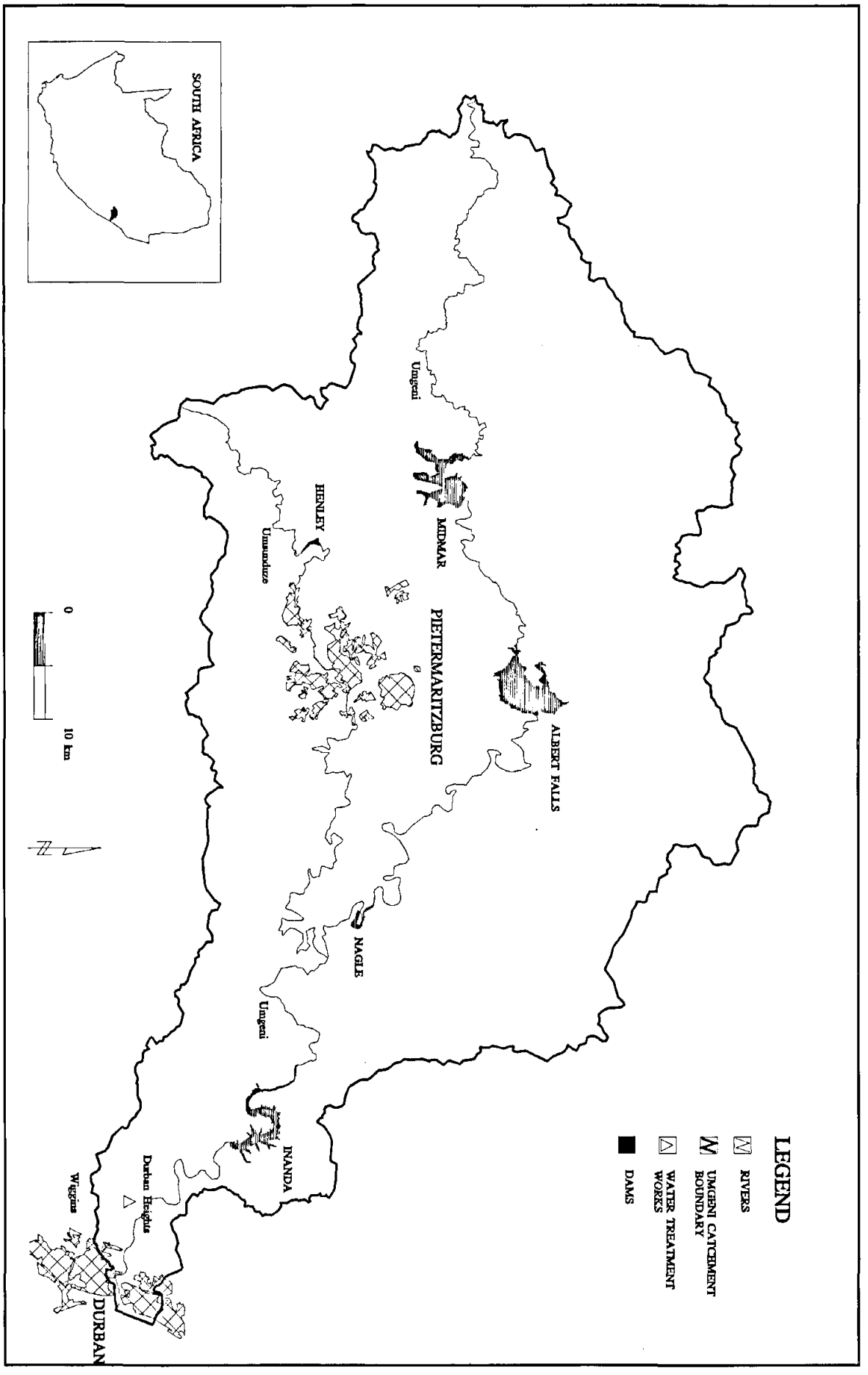

Figure 1: **Location of Nagle and Inanda Dams and Durban Heights and Wiggins Waterworks in KwaZulu-Natal.**

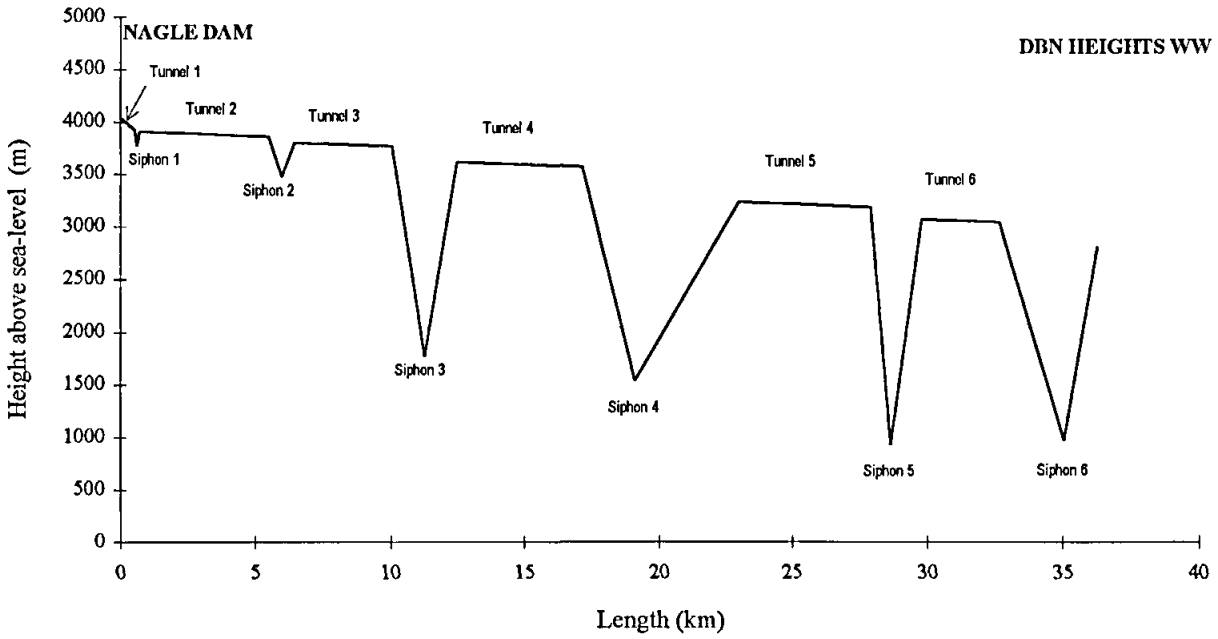

Figure 2: **Schematic longitudinal section of aqueducts 3 & 4 linking Nagle Dam to Durban Heights WW. (Siphon and tunnel numbers as shown in Table 1).**
Note: The drawing is vertically exaggerated so that the vertical scale is 10X the horizontal scale.

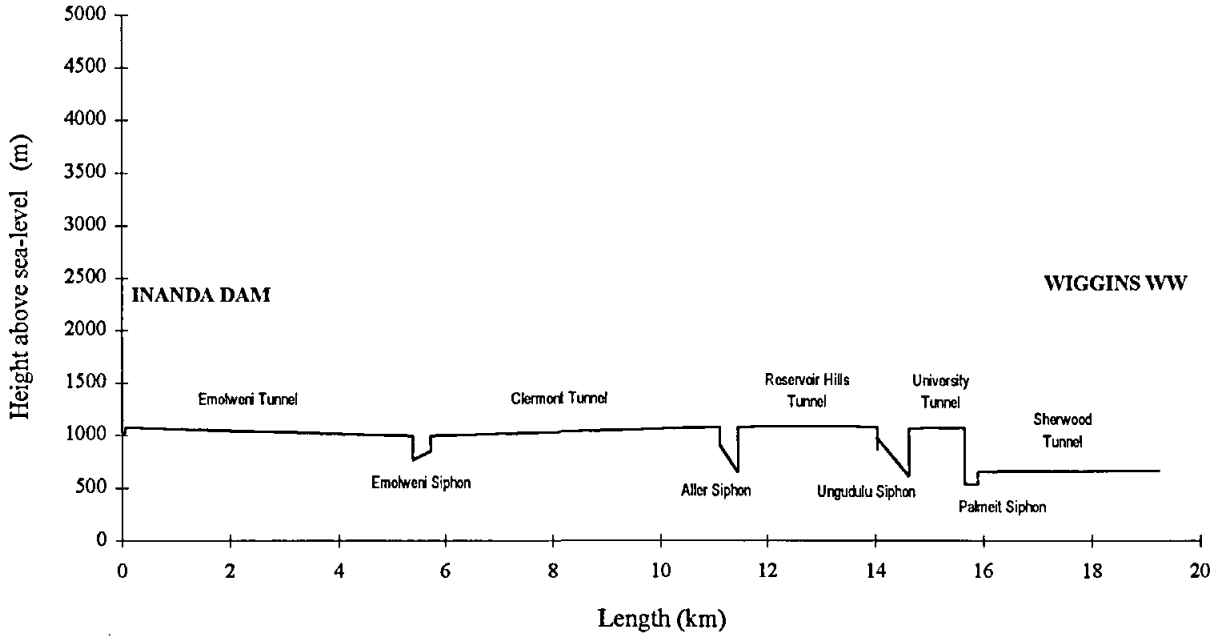

Figure 3: **Schematic longitudinal section of tunnels and siphons linking Inanda Dam to Wiggins WW. (Siphon and tunnel names as shown in Table 2).**
Note: The drawing is vertically exaggerated so that the vertical scale is 10X the horizontal scale.

CHAPTER 3

TECHNIQUES

3.1 Historical evidence of algal rupture

As indicated in Chapter 2 "Location", there are two abstraction points at Nagle Dam, the "old" (Umgeni Water sample point 17) and "new" (UW sample point 18) abstractions. Abstracted water from these two points remain separate in aqueducts *en route* to Durban Heights and only mix in a single channel entering the water works (UW sample point 316). These points are generally sampled on the same day on a weekly basis and analysed for, amongst other things, algae. A record is also made of the concurrent flow at the respective abstraction points.

Paired couplets of data were derived for the analyses by extracting the historical weekly algal sample data for the respective sample points (dam and WW). The date of the flow data was also checked against the collection of the algae samples.

Data couplets were dropped from the analyses if there were instances where couplets of paired data were incomplete due to either missing algae samples, samples collected on different days from sample points or flow data being unavailable or measured on a different day to sample collection. This was to ensure that paired couplets were as far as possible representative of conditions in the dam and flow conditions in the aqueducts.

Notwithstanding these limitations there was still a statistically large data set over the four and a half year date range considered (161 couplets of paired data showing algal differences).

Due to the generally unequal flow regimes at the two abstraction points, the abundance of the historically enumerated dam algal genera had to be adjusted to establish the weighted average of the combination of these two points. This flow weighted average was then used to compare the two relative sample points (Nagle Dam and Durban Heights WW) with each other as paired couplets.

The frequency distributions of each sample point, and the differences between the dam and WW sample points, were checked and shown to be generally log-normal distributed (tested using the Kolmogorov-Smirnov test). This was most marked for the algal data from "individual" sample points while the data for "differences" between the dam and WW were generally more normally distributed. This essentially cautioned against the use of parametric tests of significance. However because the sample size was high (i.e. >100 paired couplets) Student's method of paired differences was the first method used to analyse the data. This technique was employed because, as is generally acknowledged in many statistical texts, under the *central limit theorem* when the sample size becomes large (i.e. >100 sample observations) the shape of the sampling distribution approaches normal even if the distribution of the variable in question is not normally distributed in the

population or is not measured very well. Parametric methods are also acknowledged to be more sensitive (i.e. have more statistical power). A nonparametric alternative to this test, the Wilcoxon matched pairs test, was also investigated and found to produce similar results. Tests and analyses were performed using the statistical software package Statistica (1993).

3.1.1 Student's method of paired differences and Wilcoxon matched pairs test

The dam weighted average provided the theoretical composition and abundance of algae that was expected at Durban Heights under the assumption that there had been no loss in algae due to conditions *en route* to the WW. This established the null hypothesis in this investigation i.e.

> Ho: there was ***no*** difference in algal abundance between the paired data from the weighted average of the dam (old and new) abstraction points and samples collected at Durban Heights WW.

The alternative hypothesis is of course that conditions in the aqueduct system are causing a loss in algae. Statistical tests of significance were then used to disprove the null hypothesis.

The rationale is that observed differences between members of any pair will represent the effects of the aqueduct which will be subject to less error than if there were no pairing. With paired samples the only source of experimental error is variability within pairs. The procedure of analysis is therefore to establish differences for the readings for each pair, whereupon we have a sample of differences of which the true mean of these differences must, on the null hypothesis, be zero.

Assumptions made in these analyses are:

- the body of water sampled at the two abstraction points is the same as that being sampled at Durban Heights on the same day (subsequent work has shown that a body of water in fact takes approximately 5 to 6 hours to travel the distance from the dam to the water works);
- there is thorough mixing of water from the two abstraction points on entry to Durban Heights WW;
- all types of algae would be correctly identified despite damage incurred in the aqueduct.

3.2 Measuring algal rupture in the Nagle Dam to Durban Heights Waterworks system

The rationale behind this technique was in comparing the recovery of a tracer (lithium in this case) with the recovery of algae dosed into an aqueduct at Nagle Dam after their passage down to Durban Heights WW. This was accomplished by dosing a known mass of lithium (L_{in}) and number of algae (A_{in}) into an aqueduct at Nagle Dam, sampling for these two at Durban Heights (L_{out} and A_{out} respectively), and then comparing the two ratios ($R_L = L_{out}/L_{in}$ and $R_A = A_{out}/A_{in}$) for recovery of the respective elements (lithium and algae). On the assumption that there was no loss of lithium or of algae in the system, then these two ratios should be the same. If, however, the algal ratio is smaller than the lithium ratio, then we assume that there has been a loss of algae in the aqueduct.

Estimating the proportion of lithium (L) emerging from the aqueduct

The recovery of lithium is estimated as L_{out}/L_{in}

The amount of lithium dosed (as lithium chloride) into the aqueduct (L_{in}) was 500g.

Estimating L_{out}

The amount of lithium emerging from the outlet at the Durban Heights WW at various sample-time points is recorded in Appendix I. A curve was fitted to this lithium data (Fig. 15) and this parametric curve used to estimate the area (by numerical integration) and hence total amount of lithium recovered at Durban Heights during the trial. Since the data showed the same shape as a normal density curve the curve fitted was:

$$\text{Lithium}_i = A\exp\{(-(\text{Time}_i - M)^2 / (2S^2)\}$$

where A, M and S are constants.

By comparison with the normal probability density function

$$f(\bar{x}) = (2\pi\sigma^2)^{-0.5}\exp\{-(x-\mu)^2 / (2\sigma^2)\}$$

the area under the curve will be given by

$$Area = \sqrt{2\pi}AS$$

The curve fitted used the non-linear, user defined, curve fitting module in the statistical package CSS Statistica (1993), and the results are summarised in Table 7.

The integration of the "normal curve" for the area estimate for the lithium data was very close to that obtained using Simpson's (Phillips & Taylor, 1973) as well as the trapezoidal rule. Using a Taylor's series approximation for the means and variances of a function of random variables, the area under the curve was estimated by:

$$\hat{A}rea = \sqrt{2\pi}\left[\hat{A}\times\hat{S} + \text{cov}(A,S)\right]$$

with its variance estimated as:

$$\text{var}\,\hat{A}rea = \left[\sqrt{2\pi}\hat{S}\right]^2 \text{var}(\hat{A}) + \left[\sqrt{2\pi}\hat{A}\right]^2 \text{var}(\hat{S}) + 2\sqrt{2\pi}\hat{S}\sqrt{2\pi}\hat{A}\,\text{cov}(A,S)$$

and hence the standard error of the estimate of the area is the square root of the variance.

Estimating the proportion of algae (A) emerging from the aqueduct

The proportion of algae emerging from the aqueduct is estimated as $^{Aout}/_{Ain}$

Estimating A_{in}

Prior to the dosing of algal scum into the aqueduct, independent samples were collected and accurately enumerated to estimate the total number of algae being dosed into the system (A_{in}). It was determined in this trial that simple means derived from enumerating sub samples (considered as equally weighted observations) were adequate to describe the number of algae in the dosing drums.

A_{in} = mean algal count (cells/mℓ) (*from sub samples*) x 1000 (*to cells/ℓ*) x litres of scum dosed into aqueduct

Estimating A_{out}

Samples were collected at the outlet of the aqueduct at Durban Heights WW, initially at 30 second intervals and then, during the period when the peak of the algae was expected, at 15 second intervals. In the trial two independent samples were collected to provide an estimate of the between sample variation or pure experimental error. This variation proved to be small and insignificant compared to experimental effects.

Samples from the trial were analysed by one technician and audited by a second. The first technician was also responsible for analysing the in-going (A_{in}) algal samples, and thus only this first technicians results were used in the analysis of the data. This avoided introducing an operator effect. The results for the algal samples collected in the trial are tabulated in Appendix I.

To estimate the number of algae recovered the results (in cells/mℓ) were plotted against sampling time (in seconds). Again, since the data showed the same shape as a normal density curve, the curve fitted to the data (as in the L_{out} estimations) was:

$$\text{Algae}_i = A\exp\{(-(\text{Time}_i - M)^2 / (2S^2)\}$$

By comparison with the normal probability density function

$$f(\bar{x}) = (2\pi\sigma^2)^{-0.5}\exp\{-(x-\mu)^2 / (2\sigma^2)\}$$

the area under the curve will be given by

$$Area = \sqrt{2\pi}AS$$

Again the curve was fitted using CSS Statistica (1993), and the results summarised in Table 8.

Using a Taylor's series approximation for the means and variances of a function of random variables, the area under the curves were estimated by:

$$\hat{A}rea = \sqrt{2\pi}\left[\hat{A} \times \hat{S} + \mathrm{cov}(A,S)\right]$$

with its variance estimated as;

$$\mathrm{var}\,\hat{A}rea = \left[\sqrt{2\pi}\hat{S}\right]^2 \mathrm{var}(\hat{A}) + \left[\sqrt{2\pi}\hat{A}\right]^2 \mathrm{var}(\hat{S}) + 2\sqrt{2\pi}\hat{S}\sqrt{2\pi}\hat{A}\,\mathrm{cov}(A,S)$$

and hence the standard error of the estimate of the area is the square root of the variance.

