UNIVERSITY OF SOUTHERN QUEENSLAND

# Predicting the Effects of Mechanical Destratifiers on Water Quality in Toowoomba's Reservoirs

A Dissertation submitted by

**Mahmud Achmad**

For the award of

Doctor of Philosophy

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## CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

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# ABSTRACT

ACHMAD, MAHMUD. Predicting the effect of mechanical destratifiers on water quality in Toowoomba's reservoirs. (Under supervision and direction of Associate Professor Mark Porter and Professor Rod Smith)

The study of the effect of mechanical destratifiers on water quality in Toowoomba's reservoirs is urgently needed to understand the behaviour of the reservoirs for management purposes. In this study, a 1-D hydrodynamic model (DYRESM) coupled with an aquatic ecosystem model (CAEDYM) is adopted for water quality prediction in the water column for the next 50 years. The AWBM hydrological model and the ClimGen weather generator model are used to support the data preparation for water quality prediction. The simulation results are separated into two periods which are the period November – April represented by the warm period and the period May – October represented by the cold period. The results are used to assess the sustainability aspect and risk factors in the vertical profiles of the reservoirs. A new water quality index is introduced to assess the water quality level in the storages without and with the use of the mechanical destratifiers.

The main conclusions of this study are summarized below: (1) A strong thermal stratification occurs in the storages during the warm period. In this period, Cyanobacteria have a high concentration. (2) The water quality index (WQI) in Cooby storage will be a good or an excellent level. The WQIs of Cooby tend to decrease from an excellent level to a good level without the use of the mixers. The continuous operation of the artificial mixers is able to increase the WQI values by an average of 15 grade points and produces excellent water quality for the next 50 years. (3) The WQIs of Cressbrook storage will be a good or an excellent level. The WQIs of Cressbrook reservoir have a tendency to increase from a good to an excellent level. The WQIs in the surface layer remain the same without and with the use of the

mechanical mixers. The artificial mixers are able to slightly increase the WQI values at the pumping elevation and the average of all layers by an average of four grade points. (4) Without artificial mixers, safe levels of raw water from the Cooby storage can be attained at 8 – 10 m depth. The best/optimal water quality can be achieved with multi-level withdrawals. The use of the artificial mixers can extend the withdrawal range to 9 – 20 m depth. The optimal water quality can be achieved with a fixed pumping elevation at 15 m depth. (5) Without surface mixers, the safe levels can be attained at the layer between 14 m and 30 m depth all the time. The nitrate and total phosphorus levels have a high probability of being unsafe. The use of the mechanical surface mixers is able to widen the range of the safe level between 16 m and 37 m depth. This can give more alternative layers for withdrawals.

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# GLOSSARY

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| **Albedo** | The fraction of solar energy (shortwave radiation) reflected from the water surface back into space. |
| **Alert** | An event involving an unknown or significant decrease of water quality levels for the public use. Alert is addressed to the high concentration of Cyanobacteria in a reservoir. |
| **Algae** | See **Cyanobacteria** |
| **Algicides** | Synthetic or natural chemical compounds used to kill or control unwanted algae ('cide' means killer). |
| **Algal bloom** | Rapid growth of algae in surface waters due to an increase in nutrients such as nitrogen and phosphorus. |
| **Aquatic** | Belonging to water, or living in or near water. |
| **Aquatic ecosystem** | Community of aquatic plants and animals together with the physical and chemical environment in which they live. |
| **Assessment** | The process, and the result, of analysing systematically the hazards associated with sources and practices, and associated protection and safety measures, aimed at quantifying performance measures for comparison with criteria. |
| **Attenuation** | The reduction in intensity of solar radiation passing through the surface water due to processes such as absorption and scattering. |
| **Bathymetry** | The underwater equivalent to topography. A bathymetric map gives the depth contours of the soil at the bottom of a water body such as a reservoir or a lake. |
| **Biomanipulation** | Reducing algal blooms by altering the fish community to reduce predation on certain zooplankton that can most efficiently graze on algae. |
| **Calibration** | A measurement of, or adjustment to, an instrument, component or system to ensure that its accuracy or response is acceptable. |
| **Catchments** | Area on which precipitation falls and is either absorbed by soil or channelled into storm drains and into creeks or rivers (drainage network) to a reservoir's dam. |
| **Chlorophyll** | The green pigments in plants. |
| **Circulation** | The flow, or movement, of water in or through a volume of reservoir or water body. |

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| **Cold period** | The period when the average air temperature is lower than 19°C. This period is between April/May and September/ October. |
| **Correlation coefficient** | A statistical measure of the strength of the linear relationship between two variables. The Correlation Coefficient can vary between -1 and +1. The square of the correlation is $R^2$ (coefficient of determination). Correlation is commonly used to quantify the relationship of the variables. |
| **Creek** | A stream that is smaller than a river and larger than a brook. |
| **Cyanobacteria** | Prokaryotic organisms without organised chloroplasts but having chlorophyll *a* and oxygen-evolving photosynthesis; capable of fixing nitrogen in heterocysts; commonly called ***blue-green algae***. |
| **Dam** | A constructed embankment that blocks an existing watercourse. This embankment is used to control the release of flood waters downstream of the Dam. A dam usually contains a small outlet pipe that limits the amount of water that can exit the dam. |
| **Dead storage** | The amount of water in a dam which can not physically be used or pumped. |
| **Digital Elevation Model (DEM)** | A representation of the topography of the Earth or another surface in a digital format by coordinates and numerical descriptions of altitude. DEMs are used often in geographic information systems. A DEM may or may not be accompanied by information about the ground cover. In contrast with topographical maps, the information is stored in a raster format. |
| **Dissolved Oxygen (DO)** | The amount of oxygen dissolved in water. This term also refers to a measure of the amount of oxygen available for biochemical activity in a water body, an indicator of the quality of water in milligram per litre (mg $L^{-1}$). |
| **Epilimnion** | The layer of water above the thermocline in a freshwater body. The epilimnion is the top layer of a thermally-stratified water body that is directly affected by seasonal air temperature and wind. |
| **Euphotic zone** | Surface water where sunlight penetration is sufficient to maintain photosynthesis, averagely 5 and 7 m from water surface for Cooby and Cressbrook reservoir, respectively. |
| **Eutrophication** | The enrichment of a body of water with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration. |

**Hypolimnion** The bottom and most dense layer of water in a thermally-stratified lake. It is the layer that lies below the thermocline. Typically, it is non-circulatory and remains cold throughout the year

**Metalimnion** The middle layer of a thermally stratified lake or reservoir. It separates the epilimnion (top layer) from the bottom layer (hypolimnion). This layer is the zone of temperature change from warm surface waters to cooler bottom waters.

**Model** A representation of a real system to allow analyses and calculations. A model can be a physical or a mathematical model. A model of a system or process is a theoretical description that can help to understand how the system or process works under specified (often hypothetical) conditions.

**Model calibration** The process whereby model predictions are compared with field observations and/or experimental measurements from the system being modeled, and the model adjusted if necessary to achieve a best fit to the measured/observed data.

**Model validation** The process of determining whether a model is an adequate representation of the real system being modeled, by comparing the predictions of the model with observations of the real system.

**Morphometry** Morphometry refers to the physical characteristics of a reservoir such as size and shape of a reservoir, mean depth, maximum depth, volume, drainage area, and flushing rate.

**Nutrient** Compounds required for growth by plants and other organisms. Major plant nutrients are phosphorus and nitrogen.

**Organism** An individual form of life, such as a plant or animal, bacterium or fungus.

**Parameters** A set of measurable factors that define a system and determine its behaviour, and are varied in an investigation.

**pH** A measure of the degree of acidity or alkalinity; expressed on a logarithmic scale of 1 to 14 (1 is most acid, 7 neutral and 14 most alkaline).

**Phosphorus cycle** The biogeochemical cycle that describes the movement of phosphorus through the lithosphere, hydrosphere, and biosphere. Unlike many other biogeochemicals, the atmosphere does not play a significant role in the movements of phosphorus, because phosphorus and phosphorus-based compounds are usually solids at the typical ranges of temperature and pressure found on Earth.

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| **Prediction** | A statement or claim that a particular event will occur in the future. |
| **Probability** | A measure of how likely it is that some event will occur; a number expressing the ratio of favourable cases to the whole number of possible cases. |
| **Probability of exceedence** | The probability that an event selected at random will exceed a specified magnitude. |
| **Pumping** | A technique to draw water from a reservoir. |
| **Pumping water level** | The distance from the land surface (or measuring point) to the water in the well while it is pumping. For example, "The pumping water level is 10 m from the bottom of a reservoir". |
| **Reservoir** | A human-made body of water formed by damming one end of a valley; usually to supply water and/or hydroelectric power to a nearby area or an artificial body of water. |
| **Risk** | The potential harm that may arise from some present process or from some future event. It is often mapped to the probability of some event which is seen as undesirable. Usually the probability of that event and some assessment of its expected harm must be combined into a believable scenario (an outcome) which combines the set of risk, regret and reward probabilities into an expected value for that outcome. |
| **Risk analysis** | A technique to identify and assess factors that may jeopardize the success of a project or achieving a goal. This technique also helps define preventive measures to reduce the probability of these factors from occurring and identify countermeasures to successfully deal with these constraints when they develop. |
| **Salinity** | The saltiness or dissolved salt content of a body of water. It is usually measured by weight in parts per million (ppm) or stated as parts salinity unit (psu). |
| **Scenario** | A postulated or assumed set of conditions and/or events. Most commonly used in analysis or assessment to represent possible future conditions and/or events to be modelled, such as possible future of water quality. A scenario may represent the conditions at a single point in time or a single event, or a time history of conditions and/or events. |
| **Sensitivity analysis** | A quantitative examination of how the behaviour of a system varies with change, usually in the values of the governing parameters. Parameter variations investigate the changes of one or more input parameter values within a reasonable range around selected reference or mean values. |

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| **Siltation** | The process by which a river, lake, or other water body becomes clogged with sediment. |
| **Simulation** | The formulation of a real system which is implemented as a computer program models i.e. mathematical models wich change through time. |
| **Storage** | The amount of water stored in a reservoir. |
| **Stratified** | Arranged in layers where lighter water overlies denser water, s**tratification** generally occurs as surface waters warm in summer–spring, and is broken down by mixing processes, such as strong winds and surface cooling, especially during winter. |
| **Sustainability** | The capability of a system to sustain or go for a certain period of time. |
| **Sustainability index** | A measurement or quantification of sustainability in water resources (water quality in particular). |
| **Sustainable system** | The formulation of conditions where: (1) the system does not cause harm to other systems, both in space and time; (2) the system maintains living standards at a level that does not cause physical discomfort or social discontent to the human component; (3) within the system life-support ecological components are maintained at levels of current conditions, or better. |
| **Thermal stratification** | The formation of layers of different temperatures in a reservoir or other water bodies. |
| **Total suspended solids (TSS)** | The entire amount of organic and inorganic particles dispersed in water. TSS can be measured by several methods, most of which entail measuring the dry weight of sediment from a known volume of a sub-sample of the original. |
| **Trend** | General and obvious movement or development of events. |
| **Turbidity** | The scattering of light by fine, suspended particles which causes water to have a cloudy appearance. Turbidity is an optical property of water. More specifically, turbidity is the intensity of light scattered at one or more angles to an incident beam of light as measured by a turbidity meter or nephelometer. |
| **Turnover** | A thorough mixing of stratified layers of the body of a reservoir, usually in the spring and autumn, when temperatures become uniform throughout the reservoir. |
| **Validation** | The process of determining whether a product or service is adequate to perform its intended function satisfactorily. |

**Warm period** The period when the average air temperature is above 19°C. This period is in between October/November and March/April.

**Water body** Any area that in a normal year has water flowing or standing above ground to the extent that evidence of an ordinary high water mark is established.

**Water quality** The biological, chemical, and physical conditions of a water body. It is a measure of a water body's ability to support beneficial uses.

**Water quality index** A method for measuring water quality in water bodies. Nine parameters are measured and weighted to develop the index: dissolved oxygen, Cyanobacteria, pH, salinity, water temperature, total phosphorus, nitrates, total iron, and total manganese.

# SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| **ANZECC** | Australian and New Zealand Environment and Conservation Council |
| **AWBM** | Australian Water Balance Model |
| **BGA** | Blue-green algae (Cyanobacteria) |
| **BOD** | biochemical oxygen demand |
| **BOM** | Bureau of Meteorology |
| **CAEDYM** | Computational Aquatic Ecosystem DYnamic Model |
| **cfu** | colony forming unit |
| **chl_*a*** | Chlorophyll_*a* |
| **ClimGen** | Climatic Generator |
| **CRC** | Cooperative Research Centre |
| **CSIRO** | Commonwealth Scientific and Industrial Research Organisation |
| **CWR** | Centre for Water Research |
| **DNRMW** | Department of Natural Resources, Mines and Water |
| **DO** | dissolved oxygen |
| **DYRESM** | DYnamic REservoir Simulation Model |
| **EPA** | Environment Protection Authority |
| **ET** | evapotranspiration |
| **FSH** | free surface height |
| **G** | giga ($10^9$) |
| **h** | hour |
| **ha** | hectare |
| **IQRs** | inter quartile ranges |
| **k** | kilo ($10^3$) |
| **L** | litre |
| **M** | mega ($10^6$) |
| **m** | metre |

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| **µg/L** | micrograms per litre |
| **µS/cm** | micro-siemens per centimetre |
| **mins** | minutes |
| **$mg/m^3$** | milligrams per cubic metre |
| **mg/L** | milligrams per litre |
| **mm** | millimetre |
| **n** | number of samples |
| **$NO_3$** | nitrate |
| **PLTmax** | maximum permissible layer thickness |
| **PLTmin** | minimum permissible layer thickness |
| **S** | siemens (unit of conductance) |
| **Sal** | salinity |
| **SMDI-5** | Surface Mixer Diameter 5m (a model of artificial mixers) |
| **TFe** | total iron |
| **TMn** | total manganese |
| **TP** | total phosphorus |
| **TSS** | total suspended solid |
| **TVA** | Tennessee Valley Authority |
| **Tw** | water temperature |
| **USQ** | University of Southern Queensland |
| **UWA** | University of Western Australia |
| **VPD** | vapour pressure deficit |
| **WQI** | water quality index |

# Chapter 1

# INTRODUCTION

## 1.1 Background

Toowoomba City Council is managing three dams (Cooby, Cressbrook and Perseverance dams) to supply domestic water for Toowoomba City and the surrounding area. In the last decade, these reservoirs have faced blue green algal problems. The concentration of algae in a dam can be affected by many factors including internal and external factors.

*Blue-green alga,* more correctly known as *Cyanobacteria*, has become a common topic in newspapers and other popular media as a problem in Australian waterways. The sudden spurts of cyanobacterial growth (blooms) can adversely affect water quality and induce potentially hazardous changes in local water chemistry (Codd et al. 1994; Reynolds 1987; Sanders & Porter 1994; Smayda 1997). Cyanobacterial blooms are not a new problem in Australia's water resources with references to their occurrence over the last century (Ressom et al. 1994).

There are several factors that can cause blooms. Nutrients concentrations, and levels of temperature, light, and turbidity as well as the stability of the water body are major contributors to triggering the cyanobacterial blooms (Department of Land and

Water Conservation NSW 2000; National River Authority (NRA) 1990; Ressom et al. 1994).

Cyanobacteria levels can grow exponentially if adequate levels of nutrients are available. Blooms often happen in eutrophic water bodies because of the nutrient enrichment process (eutrophication). Phosphorus and nitrogen levels are the main limiting factors in this process. However, the Department of Land Water Conservation in NSW (2000) reported that blooms of cyanobacteria could occur not only in the presence of high concentrations of nutrients, but also in fairly low concentration environments.

The weather influences the temperature of a water body. During summer, air temperatures increase and the water body also becomes warmer, the epilimnion layer in particular. The result is a suitable environmental condition for algae to develop. Vymazal (1995) noticed that a threshold temperature for growing algae at $25^{o}$C, above this temperature the growth rate increases exponentially. Photosynthesis in algae occurs in the visible spectrum. According to Borowitzka (1998), the population of blue green algae is diminished when they are exposed to long periods of high light intensity but they have optimal growth when intermittently exposed to high light intensities.

Another factor is turbidity. When the turbidity is low, sunlight can penetrate through the water column. Both low levels of turbidity and stable water conditions can stimulate the cyanobacteria to grow optimally. When algae grow, generally their suspended particles can become a major component of turbidity itself (Bowie et al. 1985). Thermal stratification produces water column stability especially in the summer and spring seasons. The upper layer of the storage becomes warmer and less dense and so floats on the denser, cooler, lower layer. The stable warm water in the upper layer encourages cyanobacterial blooms (Borowitzka 1998).

Australia's weather favours cyanobacterial blooms with long periods of sunlight that set up warm and calm water bodies (Nova Science in the News 2002).

The Department of Land and Water Conservation NSW (2000b) notes that the occurrence of large numbers of the cyanobacteria can lead to water quality problems. Management problems include: taste and odour problems; blockages in the water treatment filters and toxicity problems. Cyanobacterial toxins must be removed from the water supply before distribution to domestic users and consumers.

Many water quality problems in water bodies are associated with the development of thermal and chemical stratification (Hutchinson 1957). In temperate reservoirs, the development of density gradient starts when the surface temperature increases during the spring. The stratification persists during the summer and breaks down in the autumn when surface temperature decreases.

Water balance in reservoirs also becomes a major issue. While water consumption increases through the impact of a growing population in the city, the inflow to dams decreases because of the effect of global warming and the change of land use.

This project investigated management aspects of these problems in two of three Toowoomba's water supply dams (Cooby and Cressbrook). It was initiated on the practical need to control and reduce algal blooms in these reservoirs by removing the stratified warm surface layer using artificial mixers.

Cyanobacteria alter the physical and chemical properties of the water body and affect the level of water treatment required. Smalls (1980) describes a number of noxious effects resulting from algae in water supplies: (i) fluctuation in pH; (ii) increased turbidity and changed colour; (iii) clogging of screens and filters; (iv) unpleasant taste and odour; (v) released toxins and (vi) waterworks structures corrosion problems.

Blue green algal cells bloom in a water reservoir because they can out-compete with other organisms. They move vertically through a water column to meet their need for nutrients at depth and energy at the surface to sustain the photosynthesis process. This movement is unobstructed in a stable water body, such as a stratified reservoir (Fast 1981). Blooms in the Toowoomba reservoirs have tended to occur during the Spring – Summer period when the reservoirs are heavily stratified.

The Toowoomba City Council (who manage and operate the dams) installed mechanical destratifiers in two of the reservoirs in 2001 in an attempt to reduce the level of stratification. Since the characteristics of each dam are different, understanding the behaviour of Cooby and Cressbrook dams is very important to manage them sucsessfully. The research question becomes – have these machines worked? Have they effectively destratified the entire ponded area or at least have they reduced the frequency and intensity of bloom in the dams? What will be the future water quality condition?

## 1.2 Project Objectives

There is no established procedure for answering the research questions outlined in the previous section. This project pursues a solution by analysing an existing database of measured water qualities supplemented by computer simulations and new data obtained during this project.

There are two main objectives of this project. The primary objective is to predict the effects of surface mechanical mixers on water quality in Cooby and Cressbrook dams. The secondary objective is to establish management procedures with the surface mechanical mixers for optimum water quality.

The project adopted the following aims to meet these objectives:

(i) Evaluate possible measures for quantifying the degree of stratification in the reservoirs and adopt the most appropriate one for algal development.

(ii) Adopt a computer model to predict algal levels from other water properties in Toowoomba's dams. Calibrate this model with historical data both before and after installation of the mixers;

(iii) Quantify the frequency of algal alerts in each storage prior to and after the installation of the mixers;

(iv) Formulate the probability of occurrence of water quality parameters including cyanobacterial levels in the storages over a 50 year simulation period.

(v) Predict the sustainability of the water quality in the reservoirs without and with the use of the mechanical mixers.

The impact of top down mixing on a stratified reservoir is only generally known and appears to be reservoir specific. This attempt to determine the change in water quality as a result of mixing and the associated change in cyanobacterial concentration is novel in the literature. The outcomes from the project provide a powerful management tool for the Toowoomba City Council in its operation of the dams.

## 1.3 Outline of the Dissertation

This dissertation consists of eight chapters and four appendices. The structure and a short explanation of each chapter are presented as follows:

Chapter 1 describes water quality problems in Toowoomba's reservoirs and their consequences to the water supply operations. The objectives of the project are stated and the organization of this dissertation is described.

Chapter 2 reviews the relevant literature. This chapter includes a description of blue-green algae and water supply operation, nutrient in reservoirs, stratification and destratification in reservoirs, water balance in reservoirs and hydrologic models, water quality models, weather data generating programs, and sustainability of water supply systems.

Chapter 3 describes the reservoirs in Toowoomba. This description contains basic statistical analysis of historical water quality data including trends in the water quality.

Chapter 4 considers seasonal behaviour of reservoirs dealing with the stratification and destratification processes in Toowoomba's reservoirs. Analysis of the stratification pattern and the degree of stratification in the reservoirs is described for comparison of water quality parameters during stratified and overturn periods of the year. The impacts of artificial mixers on water quality in Cooby Dam are also investigated in this chapter.