The modelled algal recovery data and curve resulted in Figure 16

Since R_A is estimated as $^{Aout}/A_{in}$, Table 9 summarises this ratio for the *in situ* rupture trial.

A 95% confidence interval for the percentage algae recovered may be obtained using Fieller's theorem, on account that the amount going in, (A_{in}), and the number of algae emerging at the WW, (A_{out}), were independently determined.

The approximate 95% confidence limits are then given by the values:

$$\frac{\hat{R} \pm \frac{2.}{\hat{A}_{in}}\left[V_{out} + \hat{R}_A^2 V_{in} - g V_{out}\right]}{(1-g)}$$

where V_{out} is the variance of $\hat{A}_{out}$

$$V_{out} = (0.1586 \times 10^{12})^2$$

V_{in} is the variance of $\hat{A}_{in}$

$$V_{in} = (0.475 \times 10^{12})^2$$

and $g = 4\,V_{in}/(\hat{A}_{in})^2 = 3.43 \times 10^{-3}$

The preceding analyses are based on a number of assumptions viz.

(a) The algae are randomly distributed in both the scum and the abstracted water emerging at the WW. In particular the algae do not show any propensity for clustering together.

(b) The algae pass through the aqueduct in exactly the same manner and at the same rate as the lithium marker.

(c) The within-sample point variation of the algae at the outlet is constant.

The experimental procedure was designed to make these assumptions realistic. *Microcystis* is in fact not randomly distributed in water as it is a colonial genus. Routine laboratory work has shown that mixing samples in a blender for 5-10 seconds is sufficient to disperse colonies and create a random distribution of algae in the sample without destroying a significant number of the cells. It was assumed that the energies involved in turbulent flow down the aqueduct would be sufficient to mix the algal scums with the main body of water as well as to disperse the *Microcystis* cells in the water.

The shape and spread of the lithium and algal recovery graphs (Figures 15 and 16) show that these two elements do in fact pass through the aqueduct at a similar rate and manner.

It should be noted that there was a background number of algae in the water on the day of this trial (4005 cells/mℓ, of which 37 cells/mℓ were *Microcystis*) and that this would tend to inflate the estimate of the number of algae emerging (A_{out}) but has no effect on the number of algae placed into the abstraction (A_{in}) since the sub samples counted were taken directly from the scum. If anything then the estimate of the ratio of algae recovered (A_{out}) to algae dosed (A_{in}) is slightly high, and hence the number of algae destroyed greater than that implied by the results of this trial.

3.3 Algal rupture during abstraction through the Inanda Dam abstraction tower

Performing this phase of the investigation proved to be more difficult than was at first envisaged. Several trials were performed before it was established that the water in the off-take pipe in the wall was not homogenous with respect to algal counts. Differential currents were introducing algae from different layers in the water column around the abstraction tower. This meant that it was almost impossible to accurately determine the number of algae entering the abstraction and thus to estimate the loss at the outlet.

The solution to this problem was an adaptation of the technique using the lithium tracer and algal scum. In this technique a known number of *Microcystis* algae in a 20ℓ scum were thoroughly mixed with a known amount of lithium. This homogenous mix was then siphoned into the inlet of the abstraction tower via a hose and allowed to pass through to the outlet of the tower. Samples of the diluted lithium and potentially ruptured algae were collected after release through the sleeve valve.

Full supply level (FSL) for Inanda Dam is 147.0m with the outlet pipe to the abstraction tower at 114.4m. There are twelve abstraction levels to the dam with this trial having been performed using abstraction level 3 (at 136.5m). With the water level in the dam during the trial being about 1m below FSL, the head of water on the abstraction level was the equivalent of $\approx$ 9.5m of water before passage through the $\approx$ 22m of abstraction tower. The diameter of the abstraction and outlet pipes was 1.6 m.

In any one trial several sub samples of algal scum were taken to accurately determine the initial concentration of *Microcystis* cells in the scum. Samples from both the scum at the inlet and those collected after passage

through the abstraction tower were then analysed to quantify both lithium and algae according to standard Umgeni Water procedures (Umgeni Water Analytical Services, Laboratory Quality Manual). The dilution of lithium was then established and applied to the algal scums dosed into the abstraction inlet which gave the expected number of algae at the abstraction outlet. Any algal loss, therefore, would show up as a greater dilution of algae compared to the dilution of lithium in samples.

3.4 Aqueduct simulations and algal loss

A cylindrical high pressure, stainless steel chamber was constructed to withstand the pressures developed for simulations of aqueduct conditions in the respective systems (Figure 4). Fitted to this chamber was a variable speed stirrer able to operate at the high pressures. This stirrer had an 8mm shaft fitted with a 25mm×76mm×2mm stainless steel blade. Bottled synthetic air (21% O_2, 79% N_2) was used to pressurise the system via a variable pressure gauge.

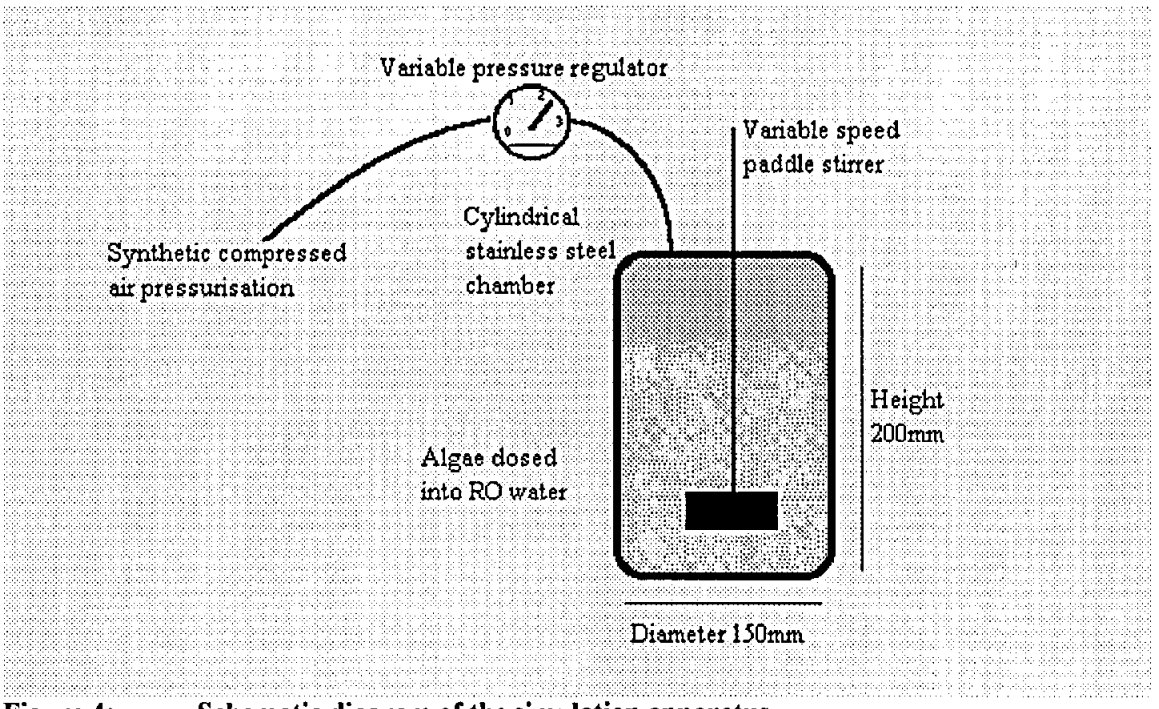

Figure 4: Schematic diagram of the simulation apparatus.

A sample of reverse osmosis (RO) water was usually inoculated with a few millilitres (depending on the concentration) of algal scum. These scums were invariably dominated by *Microcystis* and came from various sources, primarily Shongweni Dam on the Mlazi River in Natal and from Zeekoevlei in the Cape. Only scums less than a week old were used in simulation work. Scums were stored at between 2° and 8° C and exposed to a 14:10 hour light:dark cycle prior to their use in simulations.

The RO water and algae mix was briefly blended to disperse algal colonies into single cells uniformly mixed in the solution. Because of the buoyant nature of *Microcystis* algae test solutions were kept gently mixed whilst being separated into experimental and control batches. An experimental batch was then placed in the simulation chamber and subjected to the calculated pressure and shear regime for the respective system being

simulated (Table 1 and 2), whilst the control batch was kept under the same ambient temperature conditions for the duration of the simulation.

At the end of the simulation run both batches (or 'treatments') had 5 random sub samples extracted and vacuum filtered onto 0.45μm cellulose nitrate membrane filter disks according to standard Umgeni Water methods (Umgeni Water Analytical Services, Laboratory Quality Manual). Filter disks were then enumerated (again according to standard Umgeni Water methods) and algal counts made directly into a computer which conducted running statistical analyses of the algal counts. Statistical confidence for the counts was set at 95% and precision at 0.3.

Results for control and pressure/shear treated samples were then compared with each other to give a measure of rupture in the respective system.

3.4.1 Shear/stirrer velocity calculations

The fluid velocities experienced in the individual elements of the aqueducts for the respective systems were simulated in the laboratory. Calculations for this simulation were achieved in collaboration with Umgeni Water Chemical Engineers (Pryor & Maphumulo pers. comm.). It was assumed that the velocity of the water in the laboratory scale simulation apparatus should be the same as that in the aqueduct to reflect the shear forces experienced by algae in the respective systems. Based on this relationship, the maximum velocity is obviously around the perimeter of the vessel (assuming negligible drag due to friction on the side of the vessel). The rotational velocity of the fluid can therefore be related to the velocity around the perimeter by equation 1.

$$n = \frac{v}{\pi d} \qquad \text{(eqn. 1)}$$

n = rotational speed (rps)
v = velocity of fluid (ms^{-1})
d = diameter of vessel (m)

This was the first estimation of stirrer speed but considering that the impeller or blade of the stirrer would have to rotate faster than this in order that the whole fluid moved at a specific velocity, another approach would be to calculate the average velocity for the bulk of the fluid in the vessel. This is done by integrating the specific velocity of a volume portion of fluid at radius r from the centre, over the region $0 < r < R$, where R is the radius of the vessel (equation 2).

$$v_{ave} = \int_0^R v_r \frac{V_r}{V_{tot}} dr \qquad \text{(eqn. 2)}$$

$$v_{ave} = \int_0^R (n 2\pi r) \frac{(2\pi r h)}{V_{tot}} dr \qquad \text{(eqn. 3)}$$

$$v_{ave} = \frac{4\pi^2 nh}{V_{tot}} \int_0^R r^2 dr \qquad \text{(eqn. 4)}$$

$$v_{ave} = \frac{4\pi^2 nhR^3}{3V_{tot}} = \frac{4\pi Rn}{3} \qquad \text{(eqn. 5)}$$

n = rotational speed (rps)
h = height of fluid in vessel (m)
R = radius of vessel (m)
V_{tot} = total volume of vessel (m^3)

Similarly then the rotational speed is:

$$n = \frac{3v_{ave}}{4\pi R} = \frac{3v_{ave}}{2\pi d} \qquad \text{(eqn. 6)}$$

Comparing equation 6 to equation 1 it is clear that in considering the average velocity, the rotational speed is effectively increased by 50 %. In order to calculate the rotational speed in revs per minute, n (in revs per second) must be multiplied by a factor of 60.

The velocity of water in each of the tunnels and siphons of the Nagle Dam to Durban Heights WW aqueducts (Figure 2 and Table 1) was then substituted as either velocity in equation 1 or as average velocity in equation 6 in order to calculate the stirrer speeds for the laboratory simulation.

Results of several test simulation trials, using the range of calculated stirrer speeds (equations 1 and 6), indicated that the stirrer speeds based on equation 1 produced results in closest accordance with *in situ* algal losses. Hence all further simulations were conducted using equation 1 to calculate stirrer rpm from aqueduct fluid velocities.

3.4.2 Pressure calculations

Pressures were simply calculated from the hydraulic head experienced in siphons. In the Nagle system tunnels, which are exposed to the atmosphere, the pressure was effectively 0 kPa.

The calculated simulation stirrer and pressure figures for the various systems are presented in Tables 1 and 2.

During the laboratory work the various elements (tunnels and siphons) of respective systems (Nagle and Inanda Dams) had their respective simulated pressures and velocities changed in accordance with the retention time in the particular element. This was achieved by increasing the pressure and velocity in fixed steps to half the retention time in the respective element and then decreasing them at the same rate for the second half of the

element. The simulated pressures were based on the maximum hydraulic head developed over respective elements.

Table 1: Nagle Dam to Durban Heights WW aqueducts 3 & 4 flow conditions and estimated simulation stirrer velocity.

Element	Flow (m^3/sec)	Cross section area (m^2)	Length (m)	Aqueduct velocity (m/sec)	Stirrer velocity (rpm)	Time (minutes)	Hydraulic pressure (kPa)
Tunnel No 1	5.13	3.366	534.0	1.524	300	5.8	0
Siphon No 1 Aq 3	2.55	0.894	185.6	2.852	500	1.1	112
Aq 4	2.58	0.894	185.6	2.886	500	1.1	112
Tunnel No 2	5.13	3.200	4787.0	1.603	200	49.8	0
Siphon No 2 Aq 3	2.55	0.894	941.1	2.852	500	5.5	599
Aq 4	2.58	0.894	941.1	2.886	500	5.4	599
Tunnel No 3	5.13	3.150	3607.9	1.629	200	36.9	0
Siphon No 3 Aq 3	2.55	0.894	2439.9	2.852	500	14.3	1999
Aq 4	2.58	0.894	2439.9	2.886	500	14.1	1999
Tunnel No 4	5.13	3.300	4646.2	1.555	200	49.8	0
Siphon No 4 Aq 3	2.55	0.894	5869.8	2.852	500	34.3	2096
Aq 4	2.58	0.894	5869.8	2.886	500	33.9	2096
Tunnel No 5	5.13	3.168	4877.6	1.619	200	50.2	0
Siphon No 5 Aq 3	2.55	0.894	1876.0	2.852	500	11.0	2307
Aq 4	2.58	0.894	1876.0	2.886	500	10.8	2307
Tunnel No 6	5.13	2.970	2897.5	1.727	200	28.0	0
Siphon No 6 Aq 3	2.55	0.894	3592.7	2.852	500	21.0	2221
Aq 4	2.58	0.894	3592.7	2.886	500	20.7	2221

Table 2: Inanda Dam to Wiggins WW flow conditions and estimated simulation stirrer velocity.

Element	Flow (m^3/sec)	Cross section area (m^2)	Length (m)	Aqueduct velocity (m/sec)	Stirrer velocity (rpm)	Time (minutes)	Hydraulic pressure (kPa)
Emolweni Tunnel	4.05	9.08	5320.0	0.45	60	198.8	124
Emolweni Siphon	4.05	4.02	340.0	1.01	130	5.6	410
Clermont Tunnel	4.05	9.08	5387.0	0.45	60	201.3	125
Aller Siphon	4.05	4.02	321.0	1.01	130	5.31	497
Reservoir Hills to Dbn. Ht's. Shaft	4.05	9.00	1104.0	0.45	60	40.9	428
Dbn. Ht's. Shaft onwards	4.05	6.00	1455.0	0.67	90	35.9	390
Ungudulu Siphon	4.05	4.02	582.0	1.01	130	9.6	536
University Tunnel	4.05	6.00	1040.0	0.67	90	25.7	455
Palmeit Siphon	4.05	4.02	237.0	1.01	130	3.9	599
Sherwood Tunnel	4.05	6.00	3332.0	0.67	90	82.3	455

3.5 Modelling of algal rupture due to pressure, shear and time

This phase of the project was designed to experimentally investigate the effect of the two components of the abstraction process, namely pressure and shear, on algal number. In addition time (or duration) for which the pressure and or shear was applied was also investigated as it may be a significant factor affecting algal rupture.

The aim, therefore, was to investigate the response of the algal count to the levels of the three factors (pressure, shear and time). Response surface methodology was used (see Box *et al.* 1978; Mead 1988).

Four levels of pressure and shear respectively were applied to the algae as well as 7 levels of time. These are summarised in Table 3. The values chosen were estimates of the mean and maximum level of that variable in the pipeline for the particular system (see Tables 1 and 2 in section 3.4.2).

Table 3: Pressure, shear and time levels considered in response surface modelling of algal rupture.

Variables	Treatment level
Pressure	0 kPa
	Inanda mean pressure = 350 kPa
	Nagle mean pressure = 1400 kPa
	Nagle maximum pressure = 2200 kPa
Shear	0 rpm
	Inanda mean shear = 75 rpm
	Nagle mean shear = 350 rpm
	Nagle maximum shear = 500 rpm
Time	10 minutes
	20 minutes
	30 minutes
	40 minutes
	45 minutes
	120 minutes
	180 minutes

This resulted in eighteen treatment combinations made up of the four levels each of pressure and shear as well as the seven levels of time (Table 4). In terms of the experimental design requirements four of these levels were each replicated 4 times, namely mean Inanda stirrer velocity (75 rpm) and Inanda mean pressure (350 kPa) applied for 20 and 40 minutes, and mean Nagle stirrer velocity (350 rpm) and Nagle mean pressure (1400 kPa) applied for 30 and 45 minutes. Note that in a full factorial design we would have 16 shear x pressure combinations each applied at 7 times, or a total of 112 treatment combinations. Since this was not feasible, a response surface design was used. Such designs are appropriate when the interest is in fitting response surface equations such as the general second-degree polynomial

$$y = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1}^{3} \beta_{ii} x^2_i \sum_{i=1}^{3} \beta_{ii} x^2_i + \sum_{i=1}^{3} \sum_{j>i} \beta_{ij} x_i x_j$$

where x_1 denotes the amount of pressure

x_2 denotes the amount of shear

x_3 denotes the length of time for which the treatment was applied (Levin pers comm.).

From this model the "optimum" may be found i.e. the values of x_1, x_2 and x_3 that lead to the minimum algal count (and hence maximum rupture).

The usual response surface designed to fit a second degree polynomial response is known as the central composite design. An alternative design was used here, namely a San Cristobal design (Mead 1988), which allows us to consider asymmetric levels of shear and pressure.