Chapter 5 presents simulation of water quality from observed data with and without artificial mixers in operation. Calibration and validation of the DYRESM-CAEDYM model are described in this chapter. In order to simulate the future condition of the reservoirs, data generation of 50 year sequences including weather and inflow data are presented. The AWBM simulation results are also presented

Chapter 6 presents the analysis of 50 years reservoirs' behaviour including storage level/volume and water quality levels, Cyanobacteria in particular. The description of average values of all layers is presented in box plots for all categories (two periods without and with the use of the mechanical destratifiers). The introduction of a new water quality index in the reservoirs for sustainability analysis is also presented in this chapter.

Chapter 7 presents the analysis of the effect of mixers on water quality in the water column by comparing the series simulated water quality data without and with the use of the mixers. This chapter presents the probability occurrence of water quality level of all simulated parameters in different periods (called warm and cold periods) with and without mixers. By using the probability of the safe level of selected parameters in the water column, the recommendation of pumping elevation in both warm and cold periods for the dams is also presented.

Chapter 8 concludes this dissertation with suggestions for management operation of the storages without and with the use of the mechanical mixers.

Simulation files of Cooby and Cressbrook reservoirs, sensitivity of the quality of inflow, individual water quality rating, conversion of Cyanobacteria and statistical analysis are presented in Appendix A, B, C, D, and E, respectively.

# Chapter 2

# REVIEW OF LITERATURE

## 2.1 Blue-green Algae and Water Supply

### *2.1.1 Blue-green algae and limitation factors*

Blue-green algae or Cyanobacteria survive using three ways of reproduction: vegetative, asexual and sexual production. The Cyanobacteria, as a multicellular organism, reproduce by various types of *fragmentation*. The fragments have capacity to grow and develop into new individuals. This method is called vegetative reproduction (Vymazal 1995). Other methods are asexual and sexual reproduction. The asexual reproduction is achieved by the formation of various kinds of spores that germinate without fusing to form new individuals while the sexual reproduction is achieved by fusion of gametes to yield a *zygote*. Generally, sexual reproduction happens at the end of the growing season, or may be induced by unfavourable or critical changes in the environmental condition such as nutrition supply, pH of water, light, temperature or oxygen (Vymazal 1995).

Cyanobacteria pose a risk to human health because they produce toxins. These toxins can damage the liver and neurological systems of humans and in serious cases can cause death. The cell walls of all Cyanobacteria contain contact irritants which can cause gastrointestinal, skin, eye and respiratory irritations to humans and animals (Ressom et al. 1994).

A number of methods are available to control cyanobacterial blooms in water storages. There are some methods of preventing and managing the cyanobacterial blooms such as artificial destratification, reducing nutrient concentrations in water storages, biomanipulation, algicides and algistats, and water treatment (Department of Land and Water Conservation NSW 2000).

Stratification happens commonly in water bodies at the beginning of the summer season or at the end of spring. The upper layer becomes warmer and encourages algal blooms. To cope with the problem, destratifiers can be used to mix water layers and homogenise the body of water (Jungo et al. 2001).

Reducing nutrient concentration in water storages provides another method to control algal blooms. This method has to be combined with watershed management in preventing the inflow of nutrients from entering the storages.

Biomanipulation or biological control is a new method of controlling the growth of algae by changing the ecosystem, but it is not yet a viable control mechanism for algal blooms. Introducing predatory fish that can eat the planktovirous fish is one example of this method. It will lead to an increase in the numbers of zooplankton that will eat Cyanobacteria (Department of Land and Water Conservation NSW 2000).

### *2.1.2 Algal blooms in Australia*

Cyanobacterial bloom problems in Australia have been reported from early settlement (Codd et al. 1994; The Government of Western Australia 1998). It has become one of the major environmental issues confronting Australia. The exposure of the state's waterways was highlighted in 1991-92 and in 1992-93 with widespread cyanobacterial blooms. A summary of historical cyanobacterial blooms from several locations in Australia is presented in Table 2.1 (Thomas 2001).

Table 2.1 History of blooming of Cyanobacteria in several areas in Australia.

| **Location** | **Recorded Year of Cyanobacterial Blooms** |
|---|---|
| Lake Alexandrina, SA | 1878 |
| Palm Island, QLD | 1979 |
| Malpas Dam, NSW | 1983 |
| Peel-Harvey, WA | <1986 |
| Victorian Towns | 1989/90/91/92 |
| Darling/Barwon Rivers | 1991 |
| Gippsland | 1800s/ 1965/71/74/87/88/91(Post flood) /92/95/96/97/99(Post flood) |

*Source: After Thomas (2001)* http://www.eidn.com.au/kthomas99-1.html

Cyanobacterial outbreaks are natural phenomena resulting from the combination of high nutrient load (particularly of phosphorus), relatively high temperatures, calm conditions, poor mixing of the water column, low rate of flow, lack of flow and long periods of stable weather patterns (Nova Science in the News 2002). The literature shows that they are growing in frequency across Australia.

*Artificial mixing* or *destratifiers* and the use of environmental flows to increase flushing have been applied across Australia to manage nutrient enrichment in a body of water. These strategies involve the prevention of micro-environments suited to algal growth. Other strategies such as *phoslock* (phosphorus lock) – controlling phosphorus loading in reservoir, *biomanipulation* – controlling food-chains and *web-food* in reservoirs as an ecosystem, and temporarily increasing water turbidity can also be used to reduce algal blooms (Ball et al. 2001).

### *2.1.3 Algal problems in the Toowoomba water supply*

Cooby, Perseverance and Cressbrook Dams are the main sources of water supply for Toowoomba. They have all experienced water quality problems due to algal blooms. These problems have been intensively monitored during the last three years. Measurements have shown that an excess of algal cells is associated with diminishing oxygen content, changes in taste and odour, and contamination by toxins in water. It is known that high concentrations of those toxins can affect human and animal health through ingestion or physical contact. Other consequences of the occurrence of algal cells in the water supply include aesthetic effects, interruption to water supply operations, higher water treatment costs and ecological losses (Department of Primary Industries 1993).

The dam operators are concerned about the increasing level of algal cells in the three reservoirs. At the end of 2001, the Toowoomba City Council installed mechanical destratifiers in two of the three dams (Cooby and Perseverance Dams) to reduce algal levels and to improve the quality of water in those reservoirs (Clark, *pers. comm.*, 28 August 2002; Kleinschmidt, *pers. comm.*, 29 May 2003).

The Council has not been able to quantify the effectiveness of the mechanical destratifiers nor their optimum operation in the dams. Several methods are available to evaluate and assess the ecological effectiveness of destratification devices. These include assessing the impact of mechanical destratifiers in reservoirs by statistically comparing water quality parameters before and after installation of the mechanical destratifiers. Alternatively it is also possible to simulate water quality parameters and to test potential water quality parameters under several future scenarios. Simulations enable practitioners to make a decision before running a project even when the results of simulation are not exactly accurate (Soetaert & Herman 2001).

Based on weekly data from the period 1998-2002, the total number of algal alerts in Cooby and Cressbrook reservoirs was 121 and 64, respectively. A detail of the severity of these alerts is shown in Table 2.2. Alert level-3 represents the most serious level. In Cressbrook Dam the number of level-3 alerts increased from none in 1999 to four times in 2002.

Table 2.2 Frequency of algal alert in Cooby and Cressbrook reservoirs.

| Level of Alert | Cooby Dam | | | | | | Cressbrook Dam | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1998 | 1999 | 2000 | 2001 | 2002 | Total | 1998 | 1999 | 2000 | 2001 | 2002 | Total |
| Alert 1 | 1 | 14 | 15 | 5 | 11 | 46 | 10 | 5 | 5 | 7 | 0 | 27 |
| Alert 2 | 2 | 7 | 1 | 18 | 12 | 40 | 12 | 1 | 4 | 7 | 1 | 25 |
| Alert 3 | 35 | 0 | 0 | 0 | 0 | 35 | 7 | 0 | 0 | 1 | 4 | 12 |

*Note: the frequency is calculated on a weekly basis in 2003.*

A number of parameters have been identified as affecting the concentration of algae in water bodies (Herzfeld & Hamilton 2000). They are:

(i) nutrient concentrations such as phosphorus and nitrogen;

(ii) net energy input (long and short wave radiation) that drives thermal stratification;

(iii) wind speed (driving mixing processes);

(iv) turbidity; and

(v) morphometry and topography.

Available nutrient data (phosphorus and nitrogen) from Toowoomba's reservoirs have unfortunately been recorded in discrete ranges rather than as precise values. This necessitates some re-interpretation before the data can be used in this project (Kleinschmidt, *pers. comm.*, 29 May 2003).

## 2.2 Role of Nutrients in Reservoirs

Nutrients in reservoirs control the life of organisms in water. Important nutrients in water include phosphorus, nitrogen, sulphur, iron and silica. It was observed that phosphorus and nitrogen levels control the eutrophication process of reservoirs (Lee 1973). Straskraba and Tundisi (1999) identified nitrogen and phosphorus as major limitation factors of the primary production of phytoplankton in reservoirs.

### *2.2.1 Nitrogen*

Nitrogen is essential for sustaining life. Nitrogen can be available in air, water and soil bodies. Nitrogen in water enables the growth of algae and other aquatic plants, but excessive levels of these plants can choke up waterways and out-compete with native species (Summerfelt 1997).

The total nitrogen level in water should be less than 0.5 grams per cubic metre to prevent excessive growth of nuisance plants. Higher levels of nitrogen in water may result from runoff and leaching from agricultural land (Palmer et al. 2000). Runoff can contain sediment, phosphorus, and faecal matter – containing bacteria and viruses (Wetzel 2001). However, it is not easy to control the nitrogen level because of the complexity of the interaction between the various forms it takes (Department of Fisheries and Aquatic Sciences, Institute of Food and Agricultural Sciences, University of Florida 2000).

Nitrogen exists in many interacting forms in water. It has the most complex cycle interactions of all nutrients (Boulton & Brock 1999; Jorgensen & Bendoricchio 2001). Nitrogen occurs in water bodies in a number of forms or chemical structures including $N_2$, $NO_3^-$, $NH_4^+$, or $NO_2^-$. However, nitrogen in reservoirs is usually in the form of nitrate ($NO_3^-$) and comes from external sources such as surface inflows and groundwater (Davis & Cornwell 1998). Nitrogen is present in the water surface and in the deeper layers of a water body. Transformation of nitrogen in water bodies occurs through ammonification, fixation, nitrification, denitrification and other nitrate reduction processes (Wetzel 2001).

Cyanobacteria use nitrogen for growing and transform the nitrogen to amino-nitrogen ($NH_{2.}$) as an organic compound. The organic nitrogen is released as ammonia ($NH_3$) during the decomposition process of cyanobacterial dead cells. Ammonia can be reformed to nitrate by bacteria through the nitrification process. These transformations occur under aerobic conditions. In anaerobic conditions, in the hypolimnion layer and eutrophic reservoirs, for example, where the oxygen supply is depleted, anaerobic bacteria reform nitrate to nitrogen gas in the process of denitrification (Davis & Cornwell 1998; Wetzel 2001).

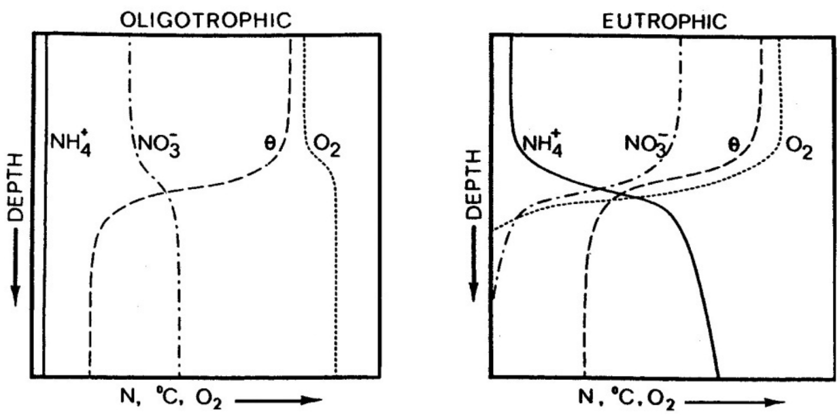
The temperature and pH of water affect the ratio of ($NH_4^+$):($NH_3$) ions in water. At lower temperatures and lower pH, the reduction-oxidation reaction shifts this ratio from left to right, decreasing the percentage of unionized (toxic) $NH_3$ form of ammonia (Summerfelt 1997). The variation of percentages of unionized ($NH_3$) at combinations of temperatures and level of pH are shown in Table 2.3.

Table 2.3 Percent unionized ($NH_3$) ammonia as a function of pH and temperature.

| Temperature °C (°F) | pH | | | | |
|---|---|---|---|---|---|
| | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 |
| 10 (50) | 0.0186 | 0.186 | 1.83 | 15.7 | 65.1 |
| 15 (59) | 0.0274 | 0.273 | 2.66 | 21.5 | 73.2 |
| 20 (68) | 0.0397 | 0.396 | 3.82 | 28.4 | 79.9 |
| 25 (77) | 0.0568 | 0.566 | 5.38 | 36.3 | 85.0 |
| 30 (86) | 0.0805 | 0.799 | 7.45 | 44.6 | 89.0 |

*Source: Summerfelt 1997* (http://aquanic.org/publicat/state/il-in/ces/summerfl.pdf).

Wetzel (2001) describes the general patterns of distribution of nitrogen species in stratified oligotrophic and eutrophic lakes as presented in Figure 2.1. There tends to be some surface depletion of fixed nitrogen in the epilimnion in both cases: the result of assimilation by algae and their subsequent descent to the hypolimnion. The principal contrasts between oligotrophic and eutrophic lakes are the total concentration of fixed nitrogen, and the shift to ammonia in the hypolimnion of a eutrophic lake as a consequence of low oxygen.




Where $NH_4^+$ and $NO_3^-$ are in mgN/L, θ is water temperature in °C, and $O_2$ is oxygen in mg/L

Figure 2.1 Generalized vertical distribution of ammonia and nitrate nitrogen in stratified water bodies of very low and high productivity (from Wetzel 2001, p. 215).

Based on the level of inorganic and organic N, Vollenweider (1968) classified lake productivity into five categories as shown in Table 2.4.

Table 2.4 General relationship of lake productivity to average concentrations of epilimnetic nitrogen

| *General level of lake productivity* | *Change in alkalinity in epilimnion in summer (meq litre$^{-1}$)* | *Inorganic N (mg m$^{-3}$)* | *Approximate average organic N (mg m$^{-3}$)* |
|---|---|---|---|
| Ultra-oligotrophic | < 0.2 | < 200 | < 200 |
| Oligo-mesotropic | 0.6 | 200 – 400 | 200 – 400 |
| Meso-eutrophic | 0.6 – 1.0 | 300 – 650 | 400 – 700 |
| Eutrophic | | 500 – 1500 | 700 – 1200 |
| Hypereutrophic | > 1.0 | > 1500 | > 1200 |

*Source; Wetzel 2001, p. 213 after Vollenweider 1968.*

Mechanisms for removing nitrogen in water bodies include N plant uptake, nitrification-denitrification, $NH_3$ volatilization, filtration-sedimentation of particulate N, and N adsorption (Koottatep, Polprasert & Oanh 2000). In constructed wetlands, removal mechanisms of N also involve several interactions and reactions as shown in Figure 2.2 (Koottatep, Polprasert & Oanh 2000).

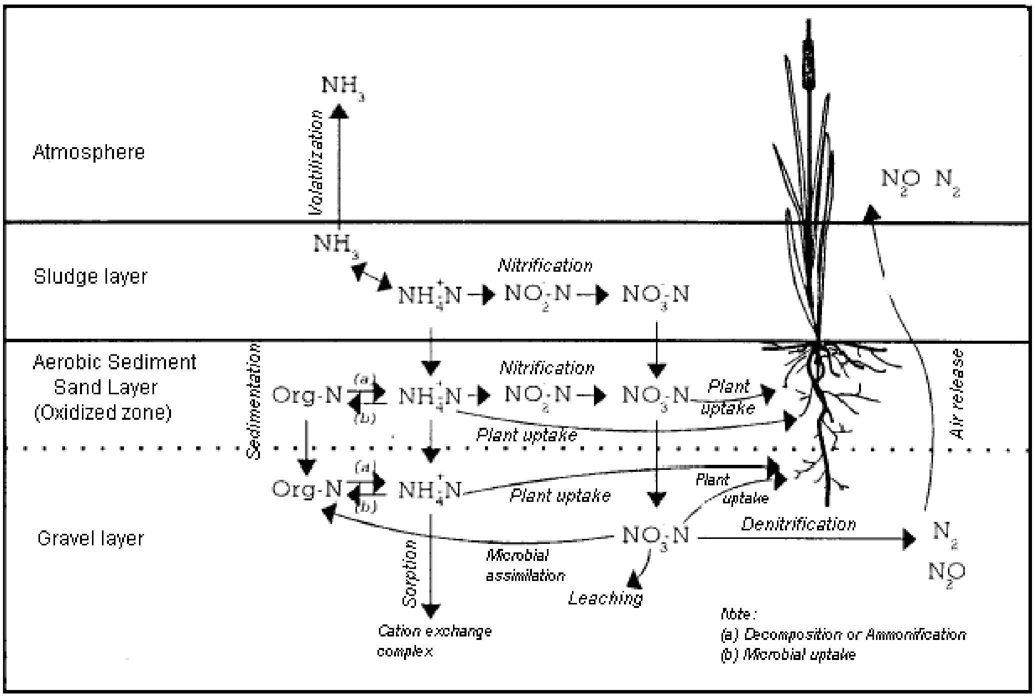



Figure 2.2 Nitrogen removal mechanisms in constructed wetlands (from Koottatep, Polprasert & Oanh 2000, p. 3 http://www.sandec.ch/files/Design_1.pdf)

### *2.2.2 Phosphorus*

Phosphorus (P) is an essential substance to all life as a component of nucleic acid and a universal energy molecule (Boulton & Brock 1999). Phosphorus is naturally present in the environment. The loading rate of phosphorus in lakes and other water systems depends mainly on the surrounding drainage basin. Phosphorus is found in several compounds such as phosphine ($PO_3$), and phosphate ($PO_4^{3-}$). The biggest molecular compound of phosphorus is phosphate. Around 90 percent of phosphorus is in organic forms and cellular constituents (Wetzel 2001).

In many natural waters, the concentration of phosphorus is relatively low. Most aquatic plants, however, need a large amount of phosphorus for their photosynthesis processes (Boyd 2000). Phosphorus in aquatic ecosystems occurs as soluble inorganic phosphorus, soluble organic phosphorus, particulate organic P in living phytoplankton and in dead detritus, and particulate inorganic phosphorus on suspended mineral particles. The soluble fraction can be filtered from the particulate fraction through a membrane filter (Kadlec & Knight 1995). Phosphorus is classified as either particulate or dissolved in terms of measuring the total phosphorus in unfiltered-water. Particulate phosphorus consists of phosphorus in organisms, in a mineral phase and in macro-organic aggregations, while dissolved phosphorus consists of orthophosphate ($PO_4^{3-}$), polyphosphates, organic colloids, and low-molecular-weight phosphate esters (Wetzel 2001).

The concentration of total phosphorus in water influences other components of water systems in the process of enriching nutrient in lakes or reservoirs. The enrichment process is mostly known as *eutrophication* (Wood, Mullins & Hajek 2002).

There are many factors that influence the vertical profile of phosphorus concentration in water. After comparing the variability of phosphorus deposition in four selected reservoirs in Kansas watersheds, it was concluded that the concentration is affected by topography and precipitation in the watershed and land management (Mau & Christensen 2000). The reservoirs exhibited different profiles of phosphorus concentration.

The inflow-outflow processes, transformation processes and the resulting accumulation of phosphorus in a water system are shown in Figure 2.3 (Boyd 2000). Land use management systems control the main source of phosphorus through water flows. Water allocations from a reservoir strongly influence losses of phosphorus through outflow from reservoirs or dams.

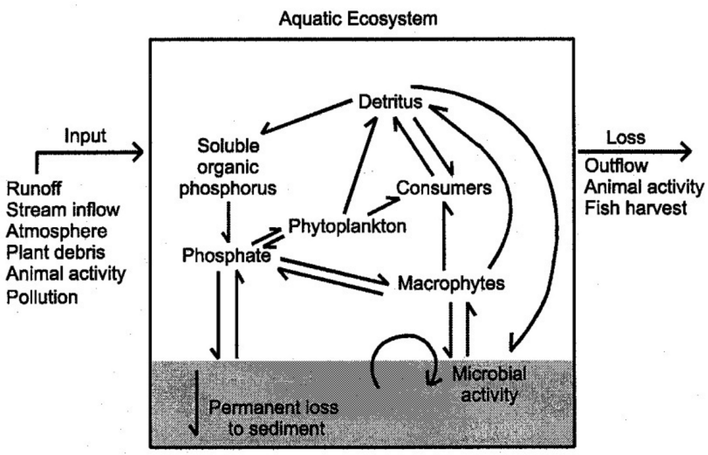
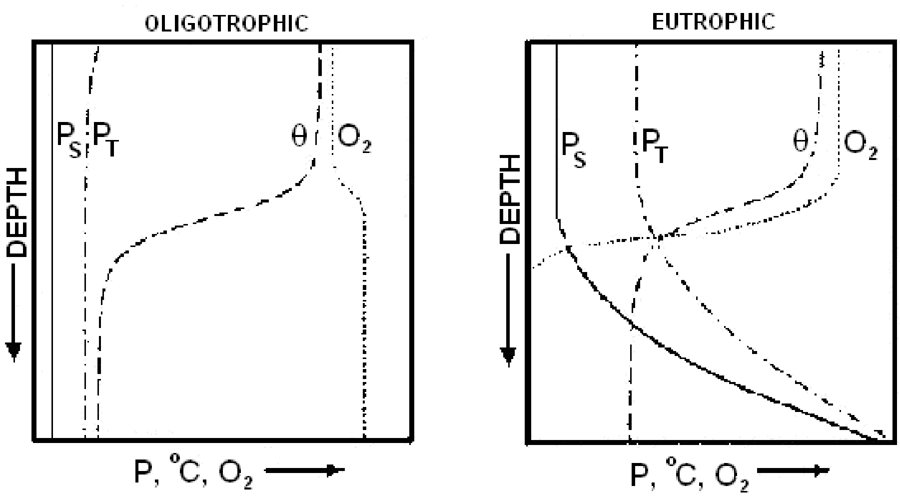



Figure 2.3 Sources and transformation of phosphorus in aquatic ecosystems (from Boyd 2000, p. 195)

When the phosphate level rises to a critical point, phosphate-uptake kinetics are known to favour blue-green algae over green algae. The maximal phosphate uptake occurs between pH 7.5 and 8.5 and it declines sharply below pH 7.

Phosphorus concentration in surface water is generally low compared to that in deeper layers. Total phosphorus is seldom more than 0.5 mg/L except in eutrophic or wastewaters. There is generally much more particulate phosphorus than soluble reactive phosphorus. Masuda and Boyd *in* Boyd (2000) found that water in eutrophic ponds contains 37% dissolved and 63% particulate phosphorus. However, most of the dissolved phosphorus was non-reactive organic phosphorus, and only 7.7% of the total phosphorus was soluble reactive and readily available to plants. Most surface waters contain less than 0.05 mg/L soluble reactive phosphorus, and the most unpolluted water only contains 0.001 to 0.005 mg/L of this fraction. Sediment in the bottom layers contains much more phosphorus than the water body. Concentrations may range from 10-20 mg/kg total phosphorus to 3,000 or 4,000 mg/kg. However, most of this is tightly bound and not readily soluble in water.

Wetzel (2001) presents the profile of phosphorus concentration in two conditions of lakes (oligotrophic and eutrophic) as shown in Figure 2.4.




Where $P_S$ is soluble phosphorus in mg/L, $P_T$ is total phosphorus in mg/L, θ is water temperature in °C, and $O_2$ is oxygen in mg/L

Figure 2.4 Stratified phosphorus in both oligotrophic and eutrophic lakes (from Wetzel 2001, p. 242)

By reducing phosphorus-load in a lake, Sas (1989) found that the production of phytoplankton such as Cyanobacteria was positively correlated to the concentration of total phosphorus in water (Reynolds 1991). Figure 2.5 shows that the reduction of total phosphorus decrease chlorophyll *a* concentrations in lakes and streams.

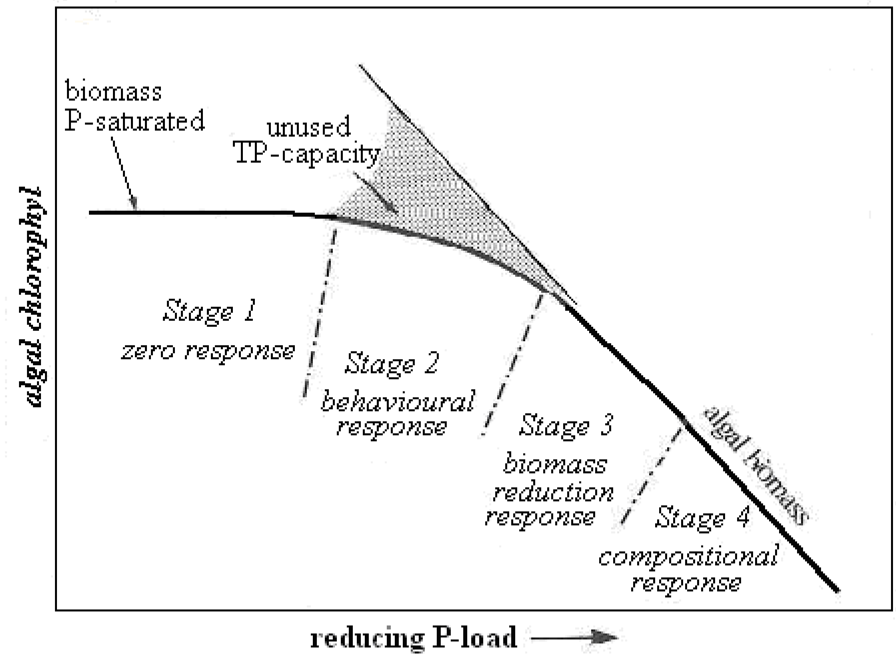



Figure 2.5 Response chlorophyll *a* concentrations to the total phosphorus reduction and in lakes and streams (from Reynolds 1991, p. 7).

It is necessary to control phosphorus levels in order to reduce algal population in aquatic ecosystems. A mass balance equation can be used to assess the amount of phosphorus concentration in water, because indirect assessment of phosphorus loading can result in an over-estimation (Schnoor 1996). Generally, controlling the input of phosphorus is not as difficult as other chemical elements because phosphorus in water has no *atmospheric storage* (Jorgensen 1980).

Kedlec and Knight (1995) found four factors that influence the transformation processes of phosphorus; depth, aeration (vertical mixing), temperature and seasons. Only aeration and temperature factors can be modified to reduce phosphorus accumulation in water.

## 2.3 Stratification and Destratification in Reservoirs

Water quality problems are often associated with the stratification behaviour of reservoirs. Stratification is a solar driven process of generating thermal layers in a reservoir or a lake. When summer starts, the water temperature in the upper layer is raised while the bottom layer remains colder. This increases the temperature driven density difference between the upper layer and bottom layer (Weitzel 1997).

A reservoir is defined as a body of water which is formed by an embankment or a dam to supply water for developing human activities and needs. Characteristics of reservoirs are similar to lakes. However, reservoirs are mainly controlled by the inflow-outflow process (Chapman 1996).

Wetzel (2001) states that lakes and reservoirs can gain heat through a number of ways: direct absorption of solar radiation as a dominant source, transfer of heat from the air and sediment to the water, condensation of water vapour at the water surface, and heat transfer from terrestrial sources via precipitation and surface runoff as well as ground water. As a consequence, lakes become thermally stratified, defined as a non-uniform temperature profile with depth within a lake system (Chapman 1996). There are three main components of thermal stratification as described in Figure 2.6 (Fisher et al 1979; Martin & McCutcheon 1998; Wetzel 2001):

1. *Epilimnion layer* is the surface water which is usually warm. The temperature of the layer is influenced by wind and wave circulation.
2. *Hypolimnion layer* is the bottom layer which is usually much colder and stable.
3. *Metalimnion* is a thin layer situated below the epilimnion. It is a transition layer of marked thermal change between epilimnion and hypolimnion, normally called the *thermocline*. This layer represents the limiting condition

that the surface wind-mixed currents can penetrate against the resistance of the temperature gradient. Maslin (1996a) states that the thermocline forms at a depth determined by the strength of the wind-induced mixing current, compared to the opposing strength of the temperature (density) gradient in the reservoirs.

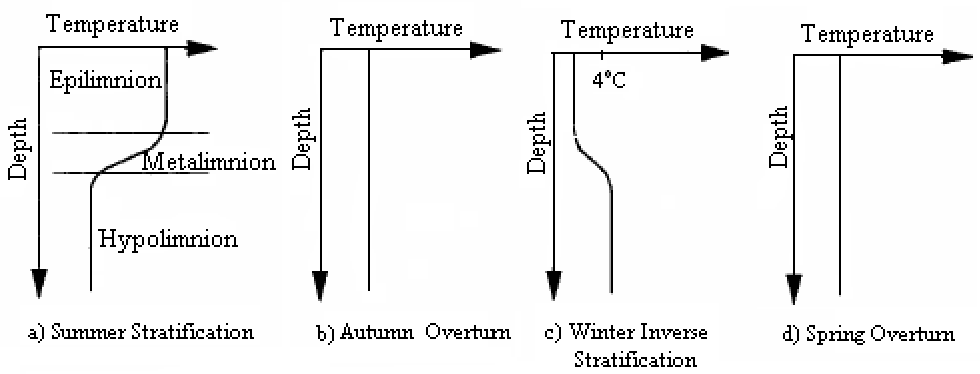



Figure 2.6 Vertical depth profile of temperature: stratification in summer and winter; overturn in autumn and spring (from: Martin & McCutcheon 1999, p. 345)

Stratification is dependent on several factors including solar radiation, the shape and depth of lakes (morphology), wind speed, and position and orientation of lakes. The water temperature profile in lakes is often paralleled by stratification of other components of water quality measurements such as pH, dissolved oxygen (DO), and density (Rowe 2001).

The temperatures of different water layers in reservoirs are also strongly determined by inflow and outflow processes which influence heat transfer in reservoirs. There are three types of flows in reservoirs (Chapman 1996):

(i) *overflow* occurs when inflow moves over the main body of water in the reservoir;

(ii) *interflow* occurs when inflow moves through the middle layer of reservoirs; and

(iii) *underflow* occurs when inflow moves into the bottom of reservoirs.

### *2.3.1 Stratification and water quality*

The major significance of stratification is that the thermocline acts as a physical barrier between the upper and lower layers of the body of water. Furthermore, the barrier also changes other water quality parameters. For example, the relationship between temperature and water density is shown in Figure 2.7. The variation of water density in the water layer strengthens the thermocline.

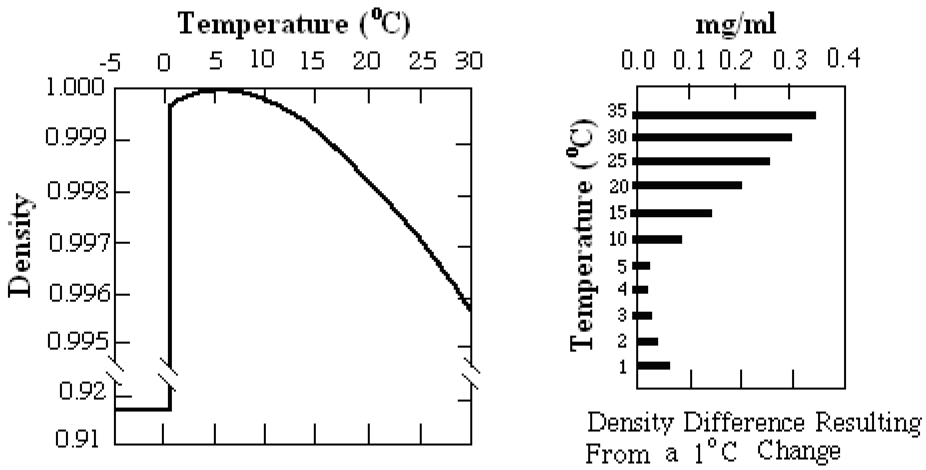



Figure 2.7 The relationship between temperatures and water densities (*left*) and density differences versus temperature (*right*) (from: Maslin 1996a, http://www.csuchico.edu/~pmaslin/limno/strat.html; Wetzel 2001, p. 12)

Straskraba and Gnauck (1985) established the following relationship between temperature (T) and water density ($\rho_w$) in natural water bodies:

$$\rho_w = a + bT + cT^2 + dT^3 \qquad (2.1)$$

where *a*, *b*, *c*, and *d* are constants:

$a$ = 0.99987885
$b$ = $6.0260168 \times 10^{-5}$
$c$ = $-7.9947027 \times 10^{-6}$
$d$ = $4.369257 \times 10^{-8}$

The vertical distribution of dissolved oxygen can be strongly influenced by temperature stratification. If only physical processes are important, the vertical distribution of dissolved oxygen can be predicted solely from the temperature. The resulting oxygen-depth curve is called an *orthograde oxygen curve* (Maslin 1996b). The shape of the curve results from the influence of temperature on the solubility of oxygen in water. Oxygen is less soluble at higher temperatures than at lower temperatures, and therefore the epilimnion of a stratified lake would contain less oxygen than the hypolimnion, if temperature was the only influence on oxygen concentration. The relationship of dissolved oxygen saturation ($DO_{sat}$ in mg $O_2$ per litre) and temperature ($T$ in $^{o}$C) is described by the following function (Straskraba and Gnauck 1985 p.116):

$$DO_{sat} = 14.6244 - 0.40776\, T + 0.00811362\, T^{2} - 0.000078765\, T^{3} \qquad (2.2)$$

Weitzal (2002) found that the hypolimnion layer slowly begins to run out of oxygen as oxygen breathing organisms such as fish, invertebrates, and aerobic bacteria in the sediment consume the available supply. Fresh oxygen cannot pass through the density gradient of the thermocline and so the hypolimnion becomes anoxic. This process has a great effect on fish location during the summer because they are forced out of the cool water of the hypolimnion.

Deeper layers are only partly isolated. Gravity brings dead algal cells and animal faeces down from higher layers to deeper layers. Photosynthesis and diffusion in the deeper layers are limited because of insufficient light. As a result of these movements, lakes always have two layers (water and sediments); sometimes have four layers (epilimnion, metalimnion, hypolimnion, and sediments); and in the case of meromictic lakes, sometimes a fourth layer (Maslin 1996b).

The availability of light decreases exponentially with depth because of light scatter and absorption. As a consequence, light energy is more available in the epilimnion than in the lower layer. The upper layer of a lake which receives sufficient light for net photosynthesis to occur is called the *photic zone*, or *trophogenic zone*, and may coincide with the epilimnion. However, the water transparency may dictate that the photic zone is less than the depth of the epilimnion, or may extend into the metalimnion.

At the end of summer and throughout autumn, the water starts to lose heat because of decreasing air temperature and lower heat input from solar radiation. The surface water in the epilimnion becomes cooler and denser. Wind-induced and convection currents create natural mixing between surface water and deeper layer. As a consequence of this process, the water density in all layers becomes similar. The relative thermal resistance of the metalimnion is gradually reduced. In the end, a circulation process in the body of water is started and *turnover* is initiated. Turnover continues with progressive cooling, often to the temperatures of maximum density of $4^{o}$C or less in cooler climates (Wetzel 2001).

### *2.3.2 Type of stratification*

Based on the thermal and circulation characteristics, Wetzel (2001) classified lakes into six types:

1. *Cold monomictic*; temperatures of water are a maximum $4^{o}$C with one period of circulation in the summer at temperature just below or at $4^{o}$C.
2. *Warm monomictic*; circulate freely once a year in the winter at or above $4^{o}$C and are stably stratified for the remainder of the year and not ice-covered.

3. *Dimictic*; circulate freely twice a year in the spring and fall, and are directly stratified in the summer and inversely stratified in the winter.
4. *Oligomictic*; thermally stratified much of the year but cooling sufficiently for rare circulation periods at irregular intervals and not ice-covered.
5. *Polymictic*; frequent or continuous periods of mixing each year and not ice-covered. This type divides into two sub-types:
    a. *Cold polymectesa*; circulate continually at or slightly above $4^oC$. It can be found in sub tropical regions where wind speed is high, humidity is low, and seasonal change of air temperature is little.
    b. *Warm polymectesa*; generally, it is a tropical lake with water temperature above $4^oC$. Here, stratifications are weak, interval of heating is short, cooling process is rapid, and variation of temperature is small.
6. *Amictic*; surface of the lakes is covered by ice. Maslin (1996a) describes that the temperatures of the layers below the ice are stable and constant.

Based on the recorded data between 1999 and 2003, Toowoomba's reservoirs are classified as warm monomictic. Overturn or mixing period occurs once a year in around the period of June-August with the surface water temperature about $14^oC$.

### *2.3.3 Quantitative aspects of stratification*

It is necessary to quantify stratification to obtain a measure of lake stability. The oldest method of defining stability is *the stratification index* (*SI*) which depends on the temperature function of density. The *SI* method is developed from the standard deviation of the density matrix (Adams & Charles 2000). A high stratification index represents intense thermal stratification and high stability, whereas a low *SI* indicates very little stratification and low stability. Darnault and Bell (2001) used *SI* in Chesapeake Bay using sigma-t method expressed as follows:

$$\delta_t = |\rho_w\text{-}1000| \tag{2.3}$$

$$SI = \frac{\delta_b - \delta_s}{\delta_{ave}} \tag{2.4}$$

where $\delta_t$ is difference from standard density of water of a layer, $\rho_w$ is the water density of a water layer (kg m$^{-3}$), $\delta_b$ is the density expressed in sigma-t at the bottom (hypolimnion), $\delta_s$ is the density expressed in sigma-t at the surface (epilimnion), and $\delta_{ave}$ is the average density. *SI* values are classified into five levels of stratification. They are: $SI < 3$ classified as very low; $SI = 3 – 5$ classified as low; $SI = 5 – 7$ classified as medium; $SI = 7 – 10$ classified as high; and $SI > 10$ classified as very high.

Some other non-dimensional parameters for quantifying mixing and stratification in standing water bodies (lakes or reservoirs) include Lake Number, Wedderburn Number, Richardson Number, and Surface Mixing Number.

#### 2.3.3.1 Lake Number ($L_N$)

*Lake Number* is a quantitative index of the dynamic stability of the water column. Lake Number indicates the depth of mixing in reservoirs, and can be described as “the ratio of the moments about the water body’s centre of volume, of the stabilizing force of gravity (resulting from density stratification) to the destabilizing forces from wind, cooling, inflow, outflow, and artificial destratification” (Hutchinson 1957). If the wind dominates forces for mixing, $L_N$ can be calculated by equation 2.5.

$$L_N = \frac{(z_g - z_o)Mg\left(1 - \frac{z_t}{z}\right)}{\rho\, u_*^{\,2} A^{3/2}\left(1 - \frac{z_g}{z}\right)} \tag{2.5}$$

where:

$z_g$ = the depth of the centre of volume (m)
$z_o$ = the depth of centre of gravity of the water mass with a density stratification ($\rho_z$) at height z above the reservoir bottom (m)
$z_t$ = the thermocline height above the reservoir bottom (m)
$z$ = the maximum depth of the reservoir (m)
$g$ = the acceleration of gravity (9.80 m $s^{-2}$)
$M$ = total mass of the reservoir (kg)
$A$ = area of surface water ($m^2$)
$\rho$ = water density at the surface (kg $m^{-3}$)
$u_*$ = water friction velocity (m/s)
due to wind stress, approximated by:

$$u_*^2 = (\rho_a/\rho) \text{ x } C_D \text{ x } U_{10}^2 \tag{2.6}$$

where: $U_{10}$ = wind velocity 10 m above the water surface (m $s^{-1}$)
$C_D$ = drag coefficient = 1.3 x $10^{-3}$ (dimensionless)
$\rho_a/\rho$ = ratio of air/water density = 1.2 x $10^{-3}$ (dimensionless)

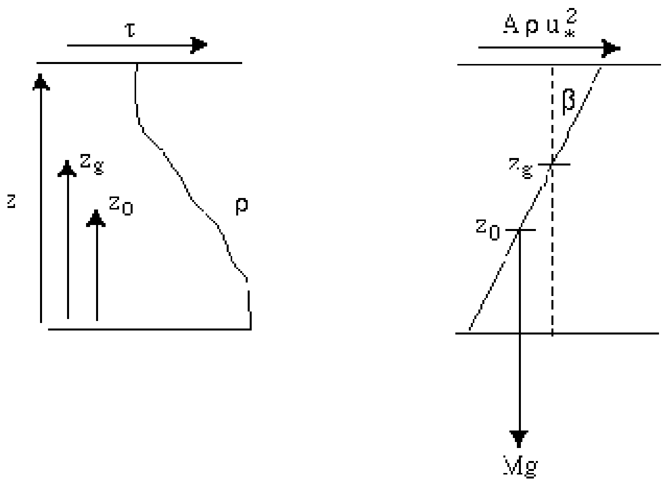



Figure 2.8 Sketch of variables used in derivation of Lake Number (from Antenucci 2000, Fig 1.2)

There are three possibilities for a $L_N$ value. Firstly, $L_N$ <<1, indicates that stratification is weak with respect to wind stress. In this condition, the seasonal thermocline is expected to experience strong seiching and the hypolimnion is expected to experience turbulent mixing due to internal shear. Secondly, $L_N$ = 1, indicates that the wind is just sufficient to force the seasonal thermocline to be deflected to the surface at the windward end of the lake. Thirdly, $L_N$ >>1, indicates that stratification is strong and dominates the forces introduced by surface wind energy. In this case, the isopycnals are predicted to be primarily horizontal. Little seiching of the seasonal thermocline and little turbulent mixing in the hypolimnion are expected (Robertson & Imberger 1994).