The San Cristobal design was applied to the 4 levels of shear and the 4 levels of pressure, giving a design with 9 treatment combinations. Each of these combinations was then applied at 2 different times, to give a total of 18 treatment combinations, detailed in Table 4. The treatments in Table 4 were then replicated twice. On each occasion it was intended to take five samples from the treated water and five samples from a control batch of water. However, due to occasional missing samples and the time consuming nature of counting algae, on some occasions only four, or in some cases three, samples of each were taken. For each run information was taken on the source and age of the algal scums used in simulations.

Table 4: Treatment codes and descriptions used in the response surface modelling.

Treatment Code	Treatment description (Sh=shear, Pr=Pressure)	Time (mins)	Shear (rpm)	Pressure (kPa)	
1	Zero Sh x Zero Pr	180	0	0	
2	Zero Sh x Zero Pr	120	0	0	
3	Zero Sh x Nagle mean Pr	45	0	1400	
4	Zero Sh x Nagle mean Pr	30	0	1400	
5	Inanda mean Sh x Inanda mean Pr	40	75	350	} Replicated
6	Inanda mean Sh x Inanda mean Pr	20	75	350	} x 4
7	Inanda mean Sh x Nagle mean Pr	45	75	1400	
8	Inanda mean Sh x Nagle mean Pr	30	75	1400	
9	Inanda mean Sh x Nagle max. Pr	20	75	2200	
10	Inanda mean Sh x Nagle max. Pr	10	75	2200	
11	Nagle mean Sh x Zero Pr	45	350	0	
12	Nagle mean Sh x Zero Pr	30	350	0	
13	Nagle mean Sh x Inanda mean Pr	45	350	350	
14	Nagle mean Sh x Inanda mean Pr	30	350	350	
15	Nagle mean Sh x Nagle mean Pr	45	350	1400	} Replicated
16	Nagle mean Sh x Nagle mean Pr	30	350	1400	} x 4
17	Nagle max. Sh x Inanda mean Pr	40	500	350	
18	Nagle max. Sh x Inanda mean Pr	20	500	350	

Note that the variables P, S and T were transformed as follows for numerical stability:

P = pressure - 350 kPa.

S = shear -75 rpm

T = time - 40 minutes

3.6 Visual appearance of algal cells treated to simulated aqueduct conditions

A sample of mixed algae (predominantly *Microcystis* and *Anabaena*) was split into a control and test solution. The latter solution was then subjected to the Nagle to Durban Heights pressure and shear regime as simulated in the previous section.

Both the control and "treated" samples were preserved in glutaraldehyde for electron microscopy work. Samples for light microscopy examination were filtered onto 0.45μm cellulose nitrate filter disks and air dried for later examination with a 63X oil immersion lens.

Standard methods were used for the scanning and transmission electron microscope work. Briefly the techniques used were as follows. Samples for the scanning electron microscope (SEM) were critical point dried in CO_2 and viewed under a Hitachi S-570 SEM at 10 kV.

TEM samples were fixed in 3% glutaraldehyde for 8 hours, gently centrifuged to concentrate the sample, washed in 2 x 0.5M sodium cacodylate buffer and then dehydrated in alcohol. These samples were then embedded in Epon resin, sectioned with a LKV 3 ultramicrotome and viewed on a 100 CX TEM at 80 kV.

3.7 The effects of algal rupture on water treatment

In order to test the treatment characteristics of water containing ruptured algae, samples of water with low cell counts were collected from Inanda Dam and then spiked with *Microcystis* algae from the same dam. This was performed both before and after the algal cells had been ruptured to yield final cell concentrations of ten thousand, one hundred thousand and one million cells per millilitre. Cells were ruptured by three freeze-thaw cycles which unfortunately yielded variable percentage rupture results that were not initially monitored. Samples of this water, at the various cell concentrations, were then tested for their treatability.

The impacts on coagulant and chlorine demand, trihalomethane formation and taste and odour problems were considered.

3.7.1 Coagulant demand

Coagulant demand using various commonly used coagulants was determined using standard jar tests on 800mℓ samples. The flash mix speed was 300rpm for 2 minutes and was followed by a slow mix of 40rpm for 15 minutes. Coagulants were mixed to 0.08% solution.

3.7.2 Chlorine demand

Chlorine demand was carried out according to Standard Methods (1992).

3.7.3 Trihalomethane formation potential

Trihalomethanes (for trihalomethane formation potentials (THMFP)) were analysed according to the basic method outlined in Standard Methods (1992).

3.7.4 Geosmin analysis

Geosmin was analysed according to the standard Umgeni Water, Analytical Services, Laboratory Quality Manual. This is essentially a liquid liquid extraction technique, using methylene chloride, followed by concentration of the extract on a rotary evaporator and analysis by gas chromatography.

CHAPTER 4

HISTORICAL EVIDENCE OF ALGAL RUPTURE

4.1 Introduction

Four and a half years of routine algal monitoring data (weekly from January 1989 to July 1993) provided the first indication that the majority of algae abstracted from Nagle Dam do not survive the journey to Durban Heights WW, some 36 km away (see Chapter 2 "Location"). This historical monitoring data was used in a statistical examination of the effects of conditions associated with the aqueducts on algal numbers.

Experimental techniques - see section 3.1

4.2 Results

Results of statistical analyses of the historical algal data between Nagle Dam and Durban Heights WW are summarised in Table 5. These results show the differences in algal counts between the dam and WW for the total as well as 27 of the most abundant algae. A total of 51 algal genera were found in samples collected from Nagle Dam and Durban Heights WW. (See Appendix II for a complete list of genera found).

Due to the non-normal distribution of the data, median percentage loss was considered as the most meaningful measure of the degree of rupture of algae between the dam and WW.

For total algal counts there is a highly significant difference between the dam and Durban Heights WW. Several of the most abundant algal genera considered also show statistically significant reduced numbers after passage through the aqueducts. Of these genera *Microcystis, Anabaena, Crucigenia, Nitzschia, Coelastrum, Oocystis, Cocconeis, Tetraedron* and *Trachelomonas* show the statistically most significant median difference between the two sample points.

Figure 5 shows the situation for the total, and *Microcystis,* algae (flow weighted average) at Nagle Dam and total algae only at Durban Heights WW. This figure clearly illustrates how, when total counts at Nagle Dam are high, these counts are almost invariably dominated by *Microcystis.* It is during these periods that the total counts at Durban Heights WW are relatively low.

Table 5: Results of analyses of historical data comparing the Nagle Dam flow weighted average with Durban Heights WW, together with the mean algal counts and the median % loss between the respective sample points.

Genus	Number of paired couplets	Significance (Student's test)	Significance (Wilcoxon test)	Nagle algae, mean flow weighted average (cells/ml)	WW algae, mean (cells/ml)	Median % loss between Nagle & Dbn Ht's WW *
Total	161	P < 0.001	P < 0.001	2548	942	47
Anabaena	77	P < 0.001	P < 0.001	780	56	100
Ankistrodesmus	32	NS	P < 0.01	8	5	100
Chlamydomonas	104	NS	NS	15	13	26
Chlorella	159	NS	P < 0.001	458	345	24
Cocconeis	8	P < 0.01	P < 0.01	5	0	100
Coelastrum	42	P < 0.001	P < 0.001	94	34	100
Cosmarium	40	NS	P < 0.01	22	13	100
Crucigenia	135	P < 0.001	P < 0.001	118	57	70
Cryptomonas	151	NS	NS	47	63	+ 16
Cyclotella	128	NS	NS	53	39	25
Cymbella	12	NS	NS	23	2	100
Diatoma	17	NS	P < 0.01	7	3	100
Melosira	154	NS	NS	296	273	23
Microcystis	133	P < 0.001	P < 0.001	1154	28	100
Navicula	109	NS	P < 0.01	13	9	41
Nitzschia	80	P < 0.001	P < 0.001	12	6	100
Oocystis	83	P < 0.001	P < 0.001	25	8	100
Oscillatoria	15	NS	P < 0.01	893	202	100
Pandorina	12	NS	NS	27	9	100
Pediastrum	22	NS	NS	50	15	100
Pteromonas	9	NS	----	3	0	100
Scenedesmus	127	P < 0.01	P < 0.001	55	34	63
Spermatozopsis	14	NS	P < 0.01	26	2	100
Stichococcus	21	NS	P < 0.001	28	4	100
Synedra	24	NS	P < 0.001	12	2	100
Tetraedron	28	P < 0.01	P < 0.001	14	5	100
Trachelomonas	23	P < 0.01	P < 0.001	4	0	100

(* Median % loss calculated as the median of all of the percentage losses between Nagle Dam and Durban Heights WW. NS - results considered statistically non-significant at P > 0.05).

Figure 5 also shows periods when the Nagle Dam total counts are closely reflected by the Durban total counts. At these times the *Microcystis* counts at Nagle Dam are generally low. This indicates that when the dam total counts are dominated by *Microcystis* there is the greatest loss of algae. Conversely, when the dam total counts are not dominated by *Microcystis* there are relatively few algae lost through the aqueduct system. This loss in *Microcystis* is also illustrated in the difference between its mean (over the study period) at the dam compared to that at the WW (1154 cells/mℓ and 28 cells/mℓ respectively. Table 5).

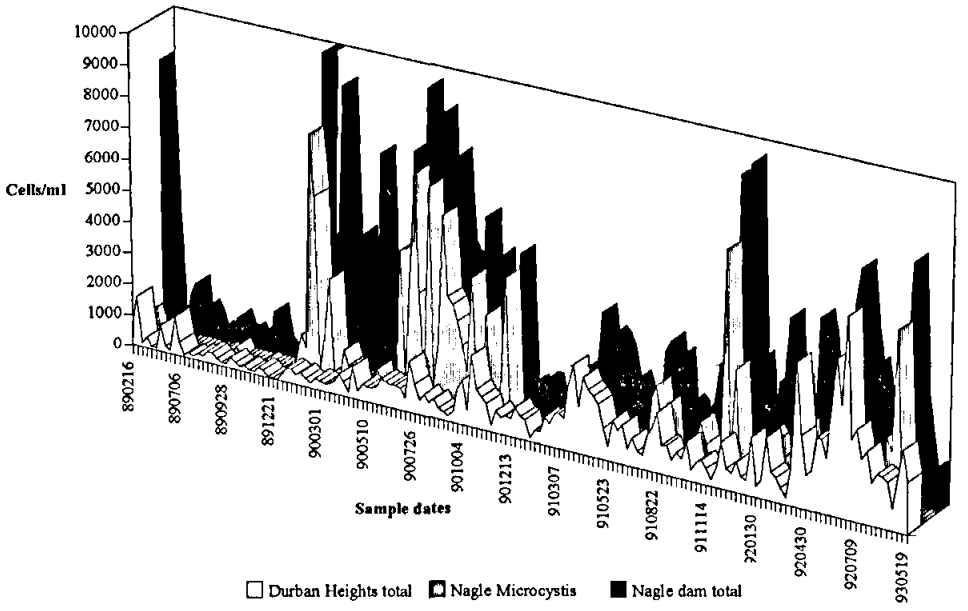

Figure 5: Flow weighted average, total algal counts and *Microcystis* counts, from Nagle Dam and total counts from Durban Heights WW for the period February 1989 to May 1993.

4.3 Conclusions

Indications from these results are that several algal genera are being lost *en route* from the dam to the WW (as evidenced by the significant differences in algae between these two points). As far as the problematic algal genera are concerned this loss appears to be most marked for *Microcystis* and *Anabaena*. A few other (traditionally less problematic) genera also show a significant median loss of 100% e.g. *Coelastrum* and *Oocystis*. This said, however, their abundances are generally low by comparison with the numerically dominant blue-green algal genera (Table 5), except possibly for *Coelastrum*.

Of the genera showing reduced abundances at the WW several are possibly an artefact of enumeration. *Microcystis, Anabaena, Ankistrodesmus, Coelastrum, Oocystis* and *Crucigenia* are colonial genera with distinctive appearances. These genera are readily identifiable in "normal" samples being enumerated. However, after passage through the aqueduct these colonies may have become dispersed due to the mixing energies in the abstracted water. On arrival at the WW then they would be less easily recognisable and hence liable to be incorrectly enumerated. In fact individual cells of *Scenedesmus* look similar to *Chlorogonium* and could easily be confused with this genus when not in their distinctive colonial form. *Microcystis, Anabaena* and *Crucigenia* also have very small individual cells and could also be mis-identified in their non-colonial state particularly as the gas vacuoles in the first two are collapsed by the pressures experienced in the aqueduct.

These explanations may account for some inaccuracy in the results where genera are considered but would not affect the results for total algal numbers (significantly different). Some other genera defy any other rationale explanation as to why they are reduced in number other than that they are rupturing in the aqueduct.

The results of these historical analyses indicate that it is generally the abundant (and often numerically dominant) vacuolate blue-green algae (*Microcystis* and *Anabaena*) that are most often reduced in numbers in the pipeline from Nagle Dam to Durban Heights WW.

Interestingly, Hemmingsen and Hemmingsen (1980) found that in cells which do not normally possess gas vesicles, there was no rupturing of bacterial cells following decompression from gas saturation pressures of up to 30 000 kPa. This may explain how the other non-vacuolate algae are apparently little affected by their passage through the aqueduct system. Their work also indicated that rupture of vacuolate bacteria cells is possible at minimal pressures of around 2 500 kPa. This is close to the range of pressures experienced in the Nagle system.

Having been alerted to the possibility that algal numbers are reduced at Durban Heights WW, due to their rupture in the aqueduct, it appeared appropriate to investigate this phenomenon further.

CHAPTER 5

EFFECTS OF ALGAL RUPTURE ON WATER QUALITY - HISTORICAL DATA

5.1 Introduction

A detailed examination was made of the historical water quality data surrounding a *Microcystis* bloom at Nagle Dam, in February 1990, which severely effected water treatment at Durban Heights. The predominantly *Microcystis* algal bloom began in mid-January 1990 (Figure 6) and tailed off at the end of April 1990. The aim of this investigation was to see if any physical or chemical parameters would give an indication of the presence of ruptured algae in the raw water inflow to the WW.

5.2 Results

Algal numbers, together with various other water quality determinands, are presented graphically (Figures 6-13) so that the trends in each could be examined.

Of all the variables examined (besides algal numbers and chlorophyll) pH appeared to be the only one indicating a consistent difference between the WW and dam (Fig. 13). This difference was due to slightly elevated pH values at the WW compared to Dam samples. This phenomenon was examined further by comparing the pH differences between the dam and WW samples during periods of relatively high algal loss with periods of low algal loss (from Fig. 13). These differences in pH were then compared with each other for the two periods (high and low algal loss) and the results presented in Table 6 and Figure 14.

During periods of high algal loss, between the Dam and WW, there are correspondingly greater differences between the dam pH and the WW pH. These differences in pH, during high and low algal loss, are not statistically significant from each other however (Table 6).

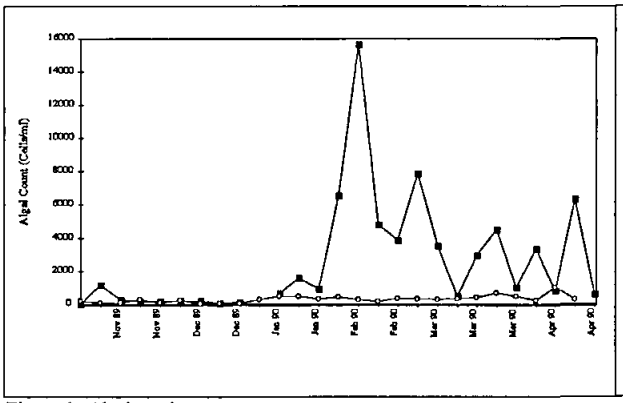

Figure 6: Algal numbers

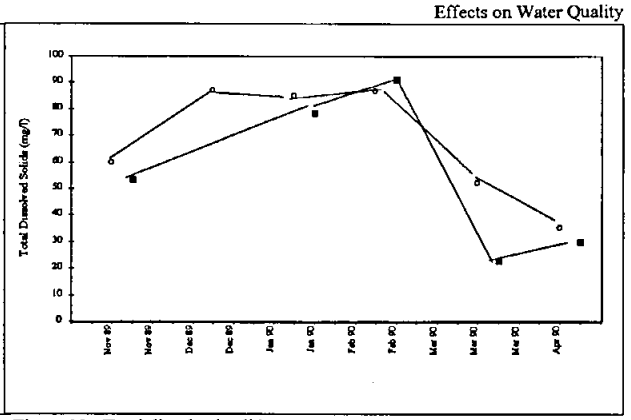

Figure 10: Total dissolved solids

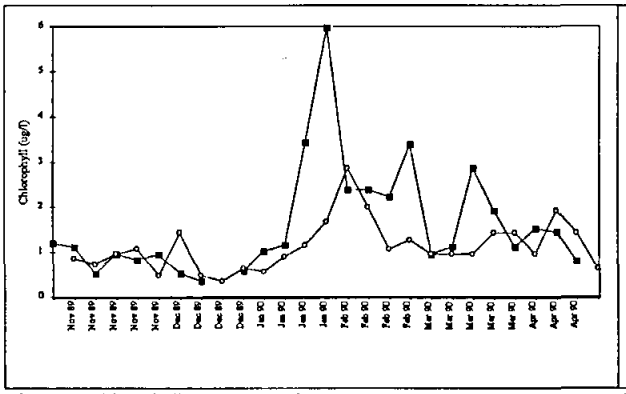

Figure 7: Chlorophyll "a" concentration

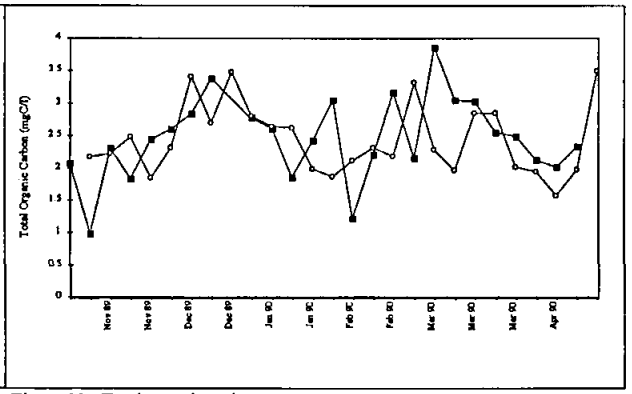

Figure 11: Total organic carbon

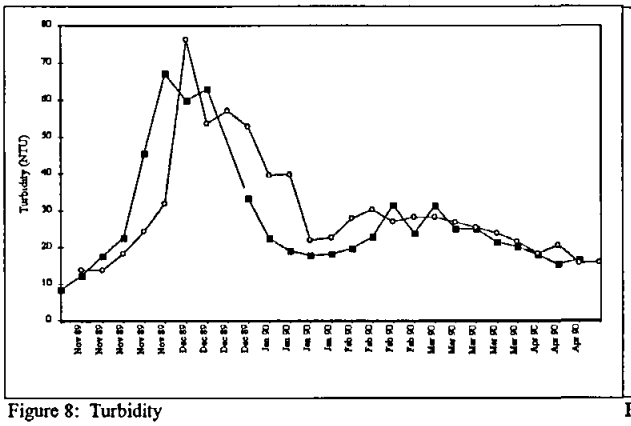

Figure 8: Turbidity

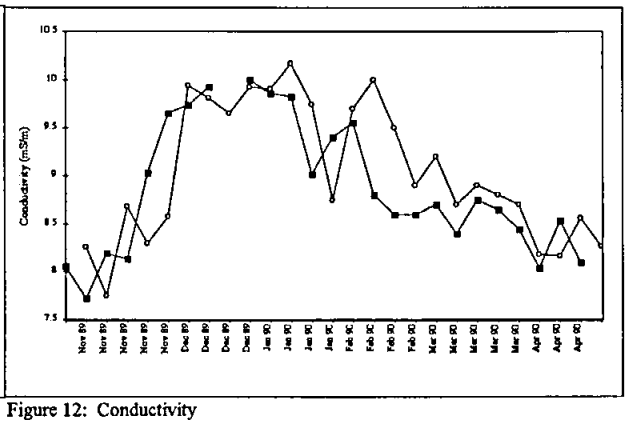

Figure 12: Conductivity

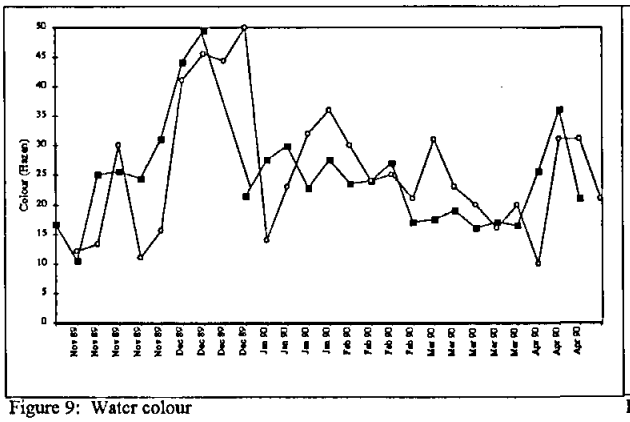

Figure 9: Water colour

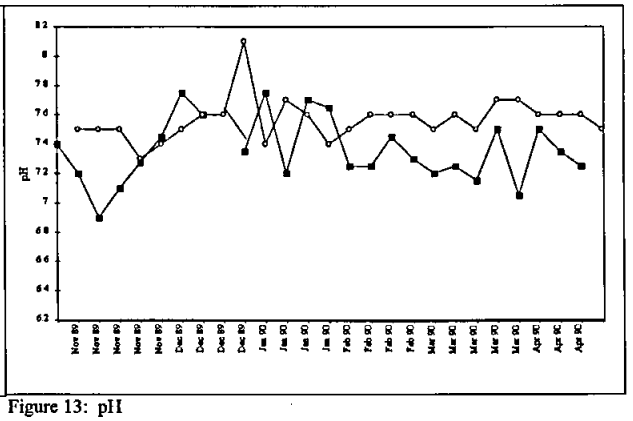

Figure 13: pH

Nagle Dam — Durban Heights

Figures 6 - 13: Water quality variables in the abstraction tower at Nagle Dam (mean of the two abstractions) and in the raw inflow to Durban Heights Waterworks (WW) during a period when severe taste and odour problems were experienced.

Table 6: pH differences between Nagle Dam and Durban Heights WW for periods of high and low algal loss.

High algal loss - pH difference between dam and WW	-0.194
Low algal loss - pH difference between dam and WW	-0.119
t - value of pH difference between the two periods	-1.09
d.f.	92
p - value	0.28

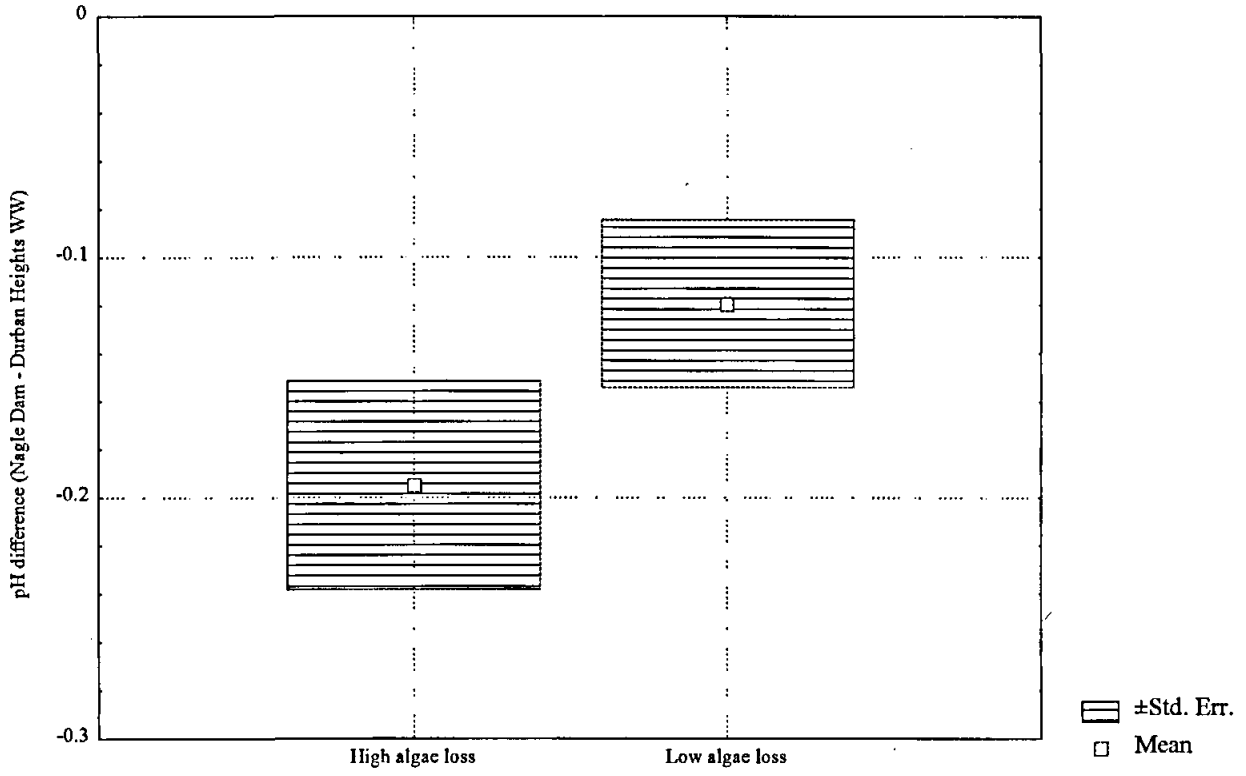

Figure 14: The difference in pH between Nagle and Durban Heights WW during periods of high and low algal loss.

5.3 Conclusions

Of the determinands investigated, besides algae and chlorophyll, only pH (and to a lesser degree conductivity) showed any difference between Nagle Dam and Durban Heights WW samples. This pH was more basic at the WW end of the aqueduct with the difference between the two sites more marked after the onset of the algal bloom. The difference between the two sites appears to be statistically unrelated to the degree of algal rupture in the aqueduct however. It has been suggested that this difference in pH may be due to the effects of the concrete pipeline.

As mentioned above algal number and chlorophyll (Figs. 6 & 7 respectively) also differed between the dam and WW ends of the aqueduct and thus indicated a loss of algae *en route*. The chlorophyll determination was less sensitive in showing algal rupture at lower cell concentrations however. It is noteworthy that the chlorophyll concentration, and thus the biomass, is low even at the height of the bloom. The explanation for this may be that individual *Microcystis* cells are small (diameter ≈5μm) and contain little chlorophyll per cell.

From the results presented (Fig. 8) it is clear that a significant increase in turbidity in early December 1989 (the result of a flood event) preceded the rapid increase in algal numbers (Fig. 6). This was also reflected in the colour of the water (Fig. 9). The total dissolved solids (Fig. 10) indicated an increase which spanned both the turbid water inflow and the algal bloom but did not provide much useful information. Significantly, total organic carbon (Fig. 11) was unable to indicate the presence of the bloom. Conductivity increased with the inflow of flood water (Fig. 12) as did the pH (Fig. 13). The flood event, by providing a large input of nutrients, was the probable cause of the algal bloom.

Clearly of all the routine water quality determinands examined none, besides the comparison of algal numbers and chlorophyll 'a' between the Dam and WW, gave a clear indication of a change in water quality, due to the presence of an algal bloom or due to the rupture of algal cells in the aqueduct, although pH (and to a lesser degree conductivity) was slightly elevated at the WW compared to the Dam. It is possible that pH may be co-varying with some other, as yet unidentified, water quality variable.

Detailed investigations involving pH and conductivity meters, sensitive to the third decimal place and $\mu S\ m^{-1}$ respectively, showed no significant difference between laboratory homogenised and ruptured *Microcystis* algae compared to control samples which had had no rupture treatment. This further confirmed that raw water pH is little affected by algal rupture.

It was obviously not possible to monitor pH as an indicator of algal blooms as this determinand was variable in its own right and dependent on local limnological conditions. No determinands measured at the inflow to the WW were able to point to the presence of an algal bloom in the dam.

CHAPTER 6

MEASURING ALGAL RUPTURE IN THE NAGLE DAM TO DURBAN HEIGHTS WATERWORKS SYSTEM

6.1 Introduction

The motivation for this aspect of the work was three fold. Firstly, to confirm the historical algal rupture trends identified in sections 4 & 5, secondly to ascertain the extent of *in situ* algal rupture in the Nagle Dam to Durban Heights WW system and finally from this last aspect to validate the laboratory scale simulation apparatus developed to predict algal rupture in systems in the design phase.

The results of detailed analyses on historical Nagle Dam and Durban Heights WW data (Chapter 4) indicated that there was probably a large degree of algal loss (particularly the vacuolate blue-green algal genera) occurring during the abstraction of water from the Dam to the WW. Even though dam and WW samples in the analyses on historical data were paired from the same day, and the differences in algal counts between the two sites examined statistically, there was still some reservation that the paired samples did not represent exactly the same body of water sampled at the dam and then re-sampled at the WW. This was because there was always a delay in the passage of this water from the Dam to the WW in Durban. During this delay different bodies of water may have been sampled although the trend identified in the analysis of historical data pointed to a consistent algal loss.

To deal with this reservation a novel technique of using a lithium chloride (LiCl) tracer was employed. During November 1991 an experiment was undertaken in which a known mass of lithium was dosed into an aqueduct at Nagle Dam. After a measured time period a known number of algae (predominantly *Microcystis*) were dosed into the same aqueduct. An in-line flame photometer was used to monitor for the lithium arriving in this aqueduct at Durban Heights WW (approximately 36 km away). The arrival of lithium at the WW indicated when sampling should begin for both lithium and algae. These samples were collected for accurate determination of both these elements. From the known mass of lithium and numbers of algae dosed at Nagle Dam and recovered at Durban Heights, an accurate assessment was made of the loss of algae in the aqueduct due to *in situ* rupturing.

Experimental techniques - see section 3.2

6.2 Results

The results for the various estimates of inputs and recoveries of lithium and algae in the *in situ* algal rupture trial are presented in the following figures and tables.

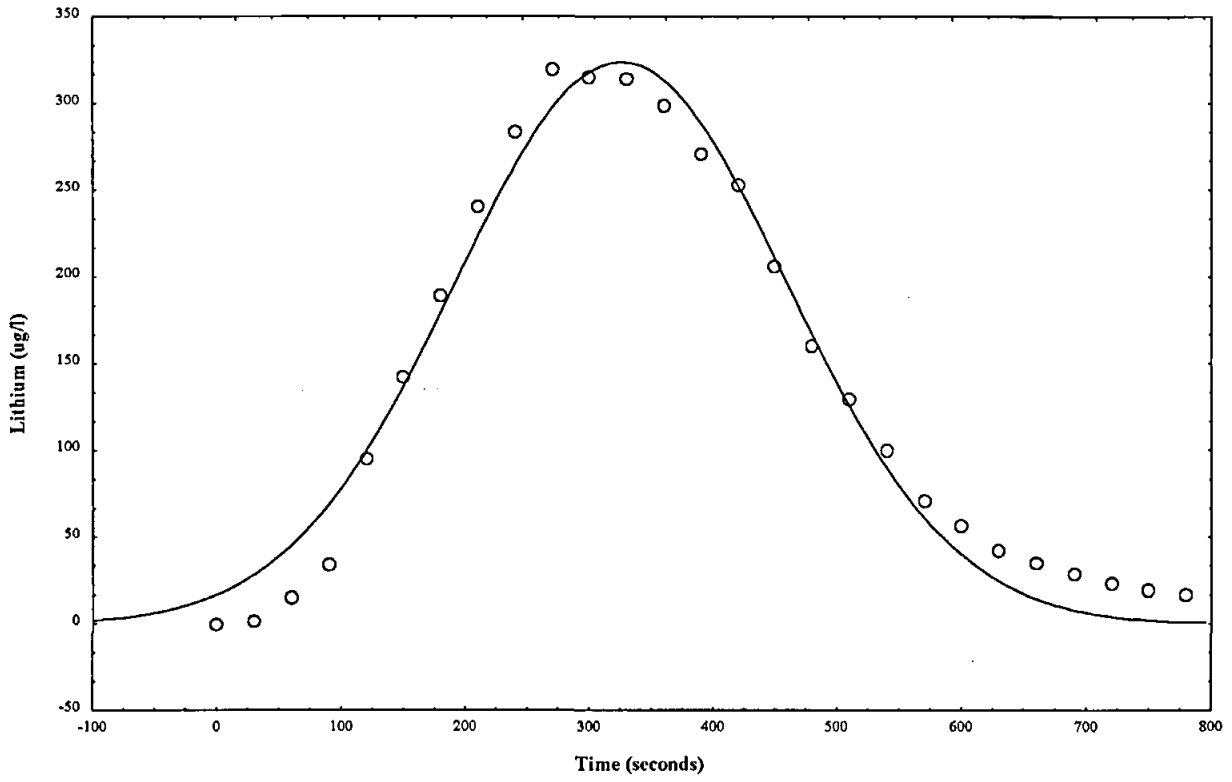

Figure 15: **Recovery of lithium from the raw water inflow to Durban Heights WW. (Lithium concentration (o) and fitted model (—)).**

The curve gave a good fit to the data, and explained 97.78% of the variation in the lithium data for the trial.

The fitted curve for the lithium data is

$$\text{Lithium}_i = 323.97 \exp\{-(\text{Time}_i - 325.48)^2 / (2 \times (133.97)^2)\}$$

Table 7: **Data used to determine the recovery of lithium (L_{out}) after passage through the aqueduct.**

Estimates	Lithium data
Estimated area under integrated "normal" curve ($\mu g\ \ell^{-1} s$)	108747.2
Standard error of estimated area ($\mu g\ \ell^{-1}\ s$)	2622.2
Aqueduct flow during trial (Mℓ/day)	378.7
Lithium passing out of aqueduct (g) (L_{out})	476.4
Lithium dosed into aqueduct (g) (L_{in})	500.0
Ratio of lithium recovered = L_{out}/L_{in}	0.953
Percentage lithium recovery	95.3

Table 8: **Summary of the algal results used to determine the total number of cells dosed into the aqueduct at Nagle Dam (A_{in}).**

Estimates	Algal data
Mean (cells/ml)	77.60×10^6
Std error of mean	2.27×10^6
litres dosed	209
Total cells dosed (A_{in})	16.22×10^{12}
Std error of estimate (A_{in})	0.48×10^{12}

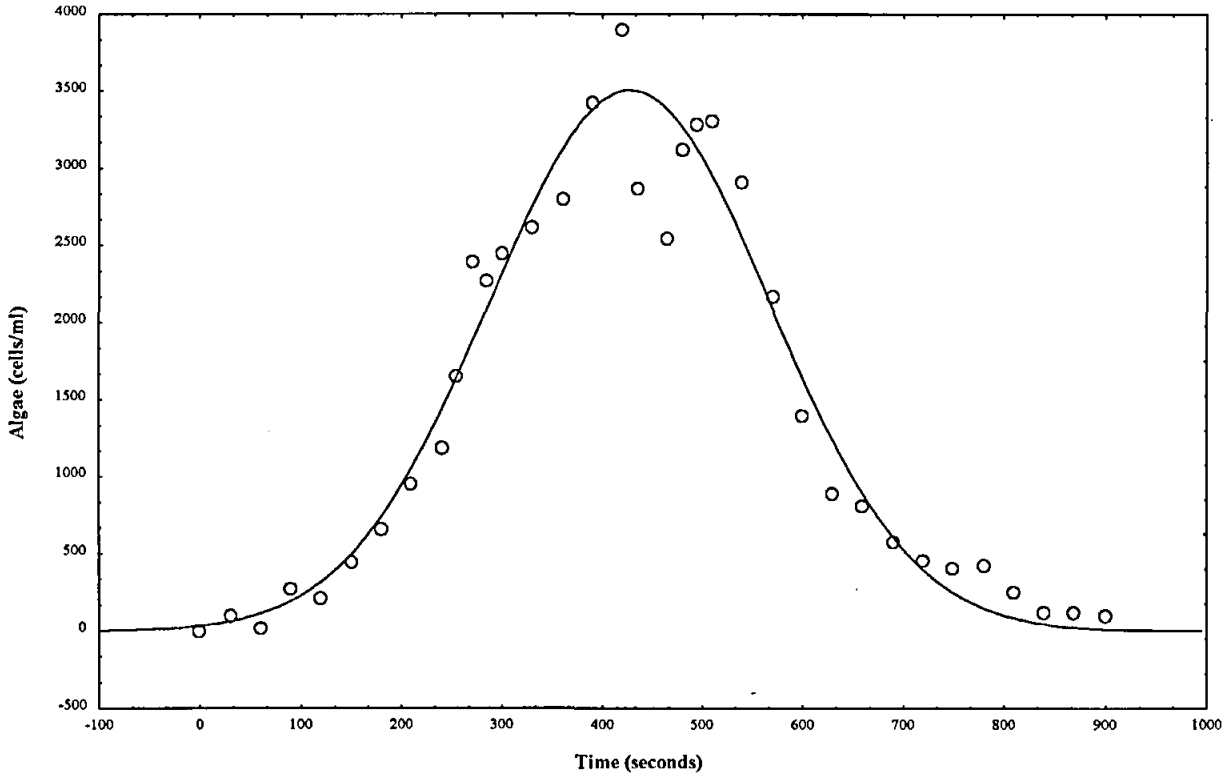

Figure 16: **Recovery of algae from the raw water inflow to Durban Heights WW. Algae data (o) and fitted model (—) from the *in situ* algal rupture trial.**

The curve generally gave a good fit and explained 95% of the variation in the algal data.