2.3.3.2 Wedderburn Number (*W*)

*The Wedderburn Number* (*W*) utilizes wind speed, ratio of epilimnion depth to overall lake depth, density of the epilimnion and hypolimnion, total lake length, and gravity (Monismith 1986).

$$W = \frac{g' h_e^2}{\mu^2 L} \tag{2.7}$$

$$g' = \frac{g(\rho_h - \rho_e)}{\rho} \tag{2.8}$$

where:

$h_e$ = height of epilimnion (m)
$\mu$ = shear velocity of the water surface (m $s^{-1}$)
$L$ = length of the lake (m)
$\rho$ = average density of the whole layers (kg $m^{-3}$)
$\rho_e$ = average density of the epilimnion (kg $m^{-3}$)
$\rho_h$ = average density of the hypolimnion (kg $m^{-3}$)
$g$ = gravity (9.8 m $s^{-2}$)

This dimensionless parameter is a measure of the effect of wind stress on the lake surface. There are four major classifications for the Wedderburn number (*W*):

1. $W > \frac{L}{4h_e}$, indicates that the lake has a strong thermal stratification, little mixing, small internal seiche amplitudes.

2. $\frac{1}{2} < W < \frac{L}{4h_e}$, indicates that the wind induced mixing is stronger than thermal stratification, more surface mixing than instability at the thermocline, large internal seiche amplitudes.

3. $\frac{h_e}{L} < W < \frac{1}{2}$, indicates that the lake has a higher degree of mixing between the epilimnion and the hypolimnion, much upwelling at the thermocline (unstable) surface at the upwind end of the basin.

4. $W < \frac{h_e}{L}$, indicates that the lake has complete overturn (mixing).

2.3.3.3 Richardson Number ($R_i$)

The Richardson Number examines the turbulence conditions between two layers which have different temperatures. The number characterises the shearing force in the water surface and the stability of density stratification (Mortimer 1974; Wetzel 2001). The ratio of the Richardson Number to the aspect ratio ($L/h_e$) can also explain the Wedderburn Number. The Richardson Number is given as:

$$R_i = \frac{g'h}{u_*^2} \tag{2.9}$$

where *g'* is the modified acceleration due to gravity across the uppermost thermocline (equation 2.8), *h* is the thickness of the surface layer and $u_*$ is defined as before in Equation 2.6. The aspect ratio, A, is the fetch length of the lake (*L*) and the depth of the diurnal thermocline defined as *h* (Imberger 2001).

When the Richardson number is less than 0.25, internal waves spontaneously appear, and break. Mixing ensues until gradients are reduced and the system again stabilizes (Wetzel, 2001). In this condition, a Kelvin-Helmholtz instability results in the interface between two homogenous fluids. When the velocity difference or shear between two layers is less than 0.25, buoyant force associated with the density difference suppress the disturbances (Mortimer 1974).

2.3.3.4 The Surface Mixing Number (*I*)

Imberger (2001) develops the Surface Mixing Number which is the ratio of the rate of working of the wind and the rate at which solar energy adds potential energy to the surface water column. The Surface Mixing Number describes diurnal surface layer formation and provides an indication of whether the water column has a tendency to stratify ($I > I$c where $I$c = 0.2 is the transition value of parameter $I$). The $I$ number can be determined by the following equations:

$$I = \frac{\dot{PE}}{\dot{W}} \tag{2.10}$$

where the potential energy of the upper water column is given by:

$$\dot{PE} = \frac{H_o h \alpha g}{c_p}\left[1 - \frac{1}{R_k}\left(1 - e^{-R_k}\right)\right] + \frac{\left(H_o e^{k_d}\right) h \alpha g}{c_p} \tag{2.11}$$

where $h$ is the reference depth, usually taken as the depth of the upper most thermocline, α is the coefficient of thermal expansion of water, $c_p$ is specific heat of water, g is the acceleration due to gravity, $R_k = k_d\ h$, $k_d$ is an extinction coefficient, and $H_o$ is the net solar short wave radiation. The rate of working by the wind, $\dot{W}$, is determined by equation 2.12.

$$\dot{W} \approx \left( \frac{C_D^S \rho_a}{\rho_o} \right)^{3/2} \rho_o U^3 \qquad (2.12)$$

$C_D^S$ is the surface drag coefficient, $\rho_a$ is the density of the air, $\rho_o$ is the density of water and $U$ is the wind speed.

The $I$ number can be used to see whether meteorological conditions are such as to cause the surface layer to stratify or mix at a particular instant in time. This is particularly useful due to the influences of the near surface temperature structure on phytoplankton production and species composition.

### *2.3.4 Destratification and water quality*

Destratification is the process of disrupting thermal layers and/or chemical layers in a body of water, particularly in lakes and reservoirs. Destratification is often associated with the mixing process because both have the same purpose to homogenise the water column for improving water quality.

Destratification can be categorised as either natural or artificial. Destratification can happen naturally when the surface water gains sufficient energy from the wind to circulate the water in a lake or a reservoir. During winter with cold weather and strong winds, water circulates completely and there is no stratification of the water column. On the other hand, in some part of Australia (e.g. Southern Queensland) during summer with warm weather and little winds, the circulation is incomplete. This leads to stratification. In this case, artificial destratifiers are needed to add energy to circulate water completely (Boulton & Brock 1999).

#### 2.3.4.1 Types of destratifiers

Destratifiers are mechanical devices for mixing or circulating water vertically from the surface to the bottom layers in order to prevent stratification in a lake or a reservoir. The two most common techniques to circulate water use air injection (diffuser) and mechanical mixing equipment (Hudson & Kirschner 1997).

a. Air injection

The air injection or diffuser system consists of an air compressor, feeder line (pipe) and air diffuser. Air is delivered from the compressor to the diffuser or perforated pipes near the bottom layer of the lake or reservoir.

The air bubbles produced by the diffuser move up to the surface water. This leads to water circulating from the upper layer to the bottom layer as a consequence of exchanging air bubble spaces. During the process, water temperature as well as dissolved oxygen levels become nearly constant in all layers. The process of aeration is shown schematically in Figure 2.9a.

b. Mechanical axial flow pumps

A mechanical axial flow pump can be used to circulate water vertically in a top-down pattern. The pump is placed near the surface so that it pushes water from the upper layers to the bottom layers (Figure 2.9b). The low oxygen water in the bottom layers is circulated to the surface layer, breaking the thermal stratification pattern.

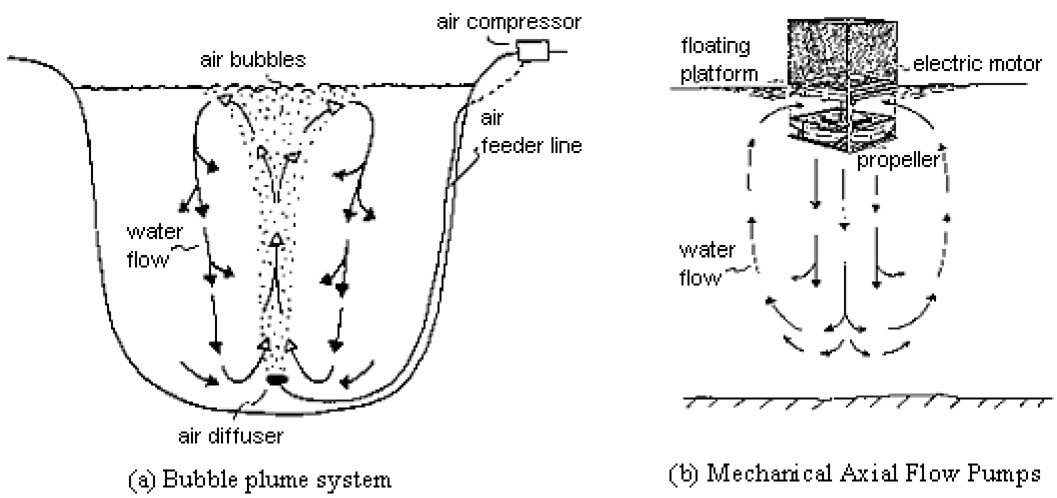



Figure 2.9 Common water circulation systems in lakes or reservoirs.

Mechanical axial flow machines can be classified into two categories. An open-impeller system was introduced by Garton and Rice (1976) while a system confining the impeller inside draft tubes was developed by Kirke and Gezawy (1997). Draft tube systems are commercially produced by the WEARS Company (Elliott & Morgan 2002). The draft tube reduces the energy requirement of the mixing process and pushes the warm water deeper than an open impeller or can be done with bubble plume system (Kirke & Gezawy 1997).

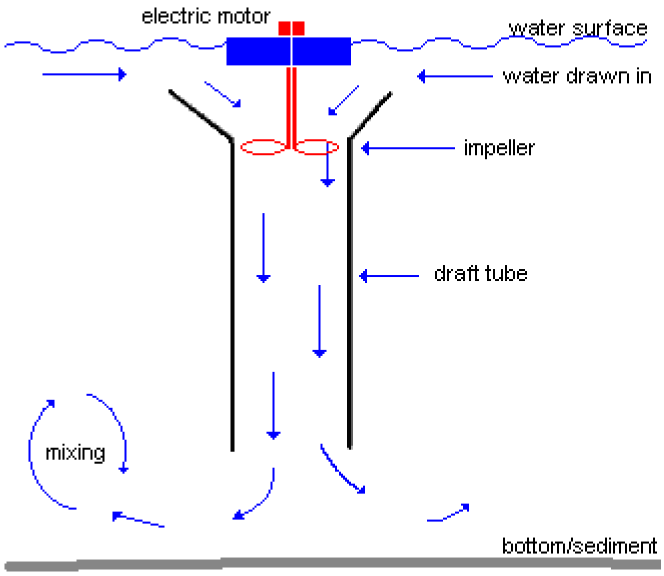



Figure 2.10 Schematic operation of impeller (surface mixers) with draft tube (after Elliott & Morgan 2002).

Other variants on these two categories of systems are available to circulate water in a lake or a reservoir:

a. Surface spray

The basic principle of this system is that the water is thrown into the air to create a fountain-shape spray above the surface. The oxygenation process occurs while the water is in the air. The water falls down into the body of water and its momentum carries it towards the bottom of the lake. The water circulation can be seen in Figure 2.11a.  This device is only effective in shallow lakes.

b. Impeller-Aspirator systems

The basic principle of this method is similar to that of the axial flow pump systems. However, the impeller or propeller in these systems forms an angle with the water surface of about 50 per cent. The rapidly turning impeller draws air down the shaft and propels water and air bubbles into a lake or a reservoir. Aeration occurs when air bubbles contact the body of water, see Figure 2.11b.

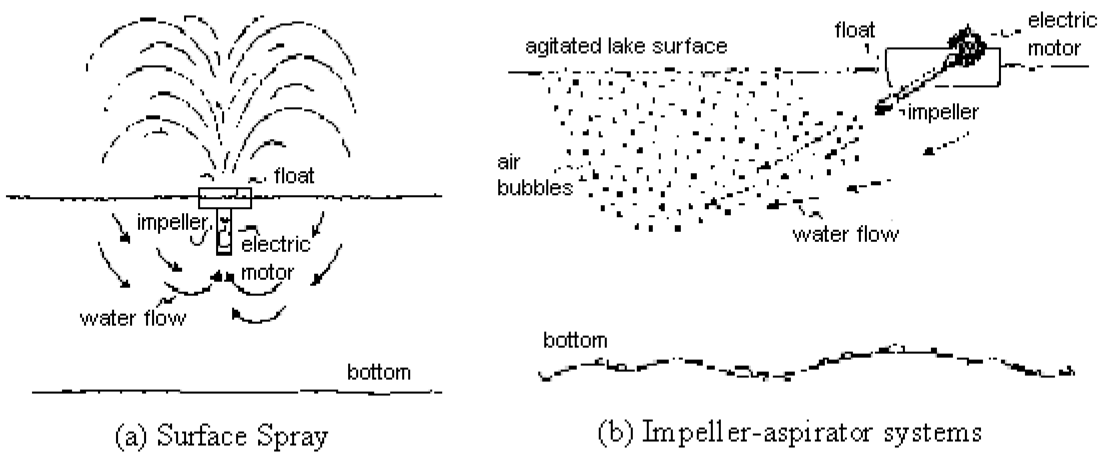



Figure 2.11 Combination of the common destratifiers.

2.3.4.2 Effects of artificial destratification on water quality

Destratification is intended to eliminate thermal or chemical layers in a body of water and so improve the overall water quality (Fast 1981; Hudson & Kirschner 1997; Jungo et al. 2001; Lewis et al. 2000; Wetzel 2001).  Jungo et al. (2001) reported that the water quality in Lake Nieuwe Meer was improved following the use of an artificial mixing bubble plume type device. Some evidence was presented to support their conclusions, with the mass of *Microcystis* up to 20 times lower than before mixing and an absence of scum on the water, the surface water temperature was also 2$^{o}$C lower as a result of the mixer. This led to a decreased total algae biomass. Lastly, the whole water-body oxygen content was consistently higher than 5 mg $L^{-1}$, increasing the living space for fish in the mixed reservoir.

Several researchers have observed an effect of artificial destratification on blue-green algae or Cyanobacteria. Fast (1981) comments that the first to measure the effects of artificial circulation on algal densities was Hooper et al. (1952). They pumped water from the hypolimnion layer to the surface in West Lost Lake, Michigan. Other researchers studied the impact of destratification on blue-green algae including Johnson (1966) who installed an artificial mixer in Erdman Lake, Washington, and McNall (1969, 1971) in Lake Roberts, New Mexico (Fast 1981).

These studies have shown increases, decreases or no change in the following phytoplankton parameters: biomass density (cell per mL; mg chl $m^{-3}$; or mgC $mL^{-1}$); total standing crop in the lake (kg); rate of reproduction (mgC $m^{-3}$); and/or algal type (cyanophyta, chlorophyta, etc.). Reduction in biomass, standing crop, reproduction and blue-green algae are considered desirable for most euthrophic lake uses. They generally result in greater water clarity, less surface scum, reduced treatment costs (drinking water), and better taste and odour. A clear, blue lake is aesthetically more pleasing to most people. Although these reductions are generally sought as benefits of the destratification system, they often do not occur and undesirable increases in some or all of these parameters can result (Fast 1981).

Hudson and Kirschner (1997) and Fang (1994) state that the most common result of destratification is an increase in dissolved oxygen levels in the body of water, particularly the hypolimnion layer.

Sherman et. al. (2000) reported that artificial destratification in Chaffey Dam increased hypolimnetic oxygen concentrations and reduced sediment nutrient release. It also increased temperature of the hypolimnion by 10$^{o}$C.

## 2.4 Water Quality Models for Reservoirs

### *2.4.1 Common water quality models*

The complexity of the interaction between algal growth, water temperature, pH, dissolved oxygen, and stratification make the use of a computer model attractive for evaluating methods of algal management. McCutcheon (1989) provides a useful way of classifying models by four levels of complexity:

(i) *level one* with steady state solution and simple kinetics, for example LAKE by ILEC (Jorgensen & Vollenweider 1989);

(ii) *level two* with steady hydrodynamics, specified or handled empirically, and steady or time variable water quality, for example AQUAMOD (Straskraba & Gnauck 1985);

(iii) *level three* with unsteady hydrodynamics but simplified solutions, simplified reservoir solutions, and dynamic water quality such as HSPF by USEPA (Bicknell et al 1996) which was developed into Water Modelling System (WMS) in 2002; and

(iv) *level four* with unsteady hydrodynamics including reservoir/river-routing equation, ability to handle backwater and stratified reservoirs, and dynamic water quality. Example of this level is DYRESM by CWR-UWA (Antenucci 2000).

Based on dimensionality of water body, water quality models can also be categorised as zero-dimensional, one-dimensional, two-dimensional and three-dimensional models.

Water quality models that are commonly used in reservoirs or lakes include:

2.4.1.1 ATV (Allgemein Verfugbares Gewassergutemodell)

The ATV (commonly called ATV Gewassergutemodell, or in English the ATV Water Quality Model) was developed in Germany as a water quality model to bridge the limitations some other models. It is designed as a series of building blocks that can be implemented as needed. The first building block is the hydrodynamic model, which solves the St. Venant equations for either the steady or unsteady case. The remaining building blocks can be added to the hydraulics as needed and include 17 water quality parameters such as water temperature, conservative tracers, COD/BOD, phosphorus, nitrogen cycle, silicon, algae, zooplankton, sediment/water exchange, suspended sediment transport, oxygen dynamics, pH dynamics, heavy metals, and organic chemicals. The solution to the transport equation uses the method of characteristics and does not have a Courant number constraint. Because of the model's modular design, simulations can be made as simple or as complicated as desired; however, the numerical expense of the hydrodynamic routine should not be underestimated. The ATV can also be coupled with a GIS system to provide geo-reference (Muller 2000).

2.4.1.2 CE-QUAL-R1

CE-QUAL-R1 is spatially one dimensional and horizontally averaged mathematical model of water quality that describes the vertical distribution of thermal energy and biological and chemical materials in a reservoir through time. The model was developed in the Environmental Laboratory of the US Army Engineer Research and Development Center. The model can simulate 27 water quality variables including physical factors (such as flow and temperature), chemical factors (such as nutrients), and biological assemblages in both aerobic and anaerobic environments in water column. The model also simulates 11 additional variables to represent materials in the sediments. Thermal stratification and water budget analysis can be performed using an independent model called CE-THERM-R1 (US Army Engineer Waterways Experiment Station 1986).

The thickness of layer in the water depending on the inflow outflow condition and the model set the layer dynamically. The distribution of inflowing waters among the layers is based on density differences. It is possible tosimulate surface flows, interflows, and underflows. The position of outflow or withdrawal of a water body can be set in the model to accommodate the multi-level withdrawal position in a reservoir (US Army Engineer Waterways Experiment Station 1986).

Some limitations of the model are: (i) longitudinal and lateral variations in water quality constituents cannot be predicted, (ii) all inflow quantities and constituents are instantaneously dispersed throughout the horizontal layers, and (iii) model predictions are probably most representative of water quality conditions near the dam or in the deepest part of the reservoir.

#### 2.4.1.3 CE-QUAL-W2

CE-QUAL-W2 (Corps of Engineers Quality Model for Two Dimensional Water bodies) is a dynamic two-dimensional, laterally averaged, hydrodynamic water quality model developed for stratified water bodies (Cole & Wells, 2003). The application of CE-QUAL-W2 requires knowledge in hydrodynamics, aquatic biology and chemistry, numerical methods, computers and FORTRAN coding, statistics, data assembly and reconstruction.

Hydrodynamic computations are influenced by variable water density caused by temperature, salinity, and dissolved and suspended solids. Developed for reservoirs and narrow, stratified estuaries, CE-QUAL-W2 can handle a branched and/or looped system with flow and/or head boundary conditions. With two dimensions depicted, point and non-point sources loading can be spatially distributed.

Version 3.2 of this model can predict water surface elevations, velocities and temperature plus 18 other water quality state variables and as many as 60 derived variables from input data, describing lake geometry and segmentation, climate, initial and boundary condition, external loading, benthic flux, spatial and time variable functions and rate constants (Cole & Wells 2003). CE-QUAL-W2 Version 3.2 has a capability to calculate ice cover and selective withdrawal heuristics including new turbulent kinetic energy-turbulent dissipation turbulence closure model. In this version CE-QUAL-W2 can estimate suspended solids re-suspension as a result of wind-wave action.

CE-QUAL-W2 has limitations when simulating vertical profiles in a water body because the model neglects vertical momentum as a consequence of using Boussinesq and hydrostatic approximations. This model also assumes no zooplankton and macrophytes and so simplifies the sediment oxygen demand.

#### 2.4.1.4 CORMIX: Cornell Mixing-Zone Model

The Cornell Mixing Zone Expert System (CORMIX) model was developed at the Oregon Graduate Institute as a near-field model for the analysis, prediction and design of aqueous toxic or conventional pollutant discharges into water bodies. A major emphasis of the model is on the computation of plume geometry and dilution characteristics within a receiving water's initial mixing zone. It also computes discharge plume behaviour at larger distances. The model has three modules - CORMIX1 for submerged single-point discharges, CORMIX2 for submerged multi-port diffuser discharges, and CORMIX3 for buoyant surface discharges. As implied by the title, the model predicts mixing (dilution) of the input chemicals, but does not allow for interaction among multiple chemicals (Jirka, Doneker & Hinton 1996).

The model equations represent on jets and plumes, which traditionally are modelled using integral equations. Integral equations rely on self-similarity to reduce the three-dimensional equations to a one-dimensional ODE. The model then solves for the three-dimensional trajectory of the plume centreline using the one-dimensional integral equations. Hydrodynamic conditions (though allowed to be unsteady) must be supplied as input to the model (Jones et al. 1996).