The fitted curve for the algal data is:

$$\text{Algae}_i = 3506.2 \exp\{-(\text{Time}_i - 427.3)^2 / (2 \times (140.3)^2)\}$$

Table 9: **Data used to determine the recovery of algae (A_{out}) after passage through the aqueduct.**

Estimates	Algal data
Estimated area under integrated "normal" curve (cells/mℓ s)	82132
Standard error of estimated area (cells/mℓ s)	2412
Aqueduct flow during trial (Mℓ/day)	378.7
Algae passing out of aqueduct (cells) (A_{out})	5.4×10^{12}
Algae dosed into aqueduct (cells) (A_{in})	16.22×10^{12}
Ratio of algae recovered = A_{out}/A_{in}	0.333
Percentage algal recovery	33.3

The calculated approximate 95% confidence limits for algal recovery (A_{out}) are 0.277 and 0.391.
i.e. of the algae dosed into the aqueduct at Nagle Dam only between 27.7 and 39.1% were recovered at Durban Heights WW (i.e. between 60.9 and 72.3% were lost due to rupture).

6.3 Conclusions

It is possible to record with a 95% confidence that during this trial between 27.7% and 39.1% of algae entering the aqueduct system at Nagle Dam emerged at Durban Heights WW. This was significantly lower than the 95.8% of lithium marker that arrived at the WW. The *in situ* trial has therefore provided very strong evidence that a significant number of algae (predominantly *Microcystis* in this case) appear to be destroyed in the process of abstraction from Nagle Dam and passage to Durban Heights WW.

CHAPTER 7

ALGAL RUPTURE DURING ABSTRACTION THROUGH THE INANDA DAM WALL

7.1 Introduction

It was suggested that rupturing of algae may take place during the passage of water through the Inanda Dam wall abstraction tower and valves (Figure 17). In this process water passes through a butterfly valve, falls to the base of the wall, passes through another butterfly valve and then out through a sleeve valve. As the abstraction tower was already functional at the time of this investigation several trials were run to test algal rupture in this section of the Inanda Dam to Wiggins WW system.

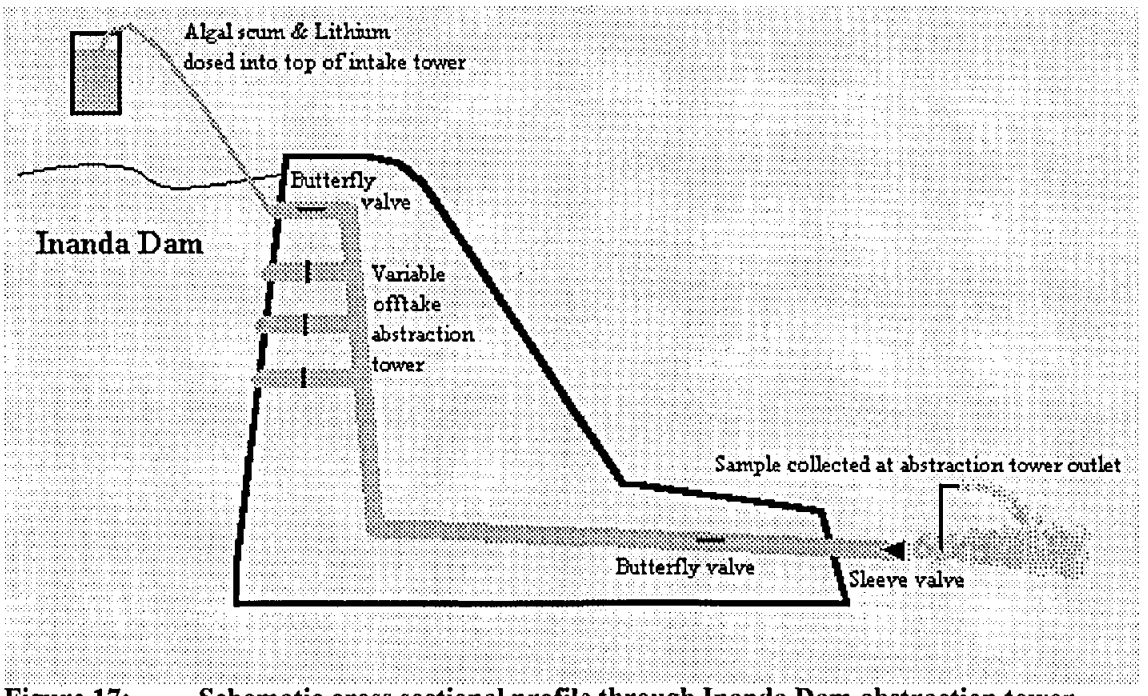

Figure 17: Schematic cross sectional profile through Inanda Dam abstraction tower.

Experimental techniques - see section 3.3

7.2 Results

Results from this aspect of the work are presented in Figure 18. Three trials were run on different days with different algal scums (dominated by *Microcystis*) which were collected on the same day from the upper reaches of Inanda Dam. Within a trial the experiment was repeated several times according to the availability of *Microcystis* scums on the day.

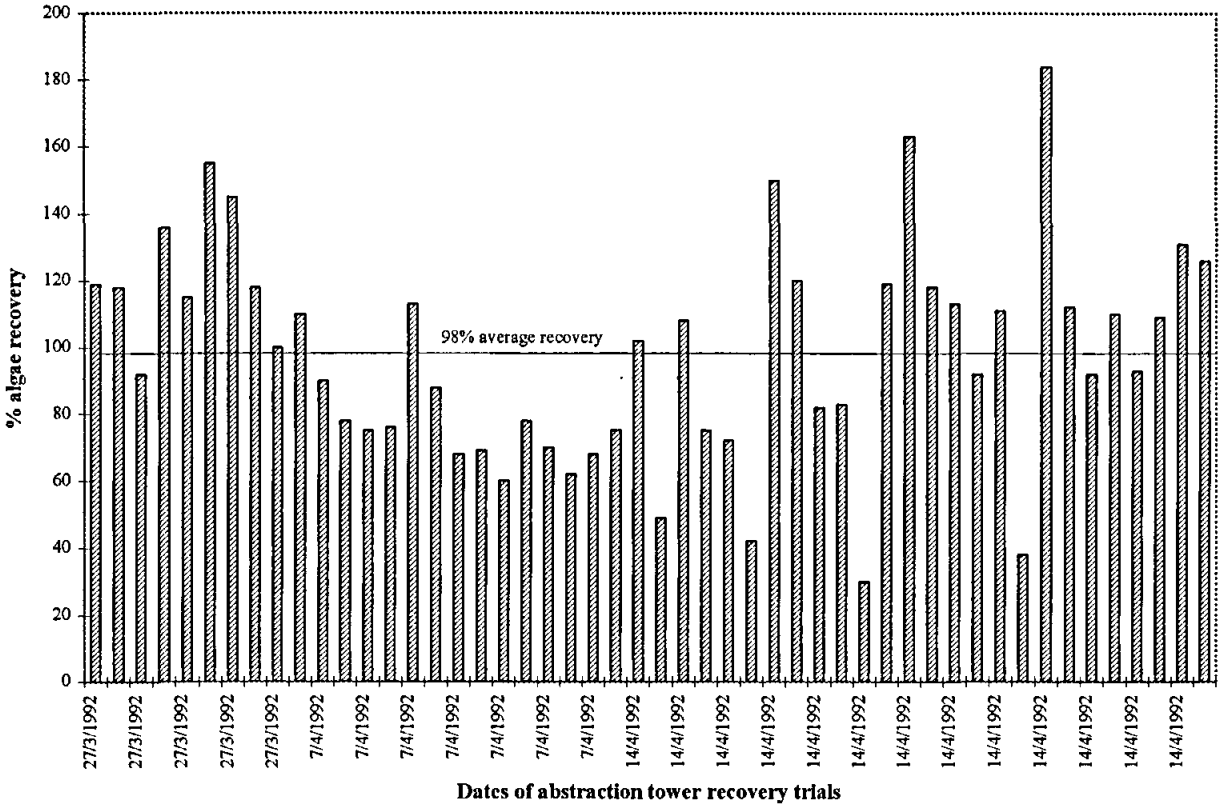

Figure 18: **Percentage algal recovery after passage through the Inanda Dam wall abstraction tower.** (Recovery is related to the recovery of lithium - assumed to be 100%). The line on the graph (98%) indicates the overall average for the three trials.

The last trial run on 14/4/92 was the most rigorous as it had the most refined experimental technique. Results from this last trial produced a mean 100% algal recovery. The overall average for the three trials (98%) indicates an insignificant loss of algae in the Inanda Dam abstraction tower.

7.3 Conclusions

The results indicate an overall insignificant loss of algae after their passage through the Inanda Dam abstraction tower. The variability associated with this technique was relatively high however. It is not known whether this is a real phenomenon, due to the varying nature and physiological state of the algal scums used, or due to experimental technique.

Supporting the conclusion that few algae are ruptured in this section of the aqueduct was the visual appearance of algae after passage through the abstraction tower. *Microcystis* cell specimens appeared unaffected, when examined under the light microscope, having their internal gas vacuoles intact and inflated. In contrast *Microcystis* cells, after *in situ* passage through the Nagle to Durban Heights system, as well as simulation of the Nagle system, had few visible vacuoles (see Chapter 10). Obviously any completely ruptured cells could not be examined due to their absence !

CHAPTER 8

AQUEDUCT SIMULATION AND ALGAL LOSS

8.1 Introduction

Having established that a large proportion of algae are destroyed in the Nagle to Durban Heights system, it appeared appropriate to try to simulate this algal loss on a laboratory scale. If this could be achieved successfully then there would be scope to attempt to simulate the as yet incomplete Inanda to Wiggins system, and to estimate the degree of algal rupture in that system. To that end the following work was undertaken.

The Nagle Dam to Durban Heights WW and Inanda Dam to Wiggins WW aqueduct systems consist of a series of tunnels and siphons the elements of which are often of dissimilar physical dimensions (Tables 1 and 2). Consequently there are changing shear and pressure forces acting on algae entrained in water in these systems. Therefore, to simulate the conditions algae experience, aqueducts for respective systems were separated into elements and the pressure and current velocity (shear) conditions calculated for respective elements. Algal samples were then placed in the simulation apparatus and subjected to the calculated varying regimes of pressure and shear. Algal counts from water treated in this manner were then compared to control samples for each simulation run. This provided a measure of algal rupture experienced in the respective systems.

Experimental techniques - see section 3.4

8.2 Results of simulation runs

After numerous trials in which the various permutations of pressure and shear were examined, as well as the various options used to calculate the rpm values for use in the stirrer, 12 simulations were run for each of the Nagle to Durban Heights WW and Inanda to Wiggins WW systems. Shear and pressure conditions were standardised for respective systems to produce repeatable and comparable simulations. Each mean and standard error is calculated from the five sub-sample disks enumerated for each treatment (control and simulation).

8.2.1 Nagle Dam to Durban Heights WW simulation

Results of simulations for this system are presented graphically in Figure 19.

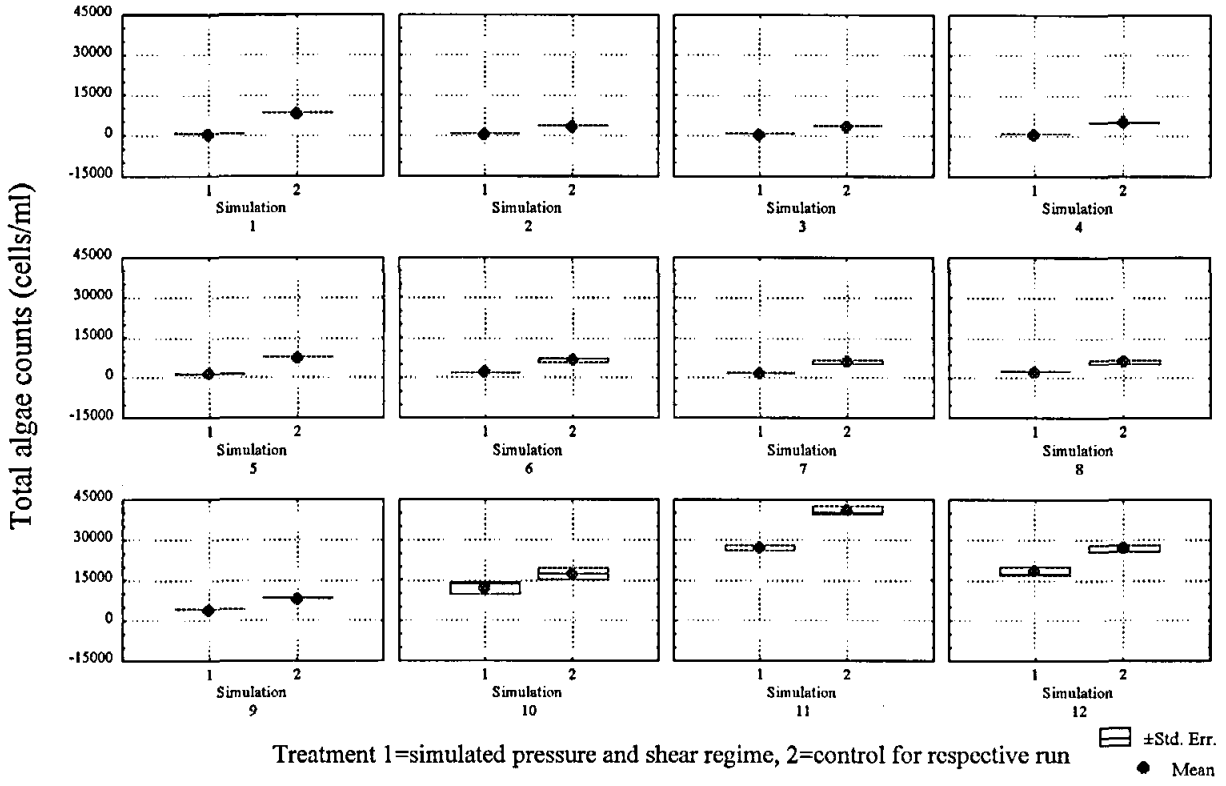

Figure 19: Total algal counts from simulations of the Nagle Dam to Durban Heights WW system.

A least significant difference (LSD) test between control and simulation treated means for each simulation run, showed statistically significant differences between the control and simulation treated samples for all 12 simulations runs i.e. the simulation consistently caused a significant degree of algal loss (Table 10). The variability between algal filter disks (within treatments and simulations), is relatively low (small standard error) compared to the differences between simulation and control treatment effects (Fig. 19).

Table 10: Nagle Dam to Durban Heights WW simulation run results and the significance of the differences between simulation and control treatments. (*Marked differences significant at $P < 0.05$).

Simulation run	Simulation mean (cells/mℓ)	Control mean (cells/mℓ)	Significance of difference between control & simulation mean
1	107	8009	*0.00**
2	294	3037	*0.01**
3	174	2975	*0.01**
4	104	4687	*0.00**
5	1074	7184	*0.00**
6	1648	6509	*0.00**
7	1563	6083	*0.00**
8	2119	6152	*0.00**
9	3800	8031	*0.00**
10	12089	17295	*0.00**
11	27000	41207	*0.00**
12	18455	27032	*0.00**

The loss in algal numbers due to the simulation treatments are presented graphically in Figure 20 as percentage algal loss for each simulation run. The mean percentage total algal loss for all Nagle/Durban Heights simulations is 69%.

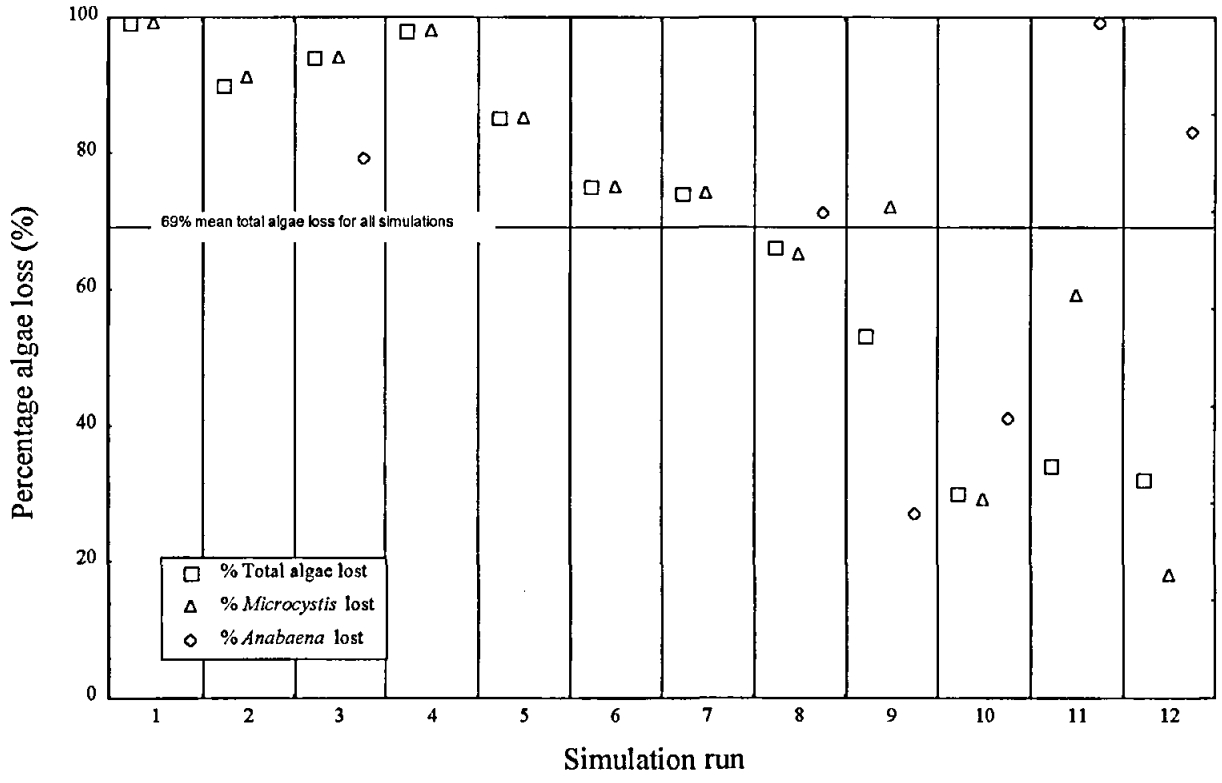

Figure 20: Summary of mean percentage algal loss between control and Nagle Dam to Durban Heights WW simulation treatments.

8.2.2 Inanda Dam to Wiggins WW simulation

Results of simulations for this system are presented graphically in Figure 21.

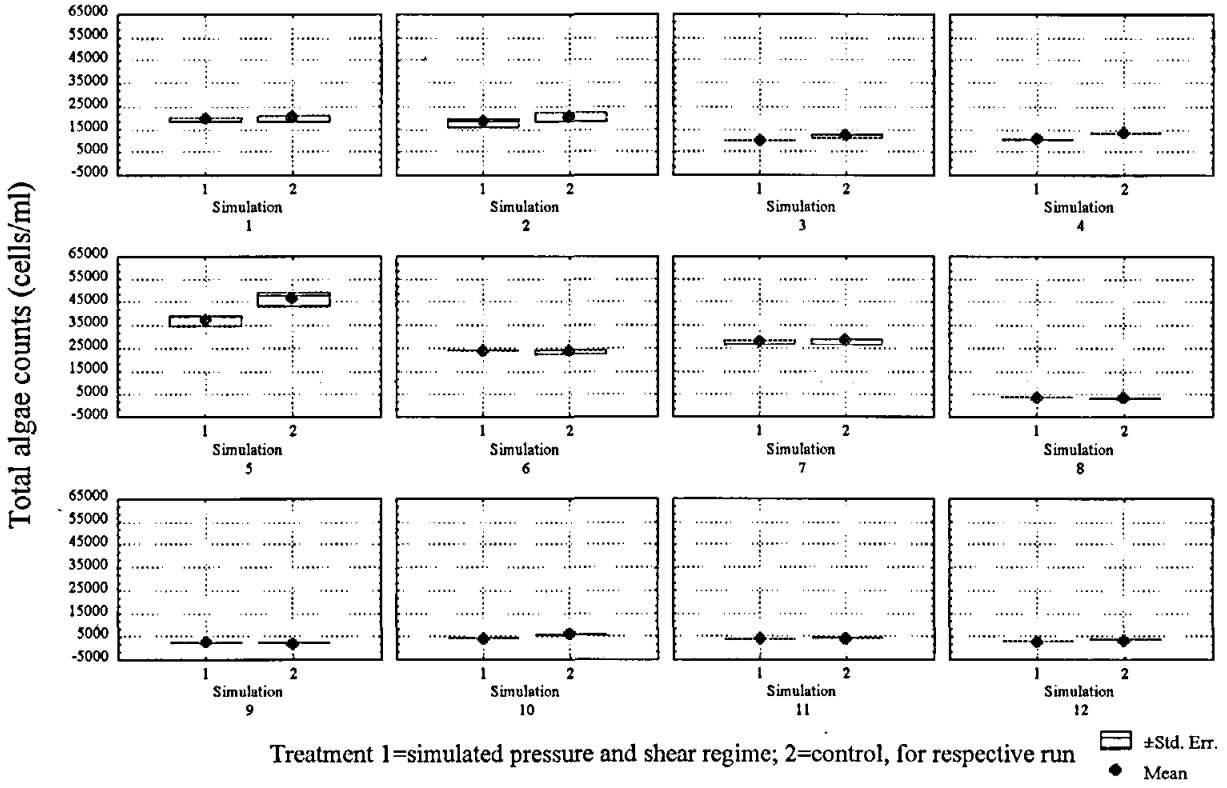

Figure 21: Total algal counts from simulations of the Inanda Dam to Wiggins WW system.

A least significant difference (LSD) test, between control and simulation treated means for each Inanda to Wiggins run showed only two out of 12 simulations where the differences between the control and simulation treated samples were significantly different i.e. where the simulation provided a significant degree of rupturing. Of these two significantly different simulations, one (simulation 4) was only marginally significant ($P < 0.04$) (Table 11).

Table 11: Inanda Dam to Wiggins WW simulation run results and the significance of the differences between control and simulation means. (*Marked differences significant at $P < 0.05$).

Simulation run	Simulation mean (cells/mℓ)	Control mean (cells/mℓ)	Significance of difference between control & simulation mean
1	19693	19863	0.90
2	17890	20505	0.06
3	9773	11961	0.11
4	10424	13247	*0.04**
5	37364	46407	*0.00**
6	23734	23439	0.83
7	27724	28204	0.73
8	2936	3048	0.93
9	2250	2049	0.89
10	4198	5720	0.27
11	3651	4060	0.77
12	2745	3162	0.76

On the whole these results show an insignificant difference between control and simulation treatments for the Inanda to Wiggins WW system i.e. no algal loss due to simulation conditions. The variability between disks in

the simulation treatments (as well as the control treatments) is generally greater than the variability between treatment and control.

8.3 Conclusions

The mean percentage algal loss for total and *Microcystis* counts for all Nagle Dam to Durban Heights WW simulations was 69% and 72% respectively. This is in good agreement with the *in situ* trial on algal loss in the Nagle Dam to Durban Heights WW system (Chapter 6 - *Microcystis* loss there between 60% and 72%) and the analysis of historical algal losses (Chapter 4 - median loss for total algal counts there ≈47%).

Having established that the simulation apparatus provided a reasonable reflection of actual *in situ* algal rupture in the Nagle to Durban Heights system, the Inanda Dam to Wiggins WW system was simulated and found to produce minimal algal rupture as the differences between treated and control algal samples were generally insignificant. Therefore it is unlikely that algae will be ruptured in the Inanda to Wiggins system.

The simulation work provides a model for the simulation of algal rupture in aqueducts carrying water from impoundments to WW. From the work presented here it appears that the phenomenon of algal rupture is only likely to occur in systems passing through steeply undulating terrain where high hydraulic pressures are generated.

CHAPTER 9

MODELLING OF ALGAL RUPTURE DUE TO PRESSURE, SHEAR AND TIME

9.1 Introduction

Having successfully simulated on a laboratory scale algal rupture in the entire Nagle Dam to Durban Heights system (Chapter 8) it seemed appropriate to try and model the response of algal numbers to pressure and shear and establish which of these forces alone or in combination accounted for maximum algal rupture. To do this a mathematical response surface model was developed relating these rupture forces (including duration of force) to algal number.

Experimental techniques - see section 3.5

9.2 Analysis and results

The mean algal count was calculated for each run and also for the control water. This response (mean treated algal count) was then analysed by means of a general linear model to look for pressure, shear and time effects with the mean control adjusted as a covariate according to the source and age of the scum. The response was weighted by the number of samples that comprised the mean (i.e. 3, 4 or 5 samples). Initially a general model investigating pressure, shear and time main effects, as well as the two way interactions was fitted. The results are given in Table 12.

Table 12: Weighted General Linear Model ANOVA: effects of pressure, shear and time.

Source	d.f.	Sum of Squares	Mean square	F-value	Pr>F
Control count	1	278.878	278.878	138.57	0.0001
Scum source	1	19.739	19.739	9.81	0.0040
Scum age	8	31.773	3.972	1.97	0.0878
Pressure	3	104.512	34.837	17.31	0.0001
Shear	3	6.767	2.256	1.12	0.3574
Pressure x Shear	2	0.897	0.448	0.22	0.8016
Time	4	7.102	1.776	0.88	0.4872
Time x Shear	3	3.474	1.158	0.58	0.6360
Time x Pressure	2	0.838	0.419	0.21	0.8133
Residual	28	56.350	2.012		
Total	55	510.329			

In the order fitted there was overwhelming evidence of a pressure effect but no evidence of a shear or time effect nor of any interaction between the three factors. Since the design is non orthogonal, a second analysis of variance was carried out, omitting all interactions, fitting shear before pressure, and partitioning each main effect into linear, quadratic and lack of fit components. The results are given in Table 13.

Table 13: Weighted General Linear Model ANOVA: linear, quadratic and lack of fit components of main effects (pressure, shear and time)

Source	d.f.	Sum of Squares ($\times 10^6$)	Mean square ($\times 10^6$)	F-value	Pr>F
Control count	1	278.878	278.878	151.71	0.0001
Scum source	1	19.739	19.739	10.74	0.0025
Scum age	8	3.972	3.972	2.16	0.0574
Shear					
Linear	1	4.076	4.076	2.22	0.1460
Quadratic	1	13.595	13.595	7.40	0.0103
Deviations	1	1.129	1.129	0.61	0.4389
Pressure					
Linear	1	67.594	67.594	36.77	0.0001
Quadratic	1	19.895	19.895	10.82	0.0024
Deviations	1	4.991	4.991	2.71	0.1089
Time					
Linear	1	0.133	0.133	0.07	0.7895
Quadratic	1	1.345	1.345	0.73	0.3985
Deviations	4	6.521	1.630	0.89	0.4826
Residual	33	60.662	1.838		
Total	55	510.329			

As we are primarily interested in the effects of pressure and shear, these are the two effects fitted first.

From Table 13 we see that:

(a) There is some evidence of a quadratic shear effect, and no evidence of any deviation from a quadratic.

(b) There is overwhelming evidence of both a linear and quadratic pressure effect and no evidence of any deviation from a quadratic.

(c) After fitting shear and pressure there is no evidence of any time effect.

Thus we can investigate a full quadratic response surface for shear and pressure and then see the effects of:

(i) omitting the shear x pressure cross product term, and

(ii) including or excluding linear and quadratic time effects.

This suggests that we consider our maximal model with terms in P, P^2, S, S^2, PS, T and T^2.

The analysis of variance for this model (again weighted according to the number of samples) is given in Table 14

Table 14: Weighted General Linear Model ANOVA: Maximal Response Surface

Source	d.f.	Sum of Squares ($\times 10^6$)	Mean square ($\times 10^6$)	F-value	Pr>F
Control count	1	278.878	278.878	155.83	0.0001
Scum source	1	19.739	19.739	11.03	0.0020
Scum age	8	31.773	3.972	2.22	0.0475
P	1	77.314	77.314	43.20	0.0001
P^2	1	24.691	24.691	13.80	0.0007
S	1	2.055	2.055	1.15	0.2906
S^2	1	2.197	2.197	1.23	0.2748
PS	1	0.390	0.390	0.22	0.6431
T	1	3.161	3.161	1.77	0.1918
T^2	1	2.127	2.127	1.19	0.2825
Residual	38	68.004	1.790		
Total	55	510.329			

Note that from Table 14 we can see that:

(i) the cross product term PS could easily be left out of the model, since there is no evidence of statistical significance;

(ii) although the terms T and T^2 are not statistically significant, they do have F values larger than 1 and hence do reduce the residual mean square and enable us to estimate the effects of the terms in P and S more precisely, and hence could be left in the model.

To investigate this further the coefficients of the terms in P, P^2,S, S^2, PS, T, and T^2 (where relevant) on fitting a range of models, using both the weighted general linear model, and a mixed model utilising sample level data (fitted using Residual Maximum Likelihood) are given in Tables 15 and 16.

Table 15: Response surface parameters (coefficients of terms) (and SE's) from Weighted General Linear Model

Para-meter	Maximal model		PS omitted		PS and T^2 omitted		T and T^2 omitted		PS, T and T^2 omitted	
P	-2.384	(0.588)	-1.842	(0.367)	-1.943	(0.360)	-1.992	(0.412)	-1.888	(0.342)
P^2	0.00109	(0.000356)	0.000812	(0.00027)	0.000884	(0.00026)	0.000918	(0.00029)	0.000862	(0.00026)
S	-4.825	(2.901)	-2.218	(1.875)	-2.734	(1.838)	-2.900	(2.025)	-2.427	(1.729)
S^2	0.0109	(0.0074)	0.00524	(0.00567)	0.00663	(0.0056)	0.00699	(0.0059)	0.00597	(0.0054)
PS	0.00188	(0.0016)					0.000494	(0.0011)		
T	-12.536	(7.415)	-9.107	(6.849)	-1.711	(3.322)				
T^2	0.0759	(0.0696)	0.0849	(0.0695)						
P_{opt}	975.23		1134.24		1098.98		1039.03		1095.13	
S_{opt}	137.277		211.64		206.18		170.72		203.266	
T_{opt}	82.58		53.63							

Table 16: Response surface parameters (coefficients of terms) (and SE's) from Mixed Model fitted using residual maximum likelihood

Para-meter	Maximal model		PS omitted		PS and T^2 omitted		T and T^2 omitted		PS, T and T^2 omitted	
P	-2.137	(0.565)	-1.738	(0.361)	-1.870	(0.405)	-2.070	(0.405)	-1.887	(0.334)
P^2	0.0010	(0.00034)	0.0008	(0.00027)	0.0009	(0.00026)	0.0010	(0.00028)	0.0009	(0.00062)
S	-3.398	(2.715)	-1.540	(1.819)	-2.09	(1.79)	-2.987	(1.964)	-2.183	(1.689)
S^2	0.0087	(0.0070)	0.0047	(0.0056)	0.0062	(0.0055)	0.0081	(0.0057)	0.0064	(0.0053)
PS	0.0014	(0.0016)					0.0009	(0.0011)		
T	-10.91	(7.739)	-8.286	(7.208)	0.525	(3.0)				
T^2	0.0866	(0.0670)	0.091	(0.068)						
P_{opt}	987.41		1086.25		1038.89		976.44		1048.33	
S_{opt}	115.847		163.83		168.55		130.14		170.55	
T_{opt}	62.99		45.53							

Clearly there is a fair amount of agreement in the estimated optimum values of P and S, found from the parameter estimates, both between the various models and between the results from the Weighted General Linear Model and the results from the Mixed Model.

For both the Weighted General Linear Model and the Mixed Model, the maximal model leads to substantially higher standard errors for all parameter estimates. It is a well known result in Multiple Regression that this indicates too many parameters in the model. Hence it is best to choose one of the other models. Since the main aim was to investigate the response to pressure and shear, this suggests the full quadratic response surface for P and S, i.e. the model with T and T^2 omitted. The results for the Mixed Model, which more exactly

reflects the experimental situation, are more reliable than those of the Weighted General Linear Model since samples in this model are nested within runs. This suggest that the values of P and S which minimise the total algae count are respectively:

P = 976 kPa

and S = 130 rpm

i.e. the values of pressure and shear (reflecting water velocity) which minimise the algal count (and thus lead to maximum rupture) are 1326 kPa and 205 rpm respectively (once the correction is taken into account for the original transformation of these parameters).

The fitted response surface is

$$y = Const - 2.070P + 0.0010P^2 - 2.987S + 0.0081S^2 + 0.0009P$$

where the constant (Const) is an overall measure of the background algae (approximately 4000 cells/mℓ).

It is worth noting that both of the values for pressure and shear which minimise the total algal count are within the experimental range considered in the simulation work. The fact that slightly different models yield different values suggests that the true response surface is "flat" in the vicinity of the optimum i.e. varying the pressure and shear by small amounts in the vicinity of the optimum (maximum rupture) will have very little effect on the algal count. It is also worth noting that the time for which the shear and pressure are applied seems to have very little effect on the algal count. These results are confirmed by looking at the mean algal counts from the weighted model with pressure, shear and time effects, adjusted for control count, scum source and scum age, given in Table 17.

Table 17: Mean algal count from Weighted General Linear Model, broken down by Pressure, Shear and Time (adjusted for control count, scum source and scum age)

Variable	Level	Adjusted mean algal count
Pressure (kPa)	0	4382
	350	4318
	1400	2963
	2200	3561
Shear (rpm)	0	4228
	75	3664
	350	3740
	500	3592
Time (minutes)	10	3962
	20	4013
	30	3632
	40	3415
	45	3539
	120	4228
	180	3852

9.3 Conclusions

The combined values of pressure and stirrer velocity that lead to maximum rupture of *Microcystis* algae are in the vicinity of 1326 kPa and 205 rpm respectively (or velocity in the aqueduct of ≈ 1.6 ms^{-1}, from equation 1 (section 3.4.1)). This value of pressure is very close to the estimated mean pressure in the Nagle Dam system and hence supports the evidence (Chapters 4, 6 and 8) of relatively high algal rupture in this system.

The experiment has established that the amount of algal rupture, as measured by the algal count in samples of treated water, may be described by a quadratic response surface in pressure and shear, with pressure having a stronger effect on the algal count than shear. The time for which the shear and pressure were applied has very little effect which suggests that rupture takes place during the initial period of application of shear and pressure forces.

CHAPTER 10

VISUAL APPEARANCE OF ALGAL CELLS TREATED TO SIMULATED AQUEDUCT CONDITIONS

10.1 Introduction

In order to try and observe the visual physical effects of pressure and shear on algal cells, light microscopy, transmission (TEM) and scanning electron microscopy (SEM) were used.