#### 2.4.1.5 DYRESM-CAEDYM (Dynamic Reservoir Simulation Model – Computational Aquatic Ecosystems Dynamics Model)

The model DYRESM is a one-dimensional hydrodynamics model for predicting the vertical distribution of temperature, salinity and density in lakes and reservoirs. It is assumed that a water body complies with the one-dimensional approximation in that the destabilizing forcing variables (wind, surface cooling, and plunging inflows) do not act over prolonged periods of time. The latest version (Version 2.4) of this model is able to accommodate mixing by artificial destratifiers; either of the bubble plume or mechanical impeller type (Antenucci 2000). DYRESM has been used for simulation periods extending from weeks to decades. Thus, the model provides a means of predicting seasonal and inter-annual variation in lakes and reservoirs, as well as sensitivity testing to long-term changes in environmental factors or watershed properties. DYRESM can be run either in isolation, for hydrodynamic studies, or coupled to CAEDYM for investigations involving biological and chemical processes. CAEDYM has been set up largely for assessment of eutrophication, modelling the N-P-Z (Nutrient-Phytoplankton-Zooplankton) interactions. This model also includes oxygen dynamics and several other state parameters. An advantage of this model is that it is able to categorize phytoplankton and zooplankton into several species (Herzfeld and Hamilton, 2000). The computational demands of DYRESM-CAEDYM are quite modest and multi-year simulations can be performed (Antenucci 2000).

Layers in DYRESM are based on a Lagrangian scheme where the layer thickness changes as a function of time. The layers are modelled as a series of horizontal layers of uniform property but variable thickness. The layer position changes with the effects of inflow, outflow, evaporation and rainfall. This is followed by layer thickness change as the layers move vertically to accommodate volume changes. Layers in the thermocline can be thinner than mixed layers in the epilimnion or the hypolimnion. The thickness of the layers is restricted by upper and lower limits to ensure that adequate resolution is achieved and that an excessive number of layers is not used. The lower limit is set small enough to accommodate the numerical process of diffusion when an excessive number of amalgamation layers occurs (Antenucci 2000).

DYRESM needs a range of data files to describe morphometry, meteorological, inflow, withdrawal, initial conditions, parameter, and configuration files. Data input are forced and translated into a NetCDF file as a reference file. DYRESM enables the simulation of a number of water quality parameters when coupled with CAEDYM.

A coupled DYRESM - CAEDYM model can simulate aquatic organisms which are important to water quality. The CAEDYM model is able to simulate seven groups of phytoplankton including freshwater Cyanobacteria, five groups of zooplankton, five kinds of fish, four groups of macro-algae, three groups of invertebrates, seagrass (*Halophila ovalis*) and jellyfish (*Phyllorhiza punctata*) (Antenucci 2000).

CAEDYM model is effectively an ecological model in that it accommodates dynamic processes in aquatic ecosystems including the limitation factors on the development of organisms, such as light, nutrient, and temperature. The model also considers respiration, mortality, and excretion processes, vertical migration and settling, as well as the effect of ambient conditions on micro-organisms such as the concentration of dissolved oxygen in water, and salinity.

Dissolved oxygen is one of the key parameters of water quality. It is determined in CAEDYM through the following processes:

1) Exchange to and from the air/water interface,
2) Utilization of oxygen at the sediment/water interface (i.e. the sediment oxygen demand),
3) Photosynthetic oxygen production and respiratory oxygen consumption by phytoplankton,
4) Photosynthetic oxygen production and respiratory oxygen consumption by the two macroalgae groups,

5) Photosynthetic oxygen production and respiratory oxygen consumption by seagrasses/macrophytes,
6) Utilization of oxygen due to the action of bacteria on organic matter (i.e. the water column biochemical oxygen demand),
7) Utilization of oxygen in the process of nitrification,
8) Utilization of dissolved oxygen due to photosynthesis and respiration in jellyfish, and
9) Utilization of dissolved oxygen due to respiration of higher organisms (zooplankton, fish).

2.4.1.6 HSPF (Hydrological Simulation Program – FORTRAN)

Developed in the late 1970s by the USGS (United States Geological Survey) and USEPA (United States Environmental Protection Agency), HSPF is a union between the Stanford Watershed Model, a continuous-simulation, process-oriented hydrologic model, and several water quality models developed by the EPA, including the Agricultural Runoff Model (ARM) and the Non-Point Source Model (NPS). The model is intended for both conventional and toxic organic pollutants. Contaminant loads are either user-input point sources or non-point sources modelled by build-up and wash-off parameterizations. It is a comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions (Bicknell et al. 1996).

An advantage of HSPF is in its software development, which resulted in a complete data-management tool. A disadvantage of HSPF is its large data requirements, which include physical data such as watershed data, river network discretization, soil types, geologic setting, vegetative cover, towns, and other regional data, meteorologic data such as hourly data for precipitation, solar radiation, air temperature, dew-point temperature, and wind speed and daily evapotranspiration. In addition, the model has a wealth of empirical calibration parameters that must be determined from handbook values and by calibrating to field measurements (Bicknell et al. 1996).

The river transport model is a tanks-in-series model that uses stage-discharge relationships (which must be input by the user from external knowledge) to simulate flood routing.

The result of this simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed. HSPF simulates three sediment types (sand, silt, and clay) in association with a single organic chemical and transformation products of that chemical. The transfer and reaction processes of hydrolysis, oxidation, photolysis, biodegradation, volatilization, and sorption are included. Sorption is modelled as a first-order kinetic process in which the user must specify a desorption rate and an equilibrium partition coefficient for each of the three solids types. Resuspension and settling of silts and clays (cohesive solids) are defined in terms of shear stress at the sediment water interface. The capacity of the system to transport sand at a particular flow is calculated and re-suspension or settling is defined by the difference between the sand in suspension and the transport capacity. Calibration of the model requires data for each of the three solids types. Benthic exchange is modelled as sorption/desorption and deposition/scour with surficial benthic sediments. Underlying sediment and pore water are not modelled (Bicknell et al. 1996).

Limitations of HSPF include the assumption that the Stanford Watershed Model is appropriate for the area being modelled. This might not be the case. Further, the in-stream model assumes that the receiving water body is well mixed throughout the width and depth, and is thus limited to well-mixed rivers and reservoirs.

#### 2.4.1.7 QUAL2E: Enhanced stream water quality model

The QUAL2E series of models has a long history in stream water quality modelling. It was primarily developed by the US Environmental Protection Agency (USEPA) in the early 1970s. Since then it has gained a broad user base, including applications outside the U.S. in Europe, Asia, and South and Central America.

The Enhanced Stream Water Quality Model (QUAL2E) is applicable to well mixed, dendritic streams. It simulates the major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, atmospheric reaeration and their effects on the dissolved oxygen balance. It can predict up to 15 water quality constituent concentrations. It is intended as a water-quality planning tool for developing total maximum daily loads (TMDLs) and can also be used in conjunction with field sampling for identifying the magnitude and quality characteristics of non-point sources. By operating the model dynamically, the user can study diurnal dissolved oxygen variations and algal growth. However, the effects of dynamic forcing functions, such as headwater flows or point source loads, cannot be modelled with QUAL2E. QUAL2E-U is an enhancement allowing users to perform three types of uncertainty analyses: sensitivity analysis, first-order error analysis, and Monte Carlo simulation (Brown & Bornwell 1987).

The model only simulates steady-state stream flow and contaminant loading conditions; the reference to dynamic modelling above refers only to water quality forcing functions of climatologic variables (air temperature, solar radiation, among others). The transport scheme in the model is the implicit backward-difference finite difference method.

2.4.1.8 WASP (Water Quality Analysis Simulation Program)

WASP Version 6 is a comprehensive surface water quality modelling package that generalizes a framework for modelling contaminant fate and transport in surface water bodies. This model helps users interpret and predict water quality responses to natural phenomena and man-made pollution for various pollution management decisions The model is flexible and compartmental to be applied in one-, two-, or three-dimensional water quality models. It has capability solving BOD, DO, nutrient and eutrophication, bacterial contamination, and toxic chemicals (organics and metals) problems. In addition, WASP has also been developed with a number of WASP sub-models for specific applications or for application to a particular type of pollutant.

Some sub-models developed for WASP are FLWASP for eutrophication model, MERC4 for simulating impact of fate and transport sediment and water, META4 for metals transport, speciation, and kinetics model, OMNIWASP for for simulating the impact of macrophytes on dissolved oxygen concentrations in estuaries, STEADY for toxicant model for screening chemicals for recontamination potential, and SALT5 for simulating water temperatures (include ice cover), coliform bacteria, and conservative tracers (Wool et al. 2002).

WASP is capable of linking with other EPA models. Predicted flows and volumes can be read by linking to the hydrodynamic model DYNHYD. Loading files from HSPF can be reformatted. Toxicant concentrations predicted by TOXI can be read and used by both the WASP Food Chain Model and the fish bioaccumulation model FGETS.

A body of water is represented in WASP as a series of computational elements or segments. Environmental properties and chemical concentrations are modelled as spatially constant within segments. Segment volumes and type (surface water, subsurface water, surface benthic, subsurface benthic) must be specified, along with hydraulic coefficients for riverine networks.

Seven types of input data are required to run WASP 6.0. Simulation and output control; model segmentation; advective and dispersive transport; boundary concentrations; point and diffuse source waste loads; kinetic parameters, constants and time functions; and initial concentrations are processed with mass balance equations and specific chemical kinetics equations to simulate extensive water quality parameters.

All the above models were compared to select the appropriate water quality model package for this project. Selection was based on four major criteria which are (i) accommodating surface mechanical mixers (destratifiers); (ii) capability to simulate at least cyanobacterial concentration, water temperature, and dissolved oxygen; (iii) suitability for Australian reservoirs; and (iv) the cost. The DYRESM-CAEDYM software package fulfils the criteria and it was chosen to predict water quality in two of the three Toowoomba's reservoirs.

### *2.4.2 Hydrologic model: Australian Water Balance Model (AWBM)*

Inflow to a reservoir is a very important part of a reservoir water balance and is required by dynamic reservoir models to simulate the water body. However, Toowoomba's three reservoirs have no recorded inflow data. Rainfall-runoff modelling can be used to predict daily inflow to a reservoir when no recorded inflow data exists (Boughton 2002).

Australian Water Balance Model (AWBM) is a rainfall-runoff model that is commonly applied to Australian catchments. The structure of the AWBM is simple and flexible as shown in Fig. 2.12. It has three input parameters (daily/monthly rainfall, monthly evaporation and daily inflow) with eight simulated parameters compared to the Sacramento and Stanford Watershed Models (each with more than 20 parameters) and the SIMHYD (7 parameters) so it is easy to use and calibrate (Boughton 2002, 2005). The latest version of the model (Version 4.0) consists of AWBM2002 for calibrating AWBM with base-flow in runoff, AWBM97 for calculating runoff from long rainfall record, SURF for calibrating AWBM with surface runoff only, BASE97 for analysing sensitivity of parameters, NEWBFLOW for analysing base-flow, CHECKAL for checking data errors and LOADDATA for loading filenames and parameter values (Boughton 2002).

Daily rainfall data and evaporation data are needed by all sub-models. Daily flow data are needed by AWBM2002, BASE97 and NEWBFLOW while monthly flow data are required by AWBM97, SURF, and BASE97.

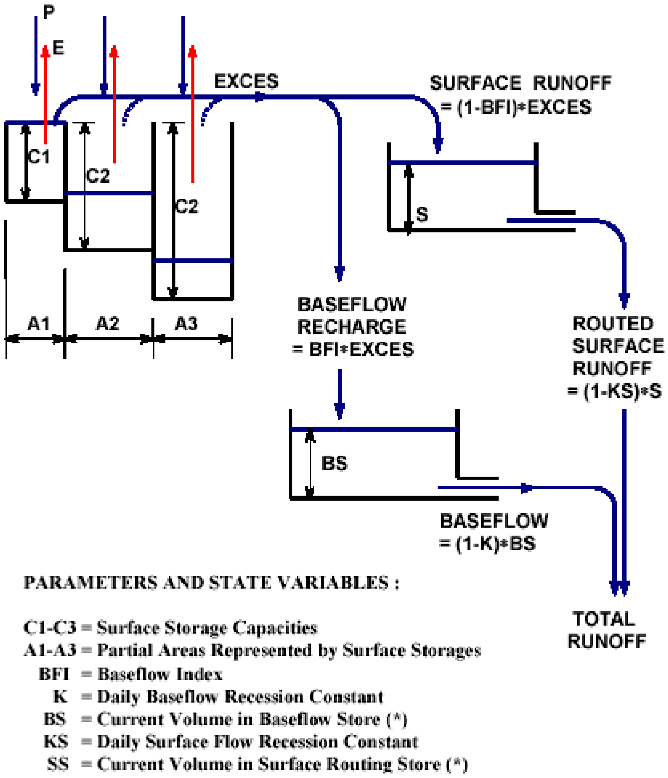



Figure 2.12 Structure, parameters and state variables of the AWBM (from Boughton 2002, http://www.catchment.crc.org.au/products/models/the_models/awbm/AWBMmanual.pdf).

The AWBM model was adopted to produce inflow data because this model was independently verified in Toowoomba's three reservoir catchments in 1994 and 1999 (Loxton 1999).

## 2.5 Weather Generator

Most water quality models need a time series of historical weather data as a main input (Antenucci & Imerito 2001; Beck & Straten 1983; Cole & Wells 2002; Straskraba & Gnauck 1985). The weather interacts with other natural resources and influences water quality parameters in open sources of water bodies.

Weather data is frequently required as input to computer programs for ecological and environmental modelling of natural systems such as reservoirs.

Weather generators are computer programs that have been developed to produce complete weather input data sets where only some of the parameters are recorded. Using the existing weather records, these computer programs are able to generate a long series of synthetic daily climatic data. Some computer program packages commonly used in this way are WGEN (Richardson & Wright 1984), CLIGEN (Nicks & Gander 1993), ClimGen (Stockle, Campbell & Nelson 1999), and LARS-WG (Semenov & Barrow 1997; Semenov et al. 1998).

Most weather models use stochastic simulation to generate data (Matalas 1967; Richardson 1981). WGEN uses as input daily series of measured precipitation, maximum and minimum temperature, and solar radiation to generate other series data. ClimGen generates data in a similar way to WGEN but with some improvements. LARS-WG is based on the series weather generator described by Racsko et al. (1991). It utilizes a semi-empirical distribution for the length of wet and dry day series, daily precipitation and daily solar radiation.

Nicks and Gander (ARS-USDA) (1993) have developed CLIGEN to produce a time series of daily weather parameters including maximum and minimum temperature, solar radiation, precipitation, wind direction, wind speed, temperature and dew point from monthly observed statistics at the site, like monthly mean, standard deviation, and skewness (Meyer et al. 2001). The ClimGen model was selected for use in this project. The following section describes parameters used in ClimGen (McKague, Rudra, & Ogilvie 2003).

### *2.5.1 Rainfall*

Precipitation is generated using the likelihood of the occurrence and the amount of precipitation on a particular day. Rainfall intensity and duration within the rain event are involved in the model. With this feature, ClimGen is able to generate data for several different purposes.

2.5.1.1 Daily rain day occurrence

Daily rain days is modelled by using a two-state Markov chain. The probability of occurrence of a wet or a dry day following either a dry or a wet day is defined using a Markov chain for the combination of conditional probabilities as described by Nicks et al. (1990).

$$P(w|d) = \alpha \tag{2.13}$$

$$P(d|d) = 1 - \alpha \tag{2.14}$$

$$P(d|w) = \beta \tag{2.15}$$

$$P(w|w) = 1 - \beta \tag{2.16}$$

where $P(w|d)$ is the probability of a wet day given a previous dry day,
$P(d|d)$ is the probability of a dry day given a previous dry day,
$P(d|w)$ is the probability of a dry day given a previous wet day, and
$P(w|w)$ is the probability of a wet day given a previous wet day.

Monthly probabilities are analysed using historic long-term precipitation data.

2.5.1.2 Amount of daily precipitation

ClimGen adopt the Weibull distribution function to generate a precipitation amount. The distribution performed best in describing the cumulative probability of precipitation at 33 United States Climate Stations (Selker & Haith 1990). The distribution is described as follows:

$$F(P) = 1 - \exp\left(-\left(\frac{P}{\beta}\right)^{\alpha}\right) \tag{2.17}$$

where $F(P)$ is the cumulative probability of a precipitation amount,

$P$, and $\alpha$ and $\beta$ are parameters of the distribution function that are calculated on a monthly basis.

Each precipitation event is sampled using the inverse method as follows:

$$P = \beta\left[-\ln(r)\right]^{1/\alpha} \tag{2.18}$$

where r is a uniform random number between 0 and 1.

The variation of the Markov chain transition probabilities and the precipitation distribution parameters with seasons in most areas were addressed by Richardson (1981). He suggests the use of a Fourier series or some other cyclical model to describe the periodic variation of these parameters.

### *2.5.2 Air temperature and solar radiation*

Statistical modelling of air temperature and solar radiation is not as difficult as precipitation. However, weather generation has to account for the dependency between precipitation and temperature and solar radiation. Air temperature levels during wet days tend to be naturally lower than during dry days (Richardson 1981). Similarly, solar radiation levels are observed to be lower on a wet day due to increased cloud cover (Richardson 1982).

Richardson (1981) developed a continuous multivariate stochastic approach to incorporate the appropriate air temperature and solar radiation levels on wet and dry days. His technique is used in WGEN, CLIGEN, CLI90, ClimGen and LARS-WG. One result of applying this method is that daily means and standard deviations for the cumulative temperature and solar radiation distributions are influenced by the occurrence of wet and dry days (Richardson 1981). To adjust for variations in season means and standard deviations, ClimGen uses a *spline-fitting* procedure which obtains the residual elements of the function by removing the periodic mean and standard deviation using the following equations (Richardson 1981):

$$\chi_{p,i}(j) = \frac{X_{p,i}(j) - \bar{X}_i^o(j)}{\sigma_i^o(j)} \qquad \text{for} \quad Y_{p,i} = 0 \tag{2.19}$$

or

$$\chi_{p,i}(j) = \frac{X_{p,i}(j) - \bar{X}_i^1(j)}{\sigma_i^1(j)} \qquad \text{for} \quad Y_{p,i} > 0 \tag{2.20}$$

where $\bar{X}_i^o(j)$ and $\sigma_i^o(j)$ are the mean and standard deviation for a dry day ($Y_{p,i} = 0$),

$\bar{X}_i^1(j)$ and $\sigma_i^1(j)$ are the mean and standard deviation for a wet day ($Y_{p,i} > 0$),

$\chi_{p,i}(j)$ is the residual component for the variable $j$ (i.e. maximum temperature ($j$=1), minimum temperature ($j$=2), or solar radiation ($j$=3)).

### *2.5.3 Wind speed*

ClimGen generates wind speed without any correlation with other variables. Average daily wind speed ($U$) is assumed following a Weibull distribution in a similar way to precipitation:

$$F_m(U) = 1 - \exp\left(-\left(\frac{U}{\beta}\right)^{\alpha}\right) \tag{2.21}$$

where $F_m(U)$ is the cumulative probability distribution of average daily wind speed in a month,

$\beta$ is a scale parameter determined from the observed wind data,

$\alpha$ is a shape parameter determined from the observed wind data.

This distribution is sampled for each day of weather generation using the inverse method:

$$U = \beta\left[-\ln(r)\right]^{1/\alpha} \tag{2.22}$$

where r is a random number ranging between 0 and 1.

### *2.5.4 Air humidity*

The daytime and nighttime dew point temperatures ($T_{dd}$ and $T_{dn}$) are calculated using a relationship between measured minimum and maximum relative humidity ($RH_{min}$ and $RH_{max}$) and measured maximum and minimum air temperature data ($T_{max}$ and $T_{min}$) as follows:

$$e^o(T_{dd}) = e^o(T_{\max})\frac{RH_{\min}}{100} \tag{2.23}$$

$$e^o(T_{dn}) = e^o(T_{\min})\frac{RH_{\max}}{100} \tag{2.24}$$

where $e^o(T)$ is the saturation vapour pressure (kPa) determined at a specified temperature (T, in $^o$C).

Dew-point temperatures are obtained by inverting the following equation.

$$e^o(T) = 0.6108\exp\left[\frac{17.27T}{T+237.3}\right] \tag{2.25}$$

A linear regression between daytime and nighttime dew point temperatures is calculated during the parameter optimization phase of ClimGen.

ClimGen calculates the maximum vapour pressure deficit ($VPD_{max}$) from the historical daily data. This maximum difference between the saturation vapour pressure and the actual vapour pressure is typically obtained at the time of minimum relative humidity and maximum temperature (Nelson 2002):

$$VPD_{\max} = e^0(T_x)\left(1-\frac{RH_{\min}}{100}\right) \tag{2.26}$$

If the aridity factor ($a$) is available, the daily maximum vapour pressure deficit can also be estimated from temperature:

$$VPD_{\max} = \frac{e^0(T_{\max}) - e^0(T_{\min})}{1-a\left[e^0(T_{\max}) - e^0(T_{\min})\right]} \tag{2.27}$$

ClimGen optimizes the aridity factor by combining the above equations. Air humidity data can be generated using the optimal aridity factor.

ClimGen is the most suitable weather generator for use in water quality modelling, however, the number of simulated weather variables is not comprehensive. Cloud cover is one parameter not generated by ClimGen.