Experimental techniques - see section 3.6

10.2 Results

Light microscopy showed cells of *Microcystis* that appeared significantly different from control cells. This appears to be due mainly to the disappearance or deflation of gas vacuoles as cells which have intact and turgid vacuoles show strong light scattering (Walsby 1970). Pressure and shear treated cells from this trial (as well as *in situ* treated algal cells) showed poor light scattering by comparison with control and untreated algal cells.

Transmission electron microscopy (TEM) clearly demonstrated that the gas vacuoles had collapsed. Scanning electron microscopy was less clear although some pressure treated cells were found with a deflated appearance. There was a fundamental flaw in this exercise however, namely that the examination was of cells that *survived* pressure treatment. Few fragments of ruptured cells were found. Visual results could therefore have been an artefact of preparation, particularly in the TEM examination, as the technique used required repeated washing of the sample with solvents which could have removed the fragments of ruptured cells. A technique adapted from Barlow (1978) of embedding sample in agar and then sectioning for TEM also failed to provide clear indications of differences between ruptured and untreated samples at the sub-cellular level.

10.3 Conclusions

Light and electron microscopy showed algal cells (which had been subject to pressure and shear) with a deflated appearance although no sub-cellular fragments were ever positively identified as coming from ruptured algal cells. It was felt however that limitations with technique prevented these fragments from being identified. The deflated appearance of pressure treated cells confirmed the work of other authors (e.g. Walsby 1970) in showing the effects of pressure on gas vacuolate algal cells.

CHAPTER 11

CONSEQUENCES OF ALGAL RUPTURE FOR WATER TREATMENT

11.1 Introduction

The consequences of algal rupture as they affect water treatment were examined from an historical, *in situ* and "projected" algal rupture point of view. Obviously there are numerous permutations of types of raw matrix water and accompanying algae which needed to be standardised to gain some measure of the effects of algal rupture on treatment processes. Therefore, for the laboratory work "clean" Inanda Dam water was used which was "spiked" with the appropriate concentrations of ruptured and unruptured *Microcystis* algal cells.

Experimental techniques - see section 3.7

11.2 Effects of historical algal rupture on water treatment for the Nagle to Durban Heights WW system

Associated with historical algal blooms in Nagle Dam there was a corresponding increase in treatment costs at Durban Heights WW. This was out of proportion to the number of algae entering the WW and could only be anticipated by monitoring algal numbers in the Dam.

The historical consequences of this algal rupture on water treatment for a period in the late 1980's is shown very clearly in Figure 22. When algal counts in the dam were relatively low the major costs incurred by the WW in treating incoming water were for coagulant. However, when algal numbers increased significantly, treatment costs reflected this by the necessary addition of powdered activated carbon to remove taste and odour compounds.

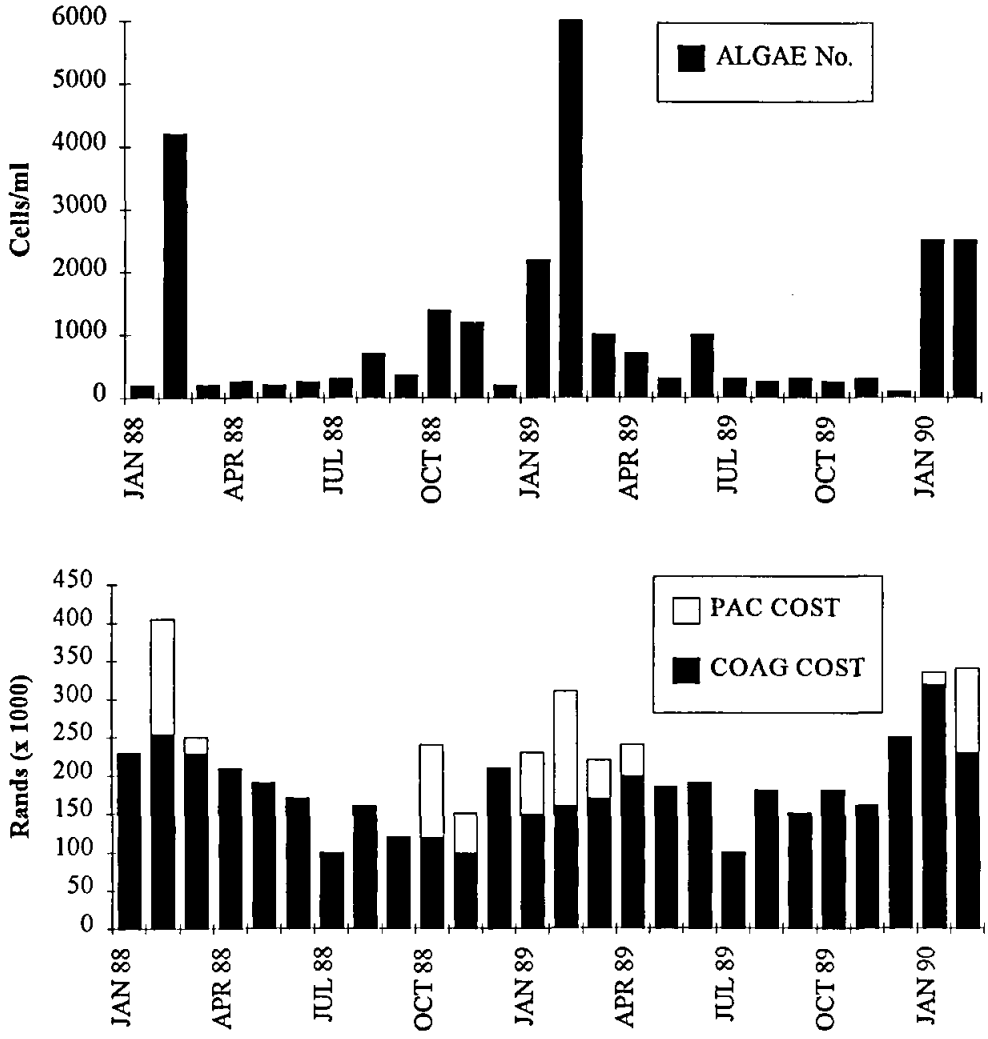

Figure 22: **Treatment cost of water at Durban Heights Waterworks as related to the mean number of algae in both abstractions at Nagle Dam.**
(Costs refer to powdered activated carbon (PAC) and coagulant).

During this period the inclusion of activated carbon (PAC) in the treatment process at Durban Heights WW incurred costs in excess of R100 000/month to cope with geosmin produced by between 4000-6000 cells/mℓ of *Microcystis* of which some 67% were being ruptured (Fig. 25). These were obviously particularly "taste and odour productive" scums as algal scums collected during the course of this investigation contained little geosmin although cell concentrations were orders of magnitude higher.

Again in early 1994 a severe bloom of *Anabaena* in Nagle Dam, with geosmin concentrations of up to 1970 ng/ℓ, necessitated dosing PAC at up to 15 mg/ℓ to remove the taste and odours produced by up to 30 000 cells/mℓ of *Anabaena*. These figures were the extremes experienced for this period but on an average dosage of 10mg/ℓ PAC, over the two month incident, costs for PAC alone were in the region of R950 000. If one included laboratory tests and personnel costs for this incident then the real costs would probably be in the region of R1 million. It is likely that the problem is being exacerbated by the rupture of a high percentage of

the *Anabaena* cells and it is predicted that treatment costs would be much lower if cell rupture did not occur. This was obviously a particularly "productive" taste and odour scum as algae collected during other phases of this investigation contained little geosmin although algal numbers were orders of magnitude higher.

Magara and Kunikane (1986) have also shown that where advanced water treatment processes (ozonation and activated carbon adsorption) have to be employed to remove taste and odours, the costs of treating that raw water increase dramatically over conventional processes (coagulation/sedimentation or coagulation/flocculation).

11.3 Coagulant demand of Durban Heights raw water

As part of the *in situ* trial, where algal scums were dosed into the aqueduct at Nagle Dam and water sampled at Durban Heights WW, samples were also collected for water treatment studies. Three different raw water samples were taken at Durban Heights WW, before, during and after the arrival of the peak of *Microcystis* from algae inserted into the aqueduct at Nagle Dam.

At the time of this investigation, a blended polyamine-polyaluminium chloride (PA-PACℓ) coagulant (from Cyanamid) was being used for coagulation and flocculation of the raw water at Durban Heights WW. The streaming current detectors were dosing this coagulant at a rate of 3,1ppm, while pH correction with white lime to 8,1 was also being carried out. The results which appear in Table 18 indicate that the presence of algae resulted in a 13,5% increase in the coagulant demand. The turbidity and pH of all three samples was the same.

Table 18: Coagulant demand (required to reduce the turbidity of the final water to <0,5NTU) of water collected from the Durban Heights inflow before, during and after a peak of dosed *Microcystis*

	Before	Peak	After
PA-PACℓ (mg/ℓ)	2,2	2,5	2,2

The number of algae present in the peak samples was ±4000 cells/mℓ. As these were the remaining cells after 67% of the cells had been ruptured, it can be calculated that the number of algae in the inflow would have been ±12 000 cells/mℓ.

Further laboratory scale investigation into the treatability of raw water containing ruptured algae was then undertaken.

11.4 Treatability test results

Methods employed in these treatability tests are detailed in section 3.6.

11.4.1 Coagulant demand

It was clearly shown that the rupture of algal cells in raw water has a significant effect on treatment. The coagulant demand to achieve filtered turbidities of <0,5 NTU (Nephelometric Turbidity Units) in samples of "clean" Inanda Dam water, spiked with different amounts of either ruptured (by three freeze-thaw cycles) or unruptured algae, increased, particularly at higher cell numbers when the *Microcystis* was ruptured (Table 19). A similar trend was observed when using different coagulants, namely a commercial blend of polyamine and polyaluminium chloride (PA-PACℓ), unblended polyaluminium chloride (PACℓ), ferric chloride or alum. The PA-PACℓ coagulant was used as an example in Figure 23 to illustrate the results obtained in Table 19.

Table 19: Coagulant Demand (± standard error of the mean) of Inanda Dam water spiked with varying concentrations of unruptured or ruptured *Microcystis* cells.

Coagulant (mg/ℓ)	Unspiked	Unruptured *Microcystis* (x 1000 cells/mℓ)			Ruptured *Microcystis* (x 1000 cells/mℓ)		
		10	100	1 000	10	100	1 000
PA-PACℓ	1.28	1.54	1.82	4.14	1.54	2.65	11.0
	±0.37	±0.26	±0.47	±1.30	±0.38	±0.74	±6.42
$FeC\ell_3$	3.40	3.17	5.00	9.67	4.17	10.67	27.00
	±1.61	±1.18	±1.22	±1.30	±1.43	±3.09	±1.41
Alum	6.50	6.50	6.50	9.50	8.00	12.50	39.00
	±0.50	±0.50	±0.50	±1.50		±0.50	±4.00
PACℓ	5.50	5.00	6.00	9.00	5.50	>10	>30.00

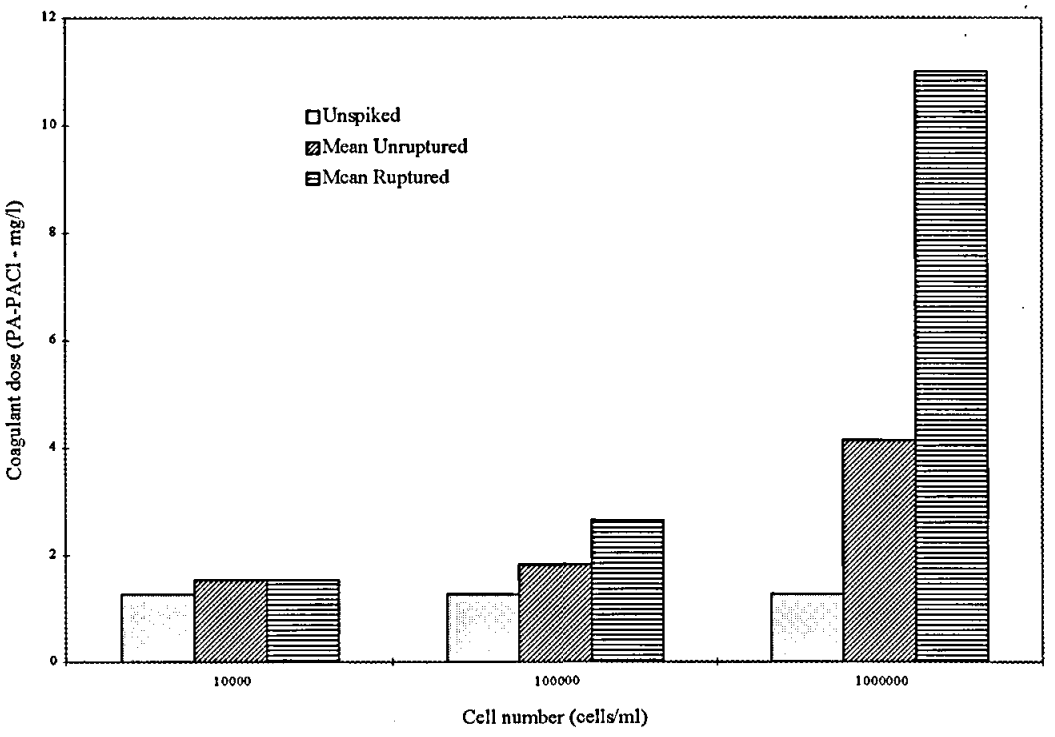

Figure 23: PA-PACℓ coagulant demand of Inanda Dam water spiked with varying concentrations of unruptured or ruptured *Microcystis* cells.

The increase in coagulant demand due to the algae being ruptured at 10 000 cells/mℓ was negligible, but at 100 000 cells/mℓ was from 1,2 to 2,4 times greater. At 1 000 000 cells/mℓ the increase in demand was more significant and ranged from 1,6 to 7,1 times. Ferric chloride and alum produced the best flocs and were the most cost effective. The PA-PACℓ and the polyaluminium chloride (PACℓ) coagulants tended to form very small light flocs which settled poorly, except at high algal cell and coagulant concentrations. Even in those cases in which larger flocs were obtained, they were generally light with fairly poor settling characteristics. Ferric chloride and alum yielded larger flocs than the polymeric coagulants and although these inorganic flocs generally settled better than the polymeric flocs, they too were found to settle slowly. The floc characteristics obtained with ferric chloride appeared to be slightly better than those obtained with alum. The use of dissolved air flotation (DAF) techniques produced final filtered water of slightly higher turbidity than did settling techniques although the pre-filtered water was of a better standard. It is possible that DAF destabilised the floc and caused its disintegration.

11.4.2 Chlorine demand

The pre-chlorination demand of untreated samples followed a similar trend irrespective of whether they contained ruptured or unruptured algae. This was expected as chlorine breaks up intact cells (Ando *et al.*, 1992). Where samples were first treated with coagulant sufficient to obtain a turbidity of <0,5 NTU and then filtered, there was a significant increase in the chlorine demand of filtrate from ruptured over unruptured samples, particularly when algal numbers were 1 million cells/mℓ.

Table 20: Chlorine demand, dissolved organic carbon (DOC) content and turbidity (± standard error) of filtrates containing different numbers of either unruptured or ruptured *Microcystis* cells.

	Unruptured *Microcystis* (cells/mℓ)			Ruptured *Microcystis* (cells/mℓ)		
	10 000	100 000	1 000 000	10 000	100 000	1 000 000
Cl_2 demand	2.84	2.19	3.46	2.40	3.40	8.13
(mg/ℓ Cl_2)	±1.17	±0.96	±2.15	±1.31	±1.35	±2.89
DOC	2.63	2.38	3.11	2.67	3.05	5.75
(mgC/ℓ)	±1.24	±1.15	±1.46	±1.30	±1.09	±2.17
Turbidity	0.74	0.78	1.27	0.63	0.93	3.70
(NTU)	±0.37	±0.51	±0.79	±0.26	±0.31	±2.14

11.4.3 Trihalomethane formation potential

Trihalomethane formation potential (THMFP) tests were performed on the samples that were used for the analyses shown in Table 20 but the results were highly variable and apparently meaningless. These results may have been due to technical difficulties experienced in their analysis. The results obtained were surprising as a definite trend was anticipated due to the results presented by Van Steenderen *et al.* (1988) who showed a dramatic increase in organohalogen formation after the lysis of *Microcystis* cells in culture.

11.4.4 Geosmin analysis

The survey by Wnorowski (1992), of South African surface waters having taste and odour problems, showed *Microcystis* to be the dominant organism in 90% of all cases, with geosmin the dominant taste and odour substance. It had been shown that geosmin concentrations as low as 10 ng/ℓ produced an odour that needed to

be removed (Krasner, *et al.*, 1983). The primary taste and odour producing substance identified in samples in this study was geosmin.

From operational data at Durban Heights, the most significant impact of algal blooms was the liberation of taste and odour compounds into the water which then required the addition of activated carbon for their removal (Fig. 22). Numerous trials were carried out where "clean" Inanda Dam water was spiked with different amounts of either ruptured or unruptured *Microcystis*. The water was filtered and the geosmin concentration determined (Table 21 and Fig. 24). It was clearly shown that there was a substantial liberation of geosmin from within cells during rupture. It is well known that geosmin occurs naturally both within and on the outside of the cells (Utkilen and Froshaug, 1992). Unfortunately at the time of this trial, concentrated *Microcystis* scums obtained from Inanda Dam contained only low concentrations of geosmin, so that at times even 1 million cells/mℓ produced insufficient geosmin to be quantified. This was unexpected as the literature indicates that there may be a positive correlation between chlorophyll *a* and geosmin concentration (Bowmer *et al.*, 1992). On other occasions geosmin concentrations in both Nagle and Inanda Dams have been found by the authors, (unpublished results) and by Wnorowski and Scott (1992), to be orders of magnitude higher than were present during this trial.

Table 21: Geosmin concentration (in ng/ℓ) in the filtrate of Inanda Dam water after spiking with increasing numbers of either ruptured or unruptured *Microcystis* cells.