### *2.5.5 Cloud cover*

Most weather generator packages are unable to produce synthetic cloud cover data. However, cloud cover values can be produced by a simple stochastic cloud generator (Raisanen et al. 2001; Raisanen 1999). Generation of cloud fraction is a defined variable $x \in [0,1]$ (cumulative frequency) such that:

$$\begin{cases} x_j \le 1 - C_j \Leftrightarrow \textit{layer } j \text{ clear for this subcolumn} \\ x_j > 1 - C_j \Leftrightarrow \textit{layer } j \text{ cloudy for this subcolumn} \end{cases}$$

The algorithm for generating *x* depends on cloud overlap assumptions. For example,

$$\begin{cases} x_j = RND \Leftrightarrow \text{random overlap} \\ x_j = x_{j-1} \Leftrightarrow \text{maximum overlap} \end{cases}$$

## 2.6 Risk Analysis and Sustainability

It is an important system requirement for water resources managers to be able to operate reservoirs satisfactorily under a wide range of possible future demands and hydrologic conditions and to provide water of an acceptable quality. The goal is to attain a sustainable water resources system. A method of quantifying the level of sustainability is required in order to attain this goal.

The American Society of Civil Engineers (ASCE) and United Nations International Hydrologic Program (UNIHP) define sustainable management of water resources as follows:

> *…sustainable water resources systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity. (ASCE & UNIHP 1998).*

This definition of a sustainable system incorporates the following elements:

1. the system does not cause harm to other systems, either in space and time;
2. the system maintains living standards at a level that does not cause physical discomfort or social discontent to humans; and
3. life-supporting ecological components are maintained at levels of current conditions, or better within the system.

### *2.6.1. Hydrological risk*

Loucks (1997) proposed criteria for the sustainability of water resources systems based on risk criteria related to reliability, resilience and vulnerability (R-R-V). He postulated a water resources system comprising $I$ users and a set of possible future scenarios. The notion *user* is not limited to consumers but should be understood as any economic, social or environmental activity dependent on the water supply from the system under consideration. The performance of an individual user $i$ can be determined from water resources system variables (such as flow, velocity, storage, depth etc.) and is denoted $X_t$. A time series of a given performance variable $X_t$ can be derived by simulation using an appropriate hydrological modelling system. For each user a threshold level $X_0$ needs to be specified to separate satisfactory from non-satisfactory values of the variable under consideration.

Given $X_t$, for $t = 1, \dots, N$, a failure has occurred when $X_t < X_0$. Let $n$ be the total number of failures or time steps where $X_t < X_0$. The duration and deficit volume of the $j$th (a failure period) are denoted by $d_j$ and $s_j$ respectively, $j = 1, \ldots, M$, where $M$ is the number of failure events. The term's duration and deficit volume are defined in Fig. 2.13. The system reliability is then estimated as:

$$\text{Rel} = P\{X_t \le X_0\} = 1 - \frac{n}{N} \tag{2.28}$$

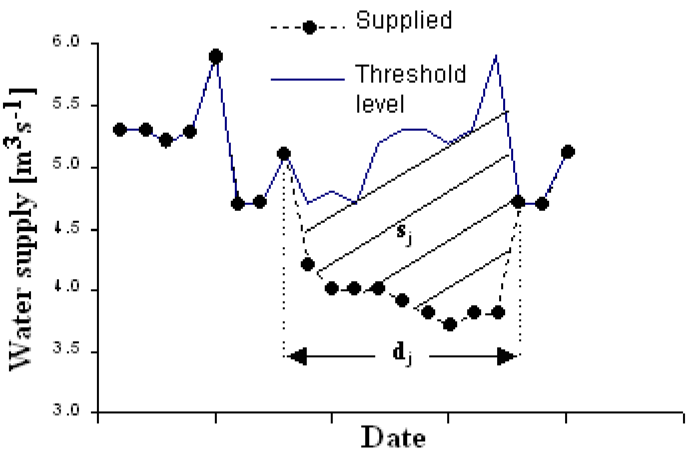



Figure 2.13 Definition of duration ($d_j$) and deficit volume ($s_j$) of a failure period.

Resilience and vulnerability are estimated as:

$$\text{Res} = \frac{1}{E\{d\}} = \left[\frac{1}{M}\sum_{j=1}^{M} d_j\right]^{-1} \tag{2.29}$$

$$\text{Vul} = E\{s\} = \frac{1}{M}\sum_{j=1}^{M} s_j \tag{2.30}$$

Finally, a sustainability index $S$ is calculated for each user as:

$$S(i) = \text{Rel}(i)\ \text{Res}(i)\ [1 - \text{rVul}(i)] \tag{2.31}$$

where

$$r\text{Vul}(i) = \frac{\text{Vul}(i)}{\text{sum of Vul}(i)\text{ from all scenarios}} \tag{2.32}$$

A final sustainability score, *rS*, for each scenario *x* is estimated as:

$$rS(x) = \sum_{i=1}^{I} w_i S(i) \tag{2.33}$$

The index *rS*(*x*) lies between 0 and 1, with large values pointing to the most sustainable scenarios. Loucks (1997) suggested that the system under consideration should be simulated 50 years into the future and for each 10 years *rS*(*x*) should be estimated to show temporal trends in relative sustainability. However, no recommendations on how to incorporate the temporal variation of *rS*(*x*) in decision-making were made.

The system performance indices R-R-V used in Loucks' sustainability criteria (Loucks, 1997) could be used to accommodate the problem of temporal variation in the sustainability criteria in decision-making.

$$rS(x) = \frac{1}{T}\sum_{t=1}^{T}\sum_{i=1}^{I} w_i S(i,t,x) \tag{2.34}$$

$$rS'(x) = \frac{1}{I}\sum_{i=1}^{I} w_i \sum_{t=1}^{T} S(i,t,x) \tag{2.35}$$

where *rS* is the relative sustainability of the *x*th scenario,
*T* is the total number of intervals in which R-R-V are estimated,
$w_i$ indicate the importance of the *i*th impact and sum to one.

### *2.6.2. Water quality indices*

In assessing the acceptability of water quality in water bodies, the manager uses and selects indicators based on the local condition to produce a single index. The purpose of using an index is to provide a better understanding of the overall condition of water quality through integrated complex parameters and to evaluate water quality trends. The index can be produced from different key parameters depending on the local values of water storages as shown in Figure 2.14.

Cude (2001) expressed the water quality condition of Oregon's Stream by integrating eight water quality parameters called the Oregon Water Quality Index (OWQI). Figure 2.14 shows the valuation of sub indices of selected water quality indicators for OWQI.

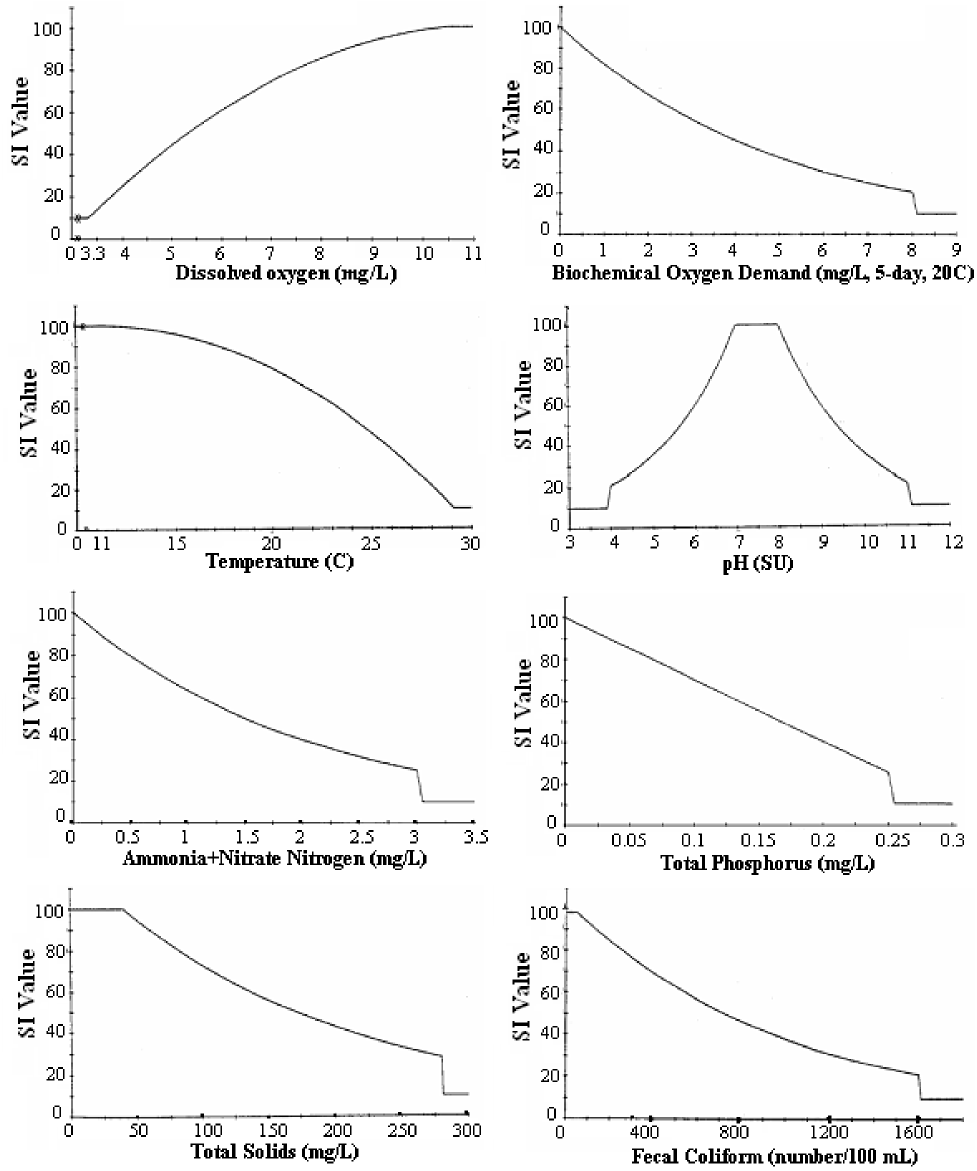



Figure 2.14 Sub index values of selected water quality indicators for OWQI (from Cude 2001, pp. 127-30).

Dojlido et al. (1994) improved the OWQI value by combining the weighted arithmetic mean formula (original formula) and the weighted geometric mean formula (McClelland 1974). The modification formula is given in Equation 2.36.

$$WQI = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{SI_i^2}}} \qquad (2.36)$$

where $n$ is the number of subindices, $SI_i$ is Subindex $i$ value.

## 2.7 Water Quality Management in a Stratified Reservoir

The spatial and temporal variation of water quality in a stratified reservoir is an issue in the management of reservoirs. Water treatment plants need a fairly constant raw material to ensure treatment to required levels before distribution to consumers. There are three general ways to improve the quality of outflow from reservoirs; (i) water quality inflow management through reservoir watershed management, (ii) the selection of a withdrawal position for the best possible quality, and (iii) the use of additional equipments to improve outflow water such as mechanical mixers and aerators (Straskraba & Tundisi 1999).

### *2.7.1 Watershed management*

Watershed management can reduce nutrient input to a reservoir and slow down the eutrophication process. This method is an effective way to improve water quality in reservoirs which have low retention times. The quality of inflow is commonly affected by human activity associated with land use management in the reservoir's catchments.

Straskraba et al. (1993) introduced some basic principles of watershed management in a reservoir's catchment: (i) spatial heterogeneity protection and improvement by maintaining the existence of riparian forests and natural vegetation, (ii) biological diversity enhancement and denitrification encouragement through protection of the recovery areas of natural wetland, (iii) source treatment of nutrient pollution, for example: pre-impoundment in the rivers or creeks, and changing agricultural practices with minimum fertilizer, (iv) sediment input reduction.

The Toowoomba City Council manages the reservoir's catchments by maintaining the forest and the natural vegetation in the catchment areas and pre-impoundment in the creeks to reduce sediment input.

### *2.7.2 Management within the reservoir*

The selection of a withdrawal level for the best possible quality of raw water is a method to get good quality outflow without an upgrade of water quality condition in reservoirs. This method is suitable for multilevel output reservoirs. Additional means such as a mechanical mixer and an aerator can also improve water quality in reservoir, particularly in an outflow layer (Straskraba & Tundisi 1999; Straskraba, Tundisi & Duncan 1993).

A summary of management options within the reservoir water body is presented in Table 2.5.

Table 2.5 Management options within the reservoir.

| Measure | Means | References |
|---|---|---|
| Hydraulic regulation | Selective withdrawal | Straskraba 1996 |
| Fish management (biomanipulation) | Zooplankton control- Phytoplankton reduction | Gulam et al 1990 |
| Artificial mixing | 1. Destratification | Symons et al 1967 |
| | 2. Hypolimnetic aeration | Benhardt 1967 |
| | 3. Epilimnetic mixing | Straskraba 1986 |
| Phosphorus inactivation | 1. Alum precipitation | Cooke & Kennedy 1988 |
| | 2. Sediment covering | Petersen 1980 |
| Sediment aeration | Sediment injection | Ripl 1976, 1985 |
| | Sediment removal | Hanson & Stefan 1985 |
| Light reduction | Shading, covering, suspension, colours | Jorgensen 1980 |

*Source: Straskraba, Tundisi & Duncan 1993, p. 269 Table XIV*

# Chapter 3

# STUDY SITE AND METHODOLOGY

## 3.1 Study Site

Field work was completed between January 2003 and November 2005, based on two of Toowoomba's reservoirs - Cooby and Cressbrook reservoirs. The dams are situated to the north of Toowoomba City in Southern Queensland as shown in Figure 3.1.

Geographically**,** Cooby and Cressbrook dams are located by latitude and longitude at 27$^{o}$24' S and 151$^{o}$55' E, and 27$^{o}$15' S and 151$^{o}$12' E, respectively. The dams are classified as sub-tropical reservoirs.

### *3.1.1 Cooby reservoir*

Cooby Dam has supplied domestic water to Toowoomba City since it was built in 1941 (Toowoomba City Council 2001). The storage is situated 40 km to the north of the city at an elevation of 478 m above sea level. It consists of an earth and rock fill wall with a 69.25 m wide concrete spillway. At full supply-level the ponded area covers an area of 301 ha and the reservoir holds a total storage volume of 23,092 ML.

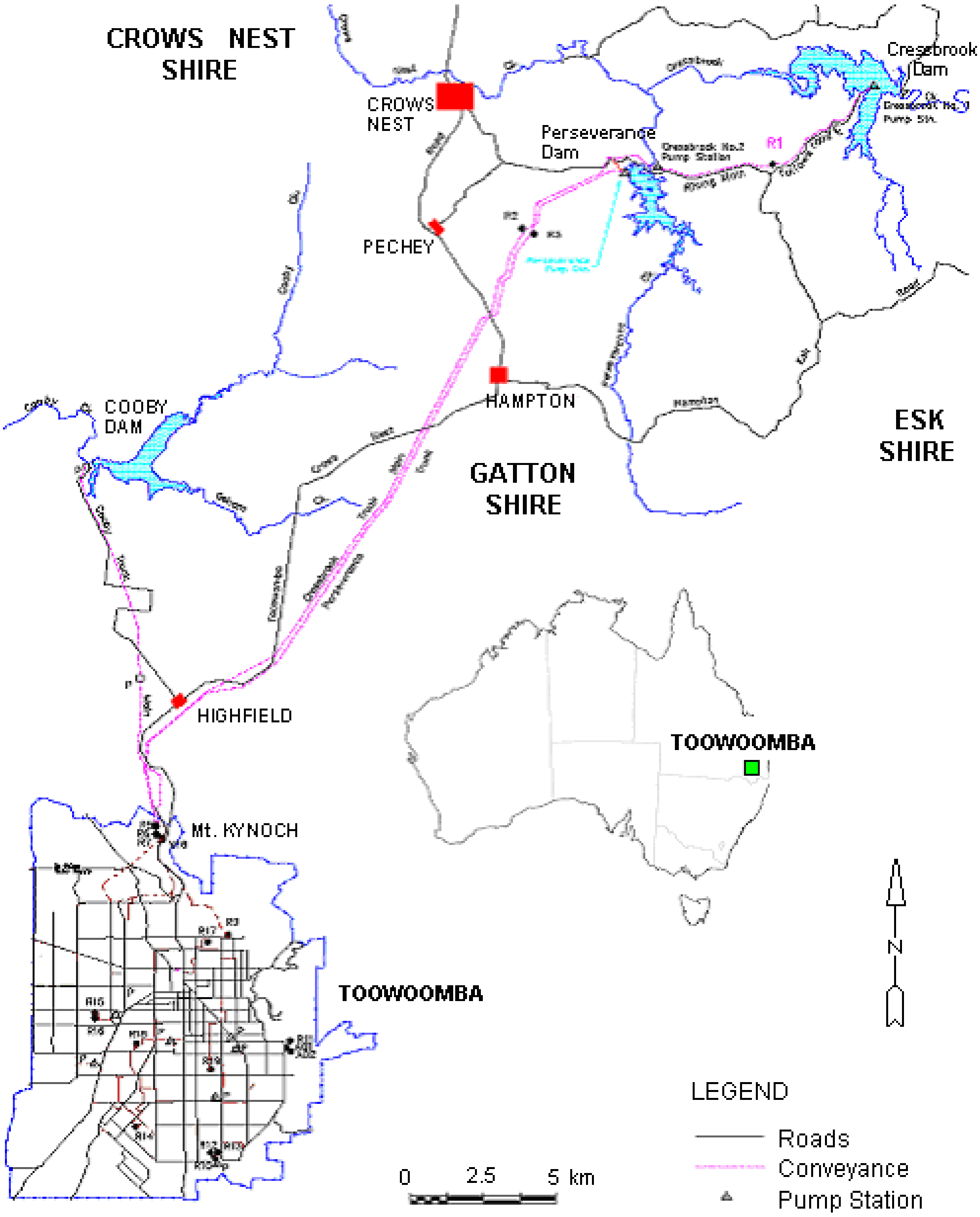



Figure 3.1 Toowoomba water supply sources and reservoirs (after Water and Waste Operation Toowoomba City Council 2001).

The total catchment area for the storage is 171 km$^2$. Of this area, 68.9 per cent is used for grazing, 16.9 per cent for residential, 6.9 per cent forests, 3.7 per cent reserves, 2.1 per cent horticulture, and 1.5 per cent for intensive livestock (Toowoomba City Council, 2001). Cooby and Geham Creeks provide two direct inflows to the reservoir. Cooby Creek combines the flows from Coobybilla and

Merritts Creeks. The detail of drainage network and creeks of the Cooby catchment can be seen in Figure 3.2.

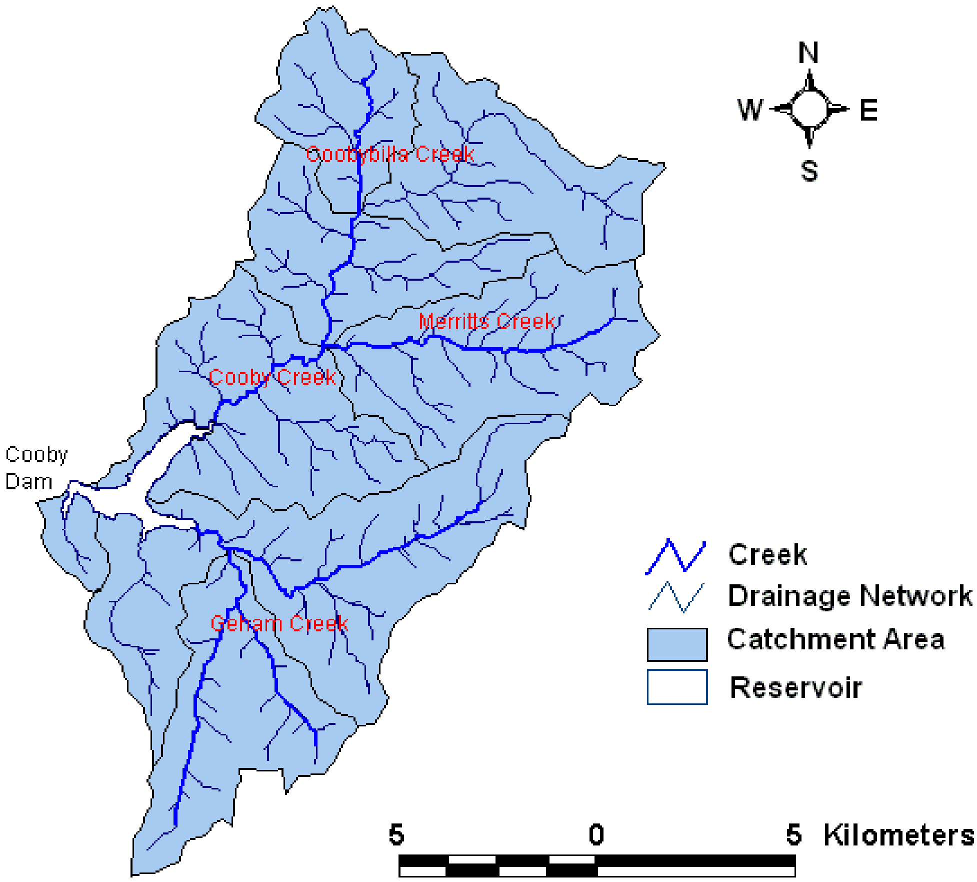



Figure 3.2 Cooby reservoir and its catchment area (the blue line represents the drainage network for Cooby reservoir (white area) and light blue indicates the Cooby catchment area).

### *3.1.2 Cressbrook reservoir*

Cressbrook Dam was built in 1983 to meet an increasing domestic water demand from Toowoomba City. The storage is located 60 km to the north of the city at an elevation of 290 m. It incorporates an earth and rock wall with a 200 m wide concrete spillway. At full supply-level the ponded area covers an area of 517 ha and the reservoir holds a total storage volume of 81,842 ML (Toowoomba City Council, 2001).

The total catchment area for the storage is 326.3 $km^2$. This area includes the catchment for Perseverance Dam (109.54 $km^2$) which lies upstream on Cressbrook Creek. The additional catchment for Cressbrook alone is about 207.89 $km^2$. Of this area, 60.1 per cent is used for grazing, 22.4 per cent reserves, 12.2 per cent for residential, 3.5 per cent horticulture, 1.7 per cent State forests, and 0.1 per cent for intensive livestock (Toowoomba City Council, 2001). There are two creeks supplying direct inflow to the reservoir as shown on Figure 3.3. Cressbrook Creek is in the western part of the reservoir and Little Oaky Creek is in the southern part of the reservoir. Cressbrook Creek contributes about 84 per cent surface flow to the reservoir. The creek accumulates inflows from Back, Old Woman's Hut, Bald Hills, and Crow's Nest Creeks including the overflow from Perseverance Dam.

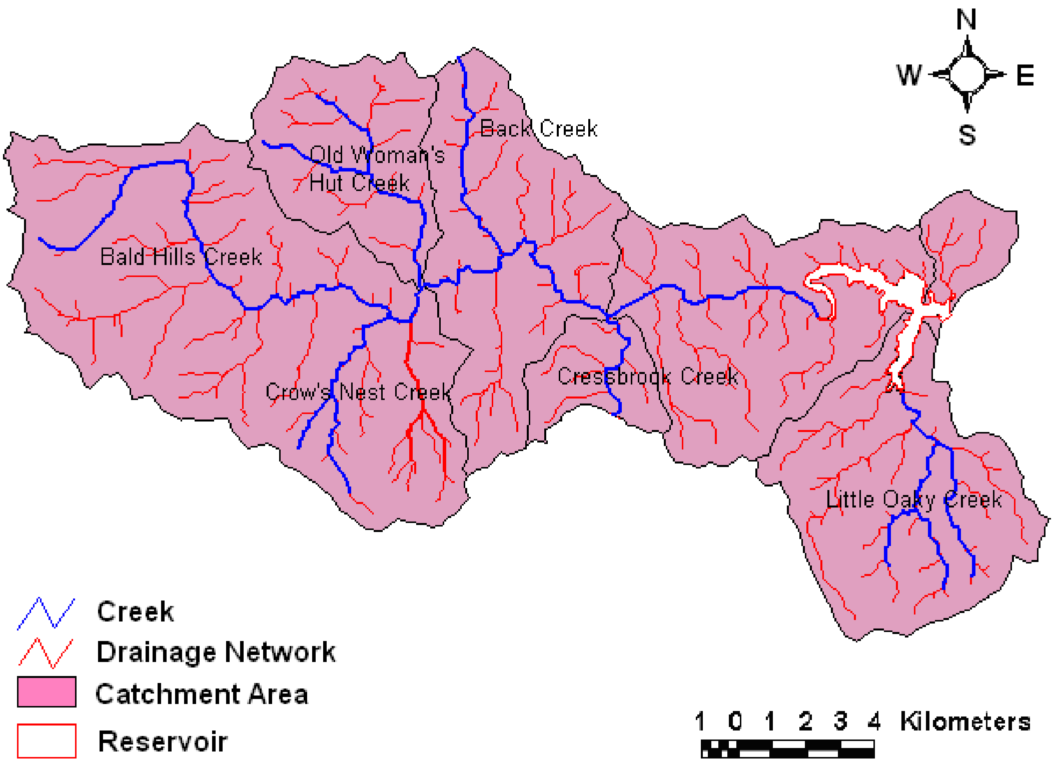



Figure 3.3 Cressbrook reservoir and its catchment area. The red line represents the drainage networks, the white area represents Cressbrook reservoir, and the pink area represent the catchment area of the reservoir.

## 3.2 Research Methodology

This thesis quantifies the effects of surface mechanical mixers in Cooby and Cressbrook dams, and then presents management options to optimise that quality. The results are based on extensive simulation of the reservoirs performance. The simulations are in turn based on historic and simulated data and quantify statistical analyses of the reservoirs' behaviour; stratification and destratification analysis; and the inflow and reservoir water quality. The adopted methodology was developed in complementary stages to meet the project objectives. Stepwise regressions were first used to establish correlations between parameters through the year for reservoir conditions before and after mixer installation. Regression analyses were also used to determine the accuracy of model results when compared to field data. Stratification analyses quantified the stability of stratification in the reservoir and consequently the energy needed to mix the whole water body. The mixing and destratification calculations enabled the process of destratification and the effect of mechanical destratifiers on water quality to be examined.

The DYRESM-CAEDYM software package was used to simulate water quality parameters with mixing and stratification processes occurring. Synthetic weather data for a 50 year period were generated using a stochastic climate generator program (CLIMGEN Version 4.1.3) and a random number generator (RNG Excell 2000). AWBM simulated inflows to the reservoirs from these synthetic weather data. The weather and inflow data were used in DYRESM-CAEDYM to indicate the future condition of the reservoirs with and without artificial mixers. The probability of the occurrence of algal-alert levels was then determined as part of these analyses as an aid for managing water quality in the reservoirs.

Each of these steps in the methodolgy is detailed below.

### *3.2.1 Statistical analysis*

Statistical analyses were undertaken using the *SPSS software package Version 11.5*. The package was used to determine the statistical distribution of climatological, inflow and water quality parameters. The package also used to test the differences between two time series of water quality values.

### *3.2.2 Stratification and mixing/destratification analyses*

The level of stratification in the water body was quantified by a simple indicators used in the literature – the Stratification Index.

The Stratification Index (*SI*) is based on the vertical standard deviation of the density of water (Equation 2.3 and 2.4). The density of water is first calculated using the Straskraba and Gnauck equation (1985) which relates water density ($\rho_w$) to temperature ($T$).

The *SI* has a similar approach to the thermal deviation developed by Schladow and Fisher (1995). The thermal response of the artificial mixers was analysed using the average deviation of the vertical temperature profile. This average deviation ($s$) is then used as an indicator of the degree of thermal stratification.

$$s = \frac{\int_0^h \left|(T(z) - \mu)\right| A(z)dz}{\int_0^h A(z)dz} \tag{3.1}$$

Where the mean of volume weighted temperature, $\mu$, is given by

$$\mu = \frac{\int_0^h T(z)A(z)dz}{\int_0^h A(z)dz} \tag{3.2}$$

where $s$ is thermal deviation of weighted vertical profile, $T(z)$ is the temperature and $A(z)$ is the reservoir area at height $z$ from the deepest point of the reservoir of total depth $h$ (Schladow & Fisher 1995).

This work fulfils an aim to meet the primary objective in this project in that it establishes the impact of the artificial mixers on stability.

### *3.2.3 Weather data generation and inflow simulation*

Weather data including rainfall, solar radiation, air temperature, relative humidity, cloud cover, and wind speed were available as measured historical data to calibrate the models. However the measured records did not allow for the reservoir behaviour with and without mixing to be compared. In order to make this comparison, fifty years of synthetic data were generated from the available records. The weather data were generated using the ClimGen model, except cloud cover values which were stochastically generated with the same characteristics as the historical record, and as a separate exercise. The data were generated without climate scenarios (no global warming).

Concurrent values of storage inflows were obtained for the synthetic weather data using the AWBM rainfall-runoff model. The weather and runoff values were then provided as input to the DYRESM-CAEDYM hydrodynamic and water quality model to simulate the reservoir performance.

The 50-year synthetic runoff values were generated assuming constant land use. The Australian Water Balance Model (AWBM) which was used for this purpose was developed by Boughton (1993). It uses eight parameters to describe soil water storage capacity (C1, C2, C3), runoff generation areas (A1, A2, A3), base-flow (BFI) and a daily recession constant (K). These parameters were assessed twice for Cooby reservoir by consultants GHD (Gutteridge Haskins & Davey Pty Ltd). GHD staff validated the model in Toowoomba’s reservoirs in 1994 and then recalibrated in 1999 using 1976-1998 data (Loxton 1999). Table 3.1 describes the AWBM parameters for each study.

Table 3.1 AWBM parameters for Cooby and Cressbrook reservoirs.

| **Model parameter** | **Cooby reservoir** | | **Cressbrook reservoir** | | |
|---|---|---|---|---|---|
| | **GHD, 1994*** | **GHD, 1999*** | **Macintosh, 1992**** | **GHD, 1994*** | **GHD, 1999*** |
| Soil storage capacity | | | | | |
| (mm) | 10 | 3 | 11 | 10 | 6 |
| C1 | 160 | 175 | 72 | 80 | 80 |
| C2 | 700 | 250 | 417 | 320 | 370 |
| C3 | | | | | |
| Partial area fraction | | | | | |
| A1 | 0.0761 | 0.050 | 0.146 | 0.1505 | 0.108 |
| A2 | 0.2605 | 0.120 | 0.236 | 0.2394 | 0.200 |
| A3 | 0.6634 | 0.800 | 0.618 | 0.6101 | 0.692 |
| Baseflow index | 0 | 0.75 | 0 | 0 | 0.30 |
| Daily recession constant | 1 | 0.95 | 1 | 1 | 0.95 |

* Loxton 1999 (study parameters in 1994 and calibrated in 1999)
** Boughton 2002

Loxton (1999) reduced the total area fraction from 100 per cent to 97 per cent in the AWBM model as a result of variability of rainfall across the Cooby catchment. These fractions produced the best inflow to be fitted in the water elevation of the reservoir (Loxton 1999) and were adopted for this project.

Calibrated values for the AWBM model were held constant for this exercise. The simulations assumed constant land use patterns over the 50 year period.

Water quality parameters were provided by DNRMW as a function of land use in the catchment. They were based on plot experiments in and around the catchment (Merz 2001 and Titmarsh 1997).

The 1999 calibrated AWBM parameters were used in this study to produce a 50-year sequence of inflow values into the reservoirs. The associated daily rainfall data were obtained from the ClimGen v.4.1.3 weather generator while monthly average evaporation data were calculated using the Penman-Monteith equation. All these values were provided as input to the reservoir model.

### *3.2.4 Simulation method*

The coupled Dynamic Reservoir Simulation Model and Computational Aquatic Ecosystems Dynamics Model (DYRESM-CAEDYM)[1] was selected to simulate the vertical distribution of temperature, salinity and density as well as some water quality parameters in Cooby and Cressbrook Dams. A 50-year period was simulated using the synthetic input data describe in the previous section.

Value for process constants needed by DYRESM-CAEDYM were obtained from the literature (Antenucci 2000; Bowie et al. 1985; Borowitzka 1998; Cole & Wells 2002; Fischer et al. 1979; Imberger 1982; Lewis et al. 2000; Peterson et al. 1994; Soetaert & Herman 2001; Straskraba & Gnauck, 1985; Wetzel 2001) and confirmed where possible with field data. Some parameters in the model had to be established by trial and error. The response in water quality to a selected inflow event was analysed to establish the required values.

Independent verification of the model results was done using data from March 2003 to March 2004. The verification results show that the validity of the model's predictions for water quality condition over 50 years in Cooby and Cressbrook reservoirs was valid for predictive purposes.

### *3.2.5 Sensitivity analysis*

After validating the DYRESM-CAEDYM model, further simulations were used to establish the probability of algal blooms over 50 years on the basis of simulated water quality parameters. Sensitivity analyses were undertaking by varying selected climatological and inflow parameters from -10 to 10 per cent of the selected value (-10, -5, 5, and 10 per cent of the synthetic data or forecasting values) and

[1] The package of software programs is available from the Centre for Water Research, University of Western Australia (CWR-UWA). Version 2.4 was adopted in this project

observing the change in model output. The selected parameters included solar radiation, rainfall, total phosphorous, nitrate, and total suspended solid concentrations.

Nine output parameters (water temperature, dissolved oxygen concentration, salinity, pH, total phosphorous, nitrate, total manganese, total iron, and blue green algae concentrations) were examined in this analysis. All output parameters of each set simulation are analysed using probability occurrence of the parameters on a weekly basis through 50 years prediction.

In order to evaluate the effectivity of the mixers, the simulation results with and without mixers were compared for both reservoirs. An analysis of water quality improvement, from the use of mixers, indicates the potential benefits of installing mixers in Cooby and Cressbrook reservoirs.

## 3.3 Hydrology and Management Data

A large amount of hydrological, meteorological and other reservoir data had to be sourced for the modelling work in this project.

### *3.3.1 Physical data and reservoir morphometry*

Physical information about the reservoir including geographical data (latitude and elevation of reservoirs), streambed half angle and slope and outlet elevation as well as catchment areas were obtained from a digital elevation model (1999 DEM data) provided by the Department of Natural Resources, Mines and Water (DNRMW) Queensland (Department of Natural Resources, Mines and Water 1999).

Topographic Maps No. 9243 and 9343 (scale 1:100000) supported by Topographic Maps No. 9243-21, 9243-22, 9343-31, 9343-32, 9343-33, 9343-34, 9343-42 and 9343-43 (scale 1:25000) were used to check and correct the DEM data.

These topographic maps were available from SunMap - Queensland Government as released in 1979 and revised in 1998. Surface areas at each elevation in the reservoirs (morphometric data) were measured by Planimeter (AMSLER Type 800/14115).

Reservoir morphometric data were obtained from a 1983 Cooby reservoir Contour Plan (revised edition) and a 1980 Cressbrook reservoir Map Plan provided by Toowoomba City Council and 1999 Digital Elevation Model (DEM) data (Department of Natural Resources, Mines and Water 1999; Toowoomba City Council 1980). Morphometry maps were reproduced using ArcView-GIS Version 3.2. The plans were prepared from surveys prior to construction of the dams.

3.3.1.1 Cooby reservoir

Figure 3.4 shows a contour map of Cooby reservoir from the bottom reservoir to just above the full supply level of the reservoir. Interpolation of elevations was used to produce an eleven line contour map from the original of nine lines.

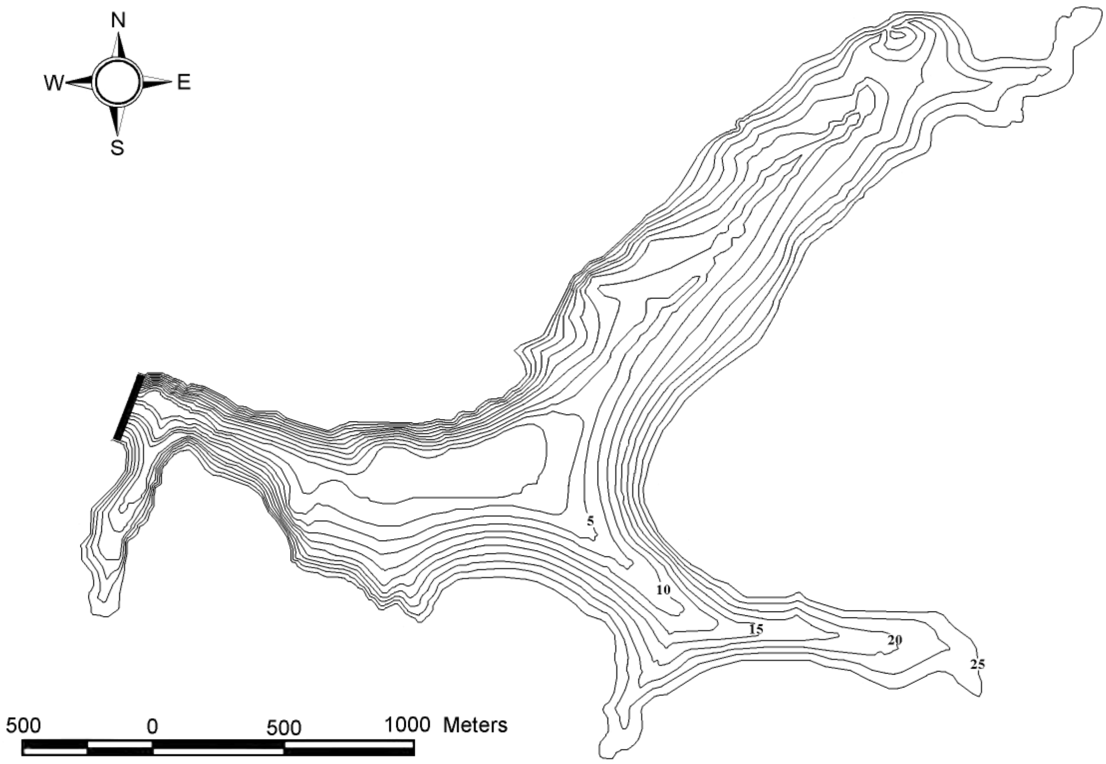



Figure 3.4 Morphometry of Cooby reservoir.

The detailed relationship between water level, surface area of contours and the volume of the storage is developed from bathymetry data presented in Figure 3.5. The volume of the storage ($V$) is calculated using the cylindrical assumption method (Florida LAKEWATCH 2001) as follows:

$$V = \frac{h\left(A_{top} + A_{bottom} + \sqrt{A_{top} \times A_{bottom}}\right)}{3} \quad (3.3)$$

where: $A_{top}$ = the area of the top of the layer,

$A_{bottom}$ = the area of the bottom of the layer, and

$h$ = the distance between contour lines

Based on the adopted original contour lines of Cooby reservoir Map Plan, the volume can be divided into nine segments from bottom to a height of 22.6 metres water (Toowoomba City Council 1983).

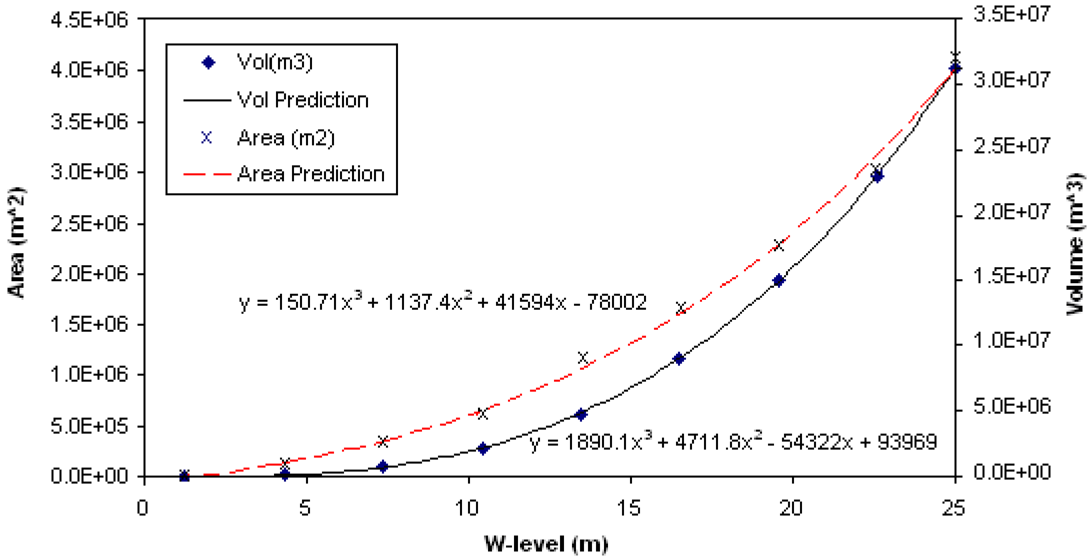



Figure 3.5 Bathymetry of Cooby reservoir. Cross indicates the area in a horizontal cross-section, solid diamond indicates cumulative volume and dash and solid lines represent the trend of area and volume, respectively.

3.3.1.2 Cressbrook reservoir

Figure 3.6 shows a contour map of Cressbrook reservoir from the lowest point to just above the maximum water level of the reservoir. The map was adopted from the Cressbrook reservoir Map Plan. It was reproduced using ArcView-GIS version 3.2 based on the original contour lines.

The detailed relationship between water level, surface area of contours and the volume of the storage is presented in Figure 3.7. The volume of the storage was calculated using the cylindrical assumption method (Florida LAKEWATCH 2001) with 10 segments.