Date	Unruptured *Microcystis* (cells/mℓ)			Ruptured *Microcystis* (cells/mℓ)		
1992	10 000	100 000	1 000 000	10 000	100 000	1 000 000
27/5	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0
9/6	<5.0	<5.0	<5.0	7.0	78.0	365
15/6	<5.0	<5.0	<5.0	<5.0	6.0	57.0
22/6	<5.0	<5.0	<5.0	<5.0	5.0	35.0
29/6	1.5	2.6	15.1	1.4	8.6	84.3
6/7	1.0	8.0	18.0	2.0	---	34.0
13/7	1.0	3.0	12.0	1.0	8.0	38.0
3/8	<5.0	5.0	23.0	15.0	63.0	130.0
10/8	<5.0	<5.0	15.0	5.0	11.0	13.0
24/8	<5.0	<5.0	5.0	<5.0	12.0	85.0
3/9	9.0	9.0	7.0	6.0	11.0	45.0
Mean	1.1	2.5	8.6	3.4	20.3	80.6

The <5.0ng/ℓ values in Table 21 were those results where geosmin was below the detection limit for the techniques available at Umgeni Water at the time of these analyses. For the purposes of this table and the calculation of the means <5.0ng/ℓ geosmin results were taken as 0ng/ℓ.

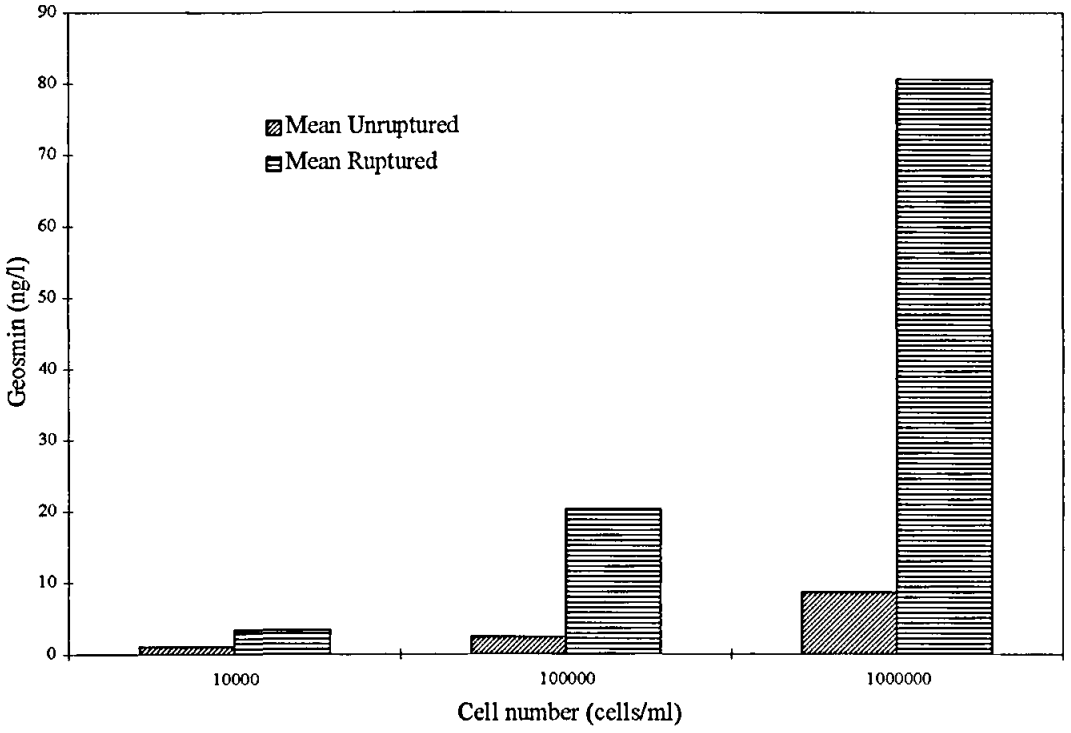

Figure 24: **Mean geosmin concentration in filtered water after removal of different numbers of either intact or ruptured *Microcystis* cells.**

11.5 Treatment Cost Implications

A cost assessment exercise was carried out using the coagulant demand data obtained using the PA-PACℓ coagulant, ferric chloride and alum. This study compared the coagulant demand of samples spiked with unruptured algal cells with that of samples spiked with completely ruptured cells. Complete rupture was assumed in three freeze thaw cycles but on later examination percentage rupture was found to be variable. Results are nevertheless recorded as for 100% and are thus likely to be conservative. The 67% rupture was calculated to represent the situation in the Nagle Dam - Durban Heights system, while the 30% rupture was calculated to gauge the effect from a system that is less vigorous. Pressures and shear forces in the Inanda - Wiggins System are considerably less than the Nagle system and simulation work (section 8.2.2) showed there to be negligible algal loss in this former system.

Ferric chloride and alum were generally, although not always, more cost effective than the organic polymeric coagulant (Table 22), but they also resulted in higher sludge production. Coagulant costs were shown to increase significantly with the percentage rupture in the water so that in many cases a 100% rupture resulted in double the expenditure. In the Nagle Dam situation the percentage rupture is between 61% - 72% and algal numbers are generally in the region of 10 000 cells/mℓ. The increase in cost resulting from cells being ruptured would thus be in the region of 4% for PA-PACℓ, 21% with $FeC\ell_3$ and 15% with alum. $FeC\ell_3$ was nevertheless the most cost effective (Table 22) but would generate 315 tons more sludge per annum than PA-PACℓ. The relative cost increases due to algal cell rupture becomes very much greater at higher cell numbers.

As a result of the 67% rupture of 100 000 cells/mℓ, costs increased by 35% (PA-PACℓ), 85% ($FeC\ell_3$) and 61% (alum). This varying efficiency reduced the price differences between the different coagulants although sludge generation made the latter two more costly.

Table 22: **Annual coagulant costs for a water treatment plant treating 350 Mℓ/day** (127 750Mℓ/annum) based on optimum coagulant dose data obtained using Inanda Dam water samples spiked with both unruptured and completely ruptured algal cells. (Costs for samples containing 30% and 67% ruptured cells were calculated by extrapolation of the experimental data.)

Algal Spike	Percent Rupture	PA-PACℓ Dose	PA-PACℓ Cost	PA-PACℓ Mass	$FeC\ell_3$ Dose	$FeC\ell_3$ Cost	$FeC\ell_3$ Mass	Alum Dose	Alum Cost	Alum Mass
Cells/mℓ	%	mg/ℓ	R/annum	Tons	mg/ℓ	R/annum	Tons	mg/ℓ	R/annum	Tons
None	0	1.43	607 392	182.7	3.4	504 715	434.4	6.5	682 568	830.4
10 000	0	1.63	692 342	208.2	3.2	475 026	408.8	6.5	682 568	830.4
	30	1.66	705 084	212.1	3.5	519 559	447.1	7.0	729 823	887.9
	67	1.70	720 800	216.8	3.9	574 484	494.4	7.5	788 104	958.8
	100	1.73	734 817	221.0	4.2	623 471	536.6	8.0	840 084	1022.0
100 000	0	1.95	828 261	249.1	4.7	697 694	600.4	6.5	682 568	830.4
	30	2.27	964 182	290.0	6.5	964 896	830.4	8.3	871 587	1 060.0
	67	2.65	1 125 586	338.5	8.7	1 294 445	1 114.0	10.5	1 104 710	1 344.0
	100	3.00	1 274 249	383.3	10.7	1 588 367	1 367.0	12.5	1 312 631	1 597.0
1 million	0	4.28	1 817 928	546.8	9.7	1 439 921	1 239.0	9.5	997 600	1 214.0
	30	7.12	3 024 217	909.6	15.0	2 223 714	1 914.0	19.6	2 052 955	2 498.0
	67	10.62	4 510 841	1 357.0	21.4	3 176 734	1 506.0	31.9	3 354 560	4 081.0
	100	13.80	5 861 544	1 757.0	27.3	4 051 562	3 488.0	43.0	4 515 452	5 493.0

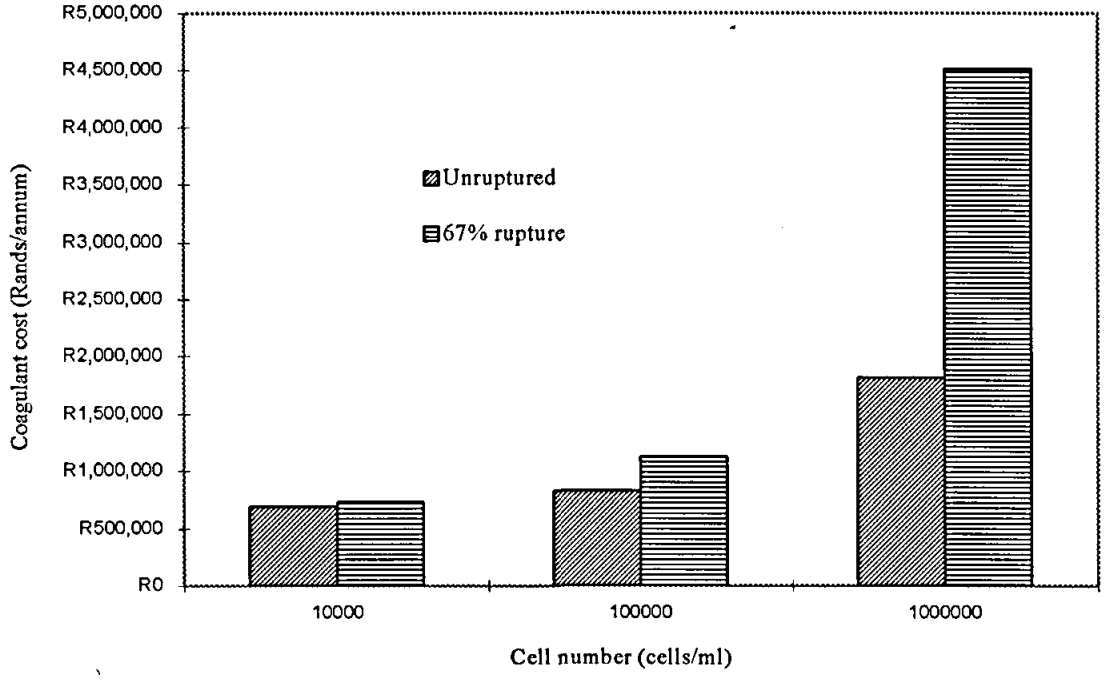

Figure 25: **Graphical representation of the effect of 67% rupture of *Microcystis* cells, at different cell numbers, on coagulant cost using PA-PACℓ.** (Based on a hypothetical Works treating 350 Mℓ/day).

CHAPTER 12

SUMMARY OF RESEARCH WORK AND DESIGN CONSIDERATIONS

The results and interpretation of the historical algal rupture data clearly showed that there was a significant reduction in algal number between Nagle Dam and Durban Heights WW. This trend appeared to be most marked for the vacuolate blue-green algal genera. Water quality determinands which are routinely monitored along with algal number, and which intuitively would be expected to reflect algal rupture, failed to give notice of this phenomenon. It was only when blue-green algae were dominant in the dam that algal rupture could be expected to take place.

In situ examination of algae in the Nagle to Durban Heights WW system also showed a significant loss of algae. This was of the same order of magnitude as that observed from the historical losses. Laboratory simulation of this system was also in good agreement with trends observed in both the historical data and *in situ* work. All of this evidence provided a sound case supporting the observation of algal rupture between Nagle Dam and Durban Heights WW.

From the successful simulation of algal rupture in the Nagle Dam to Durban Heights WW system it was possible to simulate potential algal rupture in the as yet incomplete Inanda Dam to Wiggins WW system. Results from this work indicate that there is likely to be little to no loss of blue-green algae (particularly *Microcystis*) there.

A mathematical response surface model was developed on results obtained from laboratory simulations to determine the pressure and water velocity conditions producing the greatest degree of algal rupture. These conditions were found to be of the order of 1320 kPa and 1.6 ms^{-1} respectively. These values are very close to the estimated mean pressure and velocity in the Nagle Dam to Durban Heights WW system although much greater than the Inanda Dam to Wiggins WW system. This supports the other simulation trial results which showed greatest losses in this former system and a negligible loss in the latter. The model also indicates that, of the factors potentially responsible for algal rupture, pressure is the most significant. Velocity (as shear) is less significant with duration of either pressure or shear insignificant with respect to algal rupture. The indication from this is that rupture probably takes place either during the application or withdrawal of these rupture forces and is insensitive to the duration of exposure. Repeated cycles through siphons are likely to result in further algal losses.

In an effort to find visual support for this algal rupture an examination of the appearance of the cells, using light and electron microscopy (EM), was undertaken. Unfortunately this failed to provide conclusive evidence for this phenomena. There was, however, evidence here to support previous work (Walsby 1970) showing the collapse of gas vacuoles in blue-green *Microcystis* algae. It was proposed that limitations with the EM technique prevented the identification of sub-cellular fragments from ruptured algae cells. The major

limitation in this exercise was in the examination of cells that had *survived* pressure and shear treatment rather than in being able to identify fragments of *ruptured* algal cells.

The current velocities identified by Oksiyuk (1971) as being responsible for some algal loss (0.15 to 1.5 m/sec) are significantly lower than those experienced in the Nagle Dam to Durban Heights Water Works system (viz. 1.5 to 2.8 m/sec), although comparable with those in the Inanda to Wiggins system (viz. 0.45 to 1.01 m/sec). Unfortunately Oksiyuk (*op. cit.*) does not mention the pressure conditions algae experience in "hydraulic works, pressure conduits and inverted siphons." This makes direct comparison with the conditions experienced in the Nagle and Inanda systems difficult. On the basis of a comparison with his current velocities alone, however, there is reason to believe that the shear conditions experienced by algae in the Nagle aqueducts are responsible for some of the algal loss observed in this system.

Because the Inanda system is less vigorous than the Nagle system, with respect to both current velocities and pressure regimes, the expected algal losses are likely to be less. The simulation work supported this supposition.

The principle of algal cells becoming saturated with dissolved air and the cells then rupturing with decompression is a possible contributing factor accounting for the loss of algae entrained in water between Nagle Dam to Durban Heights WW. The work of Hemmingsen and Hemmingsen (1980) indicates that cell rupture in vacuolate bacteria is possible at minimal pressures of around 2 500 kPa. This work was restricted to only three types of bacteria however and as blue-green algae are taxonomically related to bacteria they would credibly qualify for rupture due to high hydrostatic pressures. Because the particular pressure regime used by these authors was different to that used in these studies, the results are not directly comparable. They do however point in a similar direction i.e. rupturing of aquatic unicellular vacuolate organisms under hydrostatic pressure.

Further to this point, algae in the Inanda system remain pressurised from the dam to the WW, whilst algae in the Nagle system are repeatedly pressurised in siphons (together with large volumes of entrained air) and then undergo full decompression on exposure to the atmosphere in each tunnel of the system (Tables 1 & 2). This repeated pressurisation and decompression is undoubtedly a more severe rupture environment with respect to algae, and hence probably contributes to the greater degree of rupture in the Nagle compared to the Inanda system.

The rupture of algae in Durban Heights raw water was shown to cause increased coagulant demand. This trend was repeated in laboratory treatability studies with the demand increasing dramatically as the concentration of ruptured algae in "raw" water increased.

Generally the treatability of water which had ruptured algae present in it was shown to be more intensive and hence (necessarily), more expensive. This was in reasonable agreement with other work performed in the literature (e.g. Magara & Kunikane, 1986) where it was shown that "advanced" treatment processes

(particularly systems involving activated carbon etc.) were significantly more expensive to operate than "conventional" treatment processes.

The implications of this work in the design of new water abstraction systems are that future systems should attempt, as far as possible, to minimise the pressure and shear (water velocity) conditions in aqueducts, keeping these below 1320 kPa and 1.6ms^{-1} respectively. This recommendation is made so that excessive water treatment costs are not incurred through the necessity of using "advanced" treatment processes to deal with ruptured algae. Alternatively, algae should be removed from the water before entering an aqueduct where high pressures and shear forces are likely to be experienced.

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APPENDICES

Appendix I: Quantities of lithium and *Microcystis* algae emerging from the aqueduct at Durban Heights WW at various sample times for the trial on *in situ* algal rupture (Chapter 6).

Lithium sampling time (seconds)	Lithium (µg/l)	Algae sampling time (seconds)	*Microcystis* (cells/mℓ)
0	0	0	0
30	1	15	
60	15	30	103.215
90	34	45	
120	95	60	19.66
150	142	75	
180	189	90	270.325
210	240	105	
240	283	120	211.345
270	319	135	
300	315	150	442.35
330	314	165	
360	299	180	653.695
390	271	195	
420	253	210	948.595
450	206	225	
480	160	240	1184.52
510	129	255	1646.53
540	100	270	2388.69
570	71	285	2265.82
600	56	300	2437.84
630	42	315	
660	35	330	2609.87
690	28	345	
720	23	360	2791.72
750	19	375	
780	17	390	3425.76
		405	
		420	3897.6
		435	2865.45
		450	4217.07
		465	2545.97
		480	3121.03
		495	3283.22
		510	3302.88
		525	
		540	2904.77
		555	
		570	2162.6
		585	
		600	1395.86
		615	
		630	884.7
		645	
		660	806.06
		675	
		690	575.055
		705	
		720	452.18
		735	
		750	403.03
		765	
		780	427.605
		795	
		810	245.75
		825	
		840	117.96
		855	
		870	117.96
		885	
		900	103.215

Appendix II: Complete list of all genera enumerated from historical analyses from Nagle Dam and Durban Heights Waterworks (Chapter 4).

Actinastrum	Mallomonas
Anabaena	Melosira
Ankistrodesmus	Micrasterias
Botryococcus	Microcystis
Ceratium	Navicula
Chlamydomonas	Nitzschia
Chlorella	Oocystis
Chlorogonium	Oscillatoria
Chodatella	Pandorina
Chroococcus	Pediastrum
Cocconeis	Peridinium
Coelastrum	Phacus
Cosmarium	Pteromonas
Crucigenia	Scenedesmus
Cryptomonas	Siderocelis
Cyclotella	Spermatozopsis
Cymbella	Sphaerocystis
Diatoma	Staurastrum
Dictyosphaerium	Stichococcus
Dinobryon	Surirella
Euastrum	Synedra
Eudorina	Tetraedron
Euglena	Thalassiosira
Golenkinia	Trachelomonas
Gonium	Volvox
Gyrosigma	