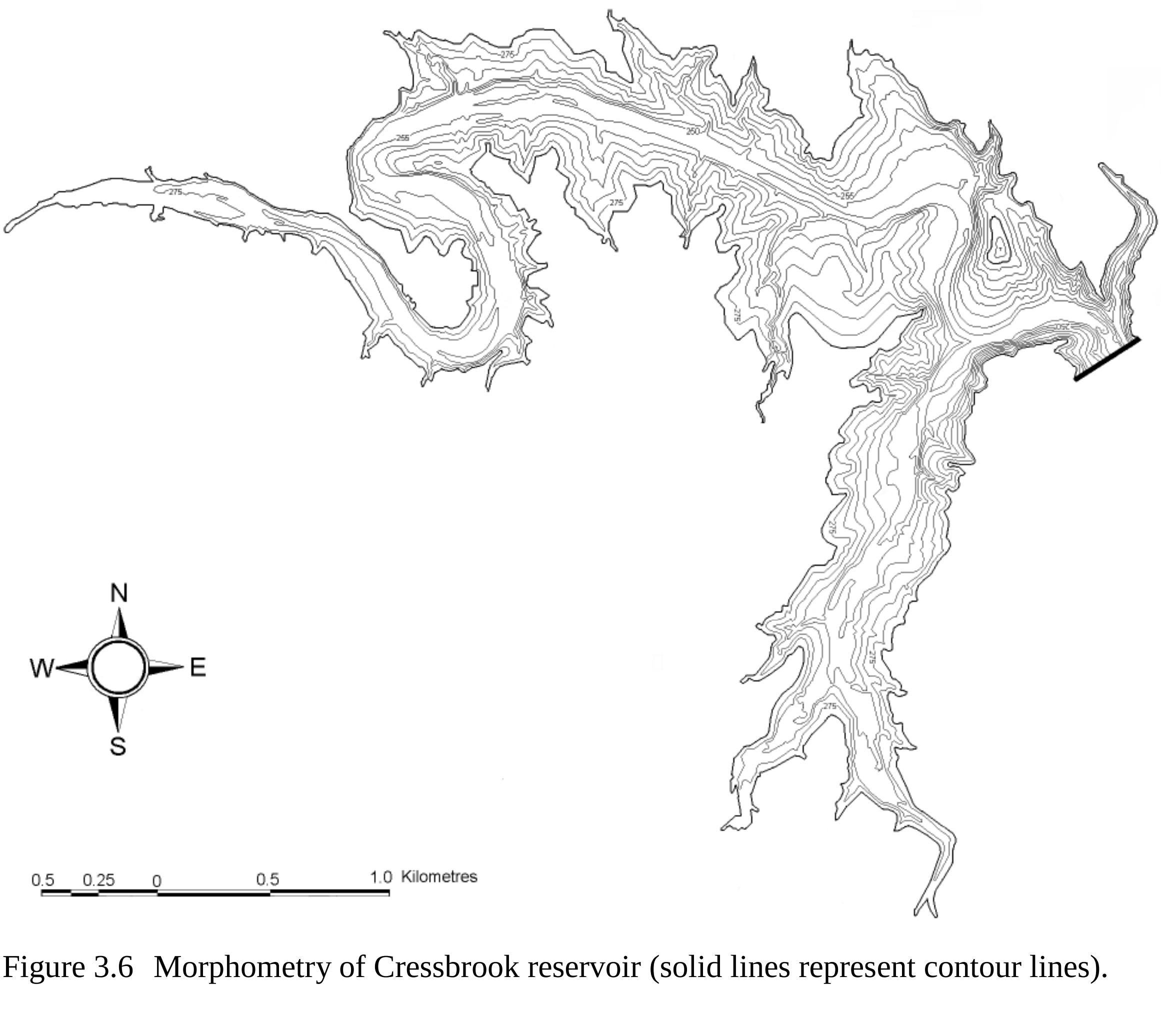



Figure 3.6 Morphometry of Cressbrook reservoir (solid lines represent contour lines).

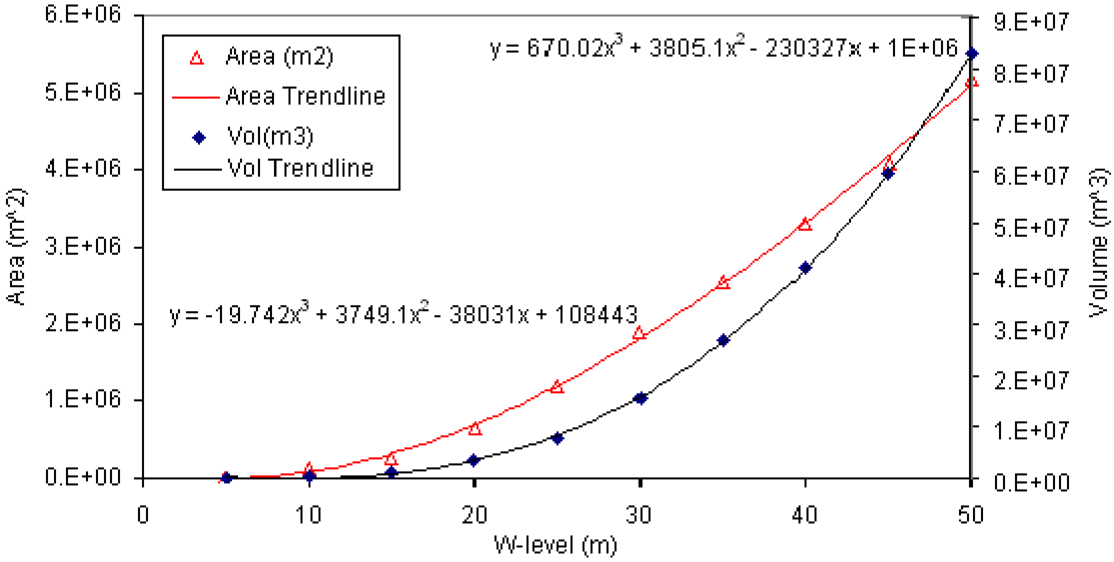



Figure 3.7 Bathymetry of Cressbrook reservoir. Triangle indicates the area in a horizontal cross-section and solid diamond indicates cumulative volume. Lines represent the trend of area and volume.

Geometric information was processed from the 1999 Queensland DEM data as a companion Storage File.

### *3.3.2 Meteorological data*

The DYRESM-CAEDYM water quality model requires a set of meteorological data. The data consist of rainfall, air temperature, short wave radiation, cloud cover, wind speed, and vapour pressure. Evaporation data and rainfall are also required by the AWBM hydrological model to produce the daily inflow values. Suitable meteorological data for modelling purposes were sourced as follows:

#### 3.3.2.1 Rainfall

Daily rainfall data (in mm, ± 0.05 mm) for the dams were recorded by Toowoomba City Council from 1943 to 2003 in Cooby and Cressbrook rainfall stations and by the DNRMW from 1998 to 2003.

Based on measured rainfall from 1978 to 2003 (25 year period), the average rainfall of Cooby and Cressbrook catchments are about 826 and 787 mm per year, respectively (Toowoomba City Council 2002). Mean rainfall values for each month for both reservoirs are presented in Figure 3.8 and Figure 3.9.

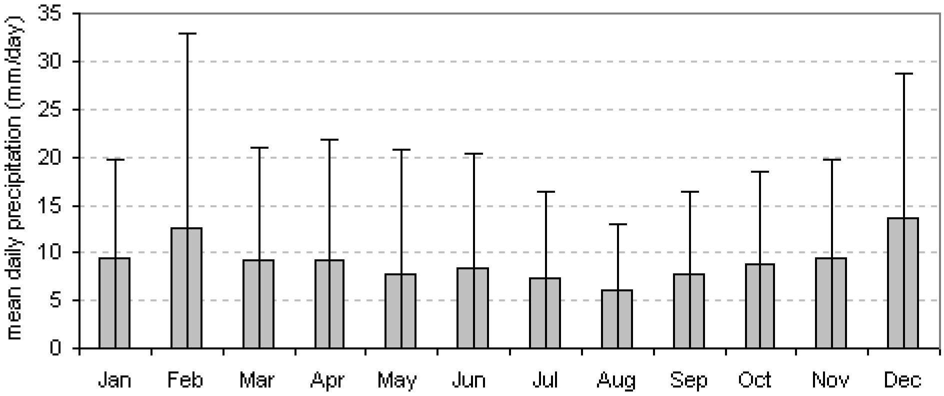



Figure 3.8 Mean daily precipitation for each month (filled bars) and maximum deviation from mean daily precipitation (line) of Cooby reservoir.

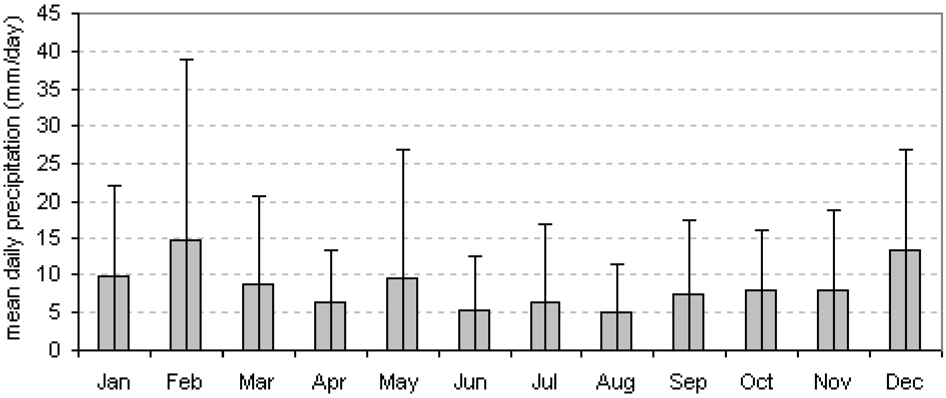



Figure 3.9 Mean daily precipitation for each month (filled bars) and maximum deviation from mean daily precipitation (line) of Cressbrook reservoir.

3.3.2.2 Air temperature

Daily average air temperature data (in C, ±0.25 C) for the dams were available from the DNRMW from 1998 to 2003. The average air temperatures of Cooby and Cressbrook reservoirs together with maximum and minimum values and standard deviations are presented in Figures 3.10 and 3.11.

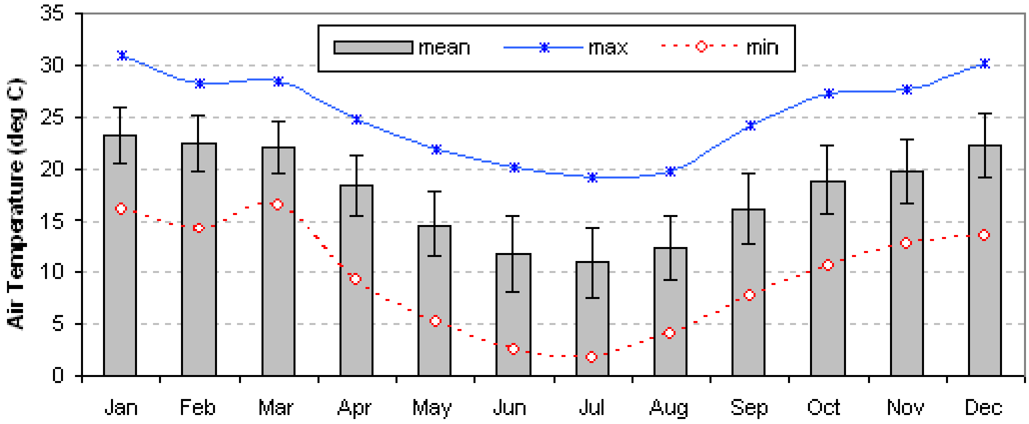



Figure 3.10 Mean daily air temperature for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily air temperature of Cooby reservoir.

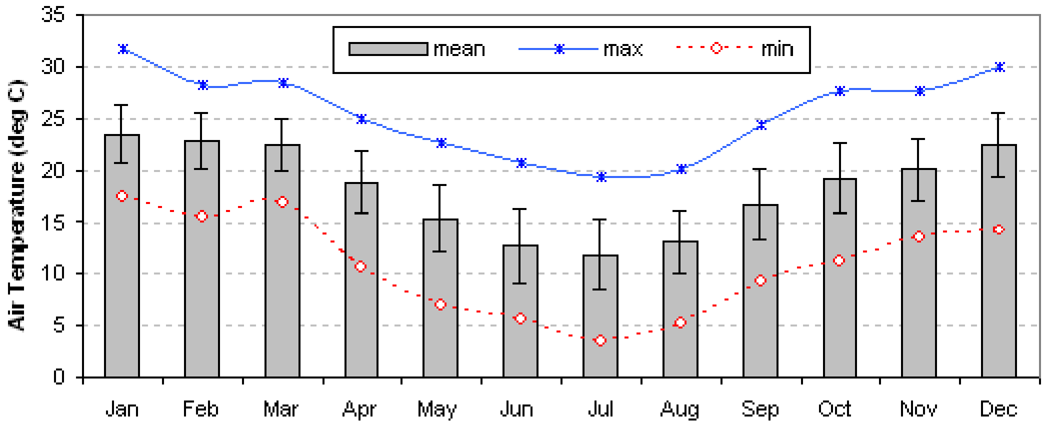



Figure 3.11 Mean daily air temperature for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily air temperature of Cressbrook reservoir.

#### 3.3.2.3 Short wave radiation

Incident short wave radiation is that fraction of solar radiation which reaches the ground. Daily short wave radiation data (in MJ $m^{-2}$, ± 0.05 MJ $m^{-2}$) for the dams were available from the DNRMW from 1998 to 2003.

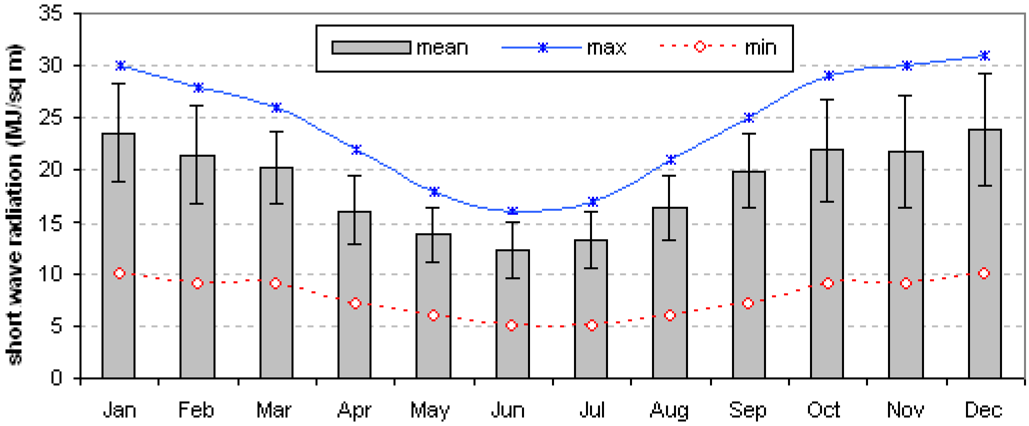



Figure 3.12 Mean daily short wave radiation for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily shortwave radiation of Cooby reservoir.

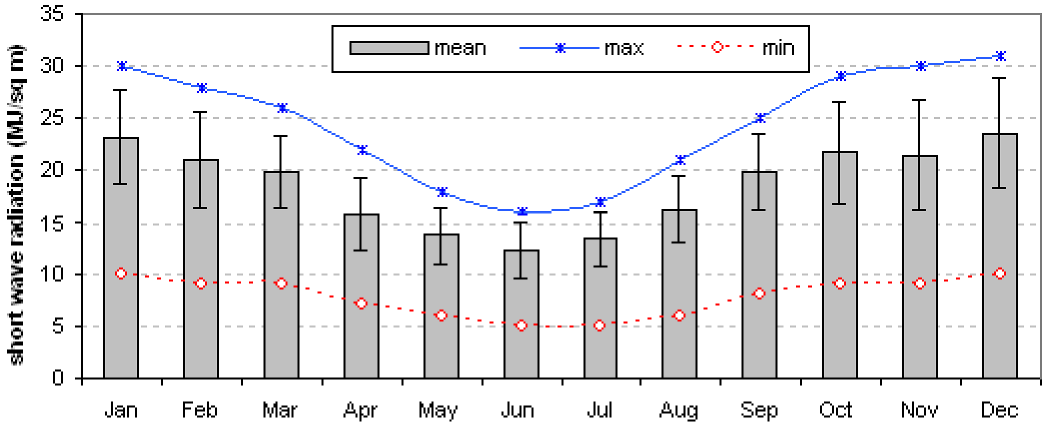



Figure 3.13 Mean daily short wave radiation for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily shortwave radiation of Cressbrook reservoir.

#### 3.3.2.4 Cloud cover

Mean total cloud cover data (in Oktas, ± 0.5 Okta) for the Toowoomba region (for both Cooby and Cressbrook region) were obtained from the Australian Bureau of Meteorology (BOM), for the years 1998 to 2003. Because the DYRESM model needs cloud cover represented in fractional form, the unit of cloud cover was converted to a decimal fraction using the WMO Code 2700 (NERC & ENCAS 2002) as presented in Table 3.2..

Table 3.2 Conversion cloud cover from okta to tenth based on World Meteorology Organization WMO Code 2700.

| Code Figure | Meaning | |
|---|---|---|
| | **Oktas** | **Fraction** |
| 0 | Clear sky | 0 |
| 1 | 1 okta or less, but not zero | 1/10 or less but not zero |
| 2 | 2 oktas | 2/10 - 3/10 |
| 3 | 3 oktas | 4/10 |
| 4 | 4 oktas | 5/10 |
| 5 | 5 oktas | 6/10 |
| 6 | 6 oktas | 7/10 - 8/10 |
| 7 | 7 oktas or more, but not 8 oktas | 9/10 or more, but not 10/10 |
| 8 | 8 oktas | 10/10 |
| 9 | Sky obscured by fog and/or other meteorological phenomena | |
| / | Cloud cover is indiscernible for reasons other than fog or other meteorological phenomena, or observation is not made | |

*Source: NERC & ENCAS 2002*

Mean daily cloud cover fraction for each month and its standard deviation for Toowoomba region is presented in Figure 3.14.

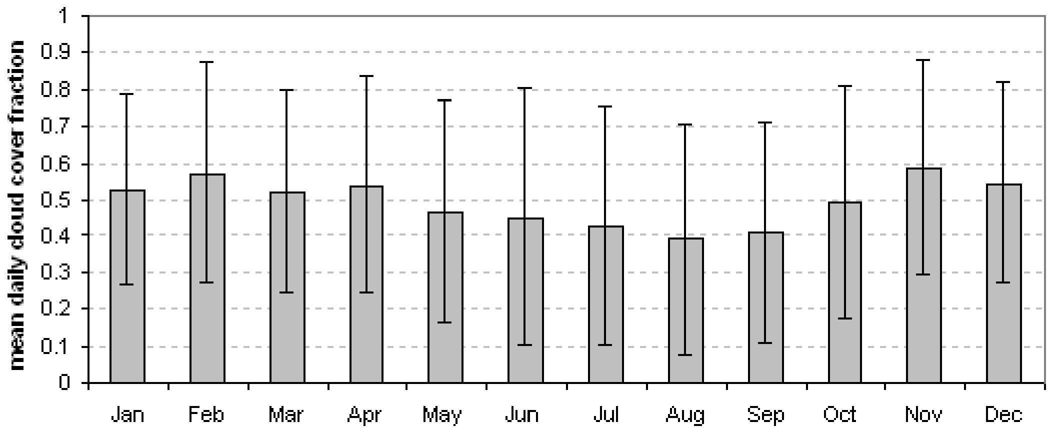



Figure 3.14 Mean daily cloud cover fraction for each month (filled bars) with standard deviation interval (line) of Toowoomba region.

3.3.2.5 Wind Speed

Mean daily wind speed data (in km $h^{-1}$, ± 0.05 km $h^{-1}$) for the Toowoomba region were provided by the Bureau of Meteorology (BOM) for the period 1998 to 2003. After converted into SI units of metre per second, mean daily wind speed for each month is presented in Figure 3.15. Mean daily average wind speed for each month has a small variability. However, the average maximum value of wind speed fluctuated from 9 to 14 m $s^{-1}$.

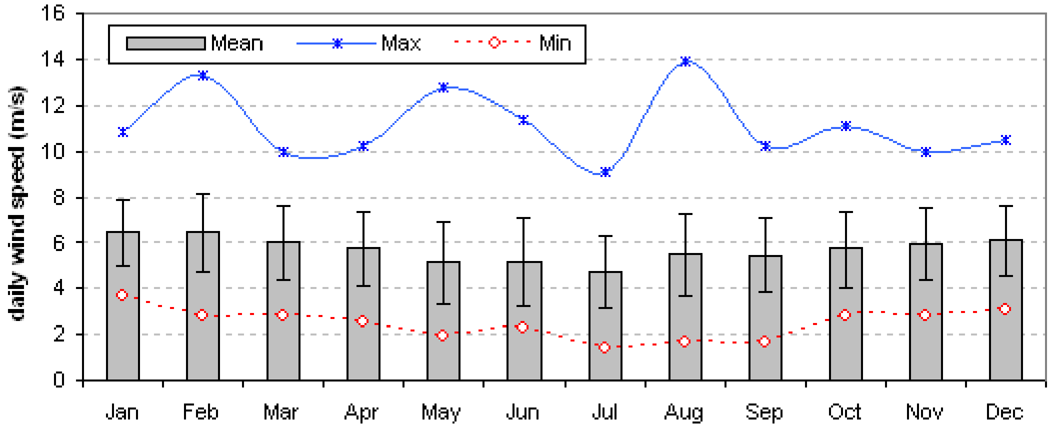



Figure 3.15 Mean daily wind speed for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily wind speed of Toowoomba region.

3.3.2.6 Vapour Pressure

Average vapour pressure data (in hPa or mbar, ± 0.5 mbar) for the dams were available from the DNRMW for the period 1998 to 2003. The mean daily vapour pressure with associated standard deviation for Cooby and Cressbrook dams is presented in Figure 3.16 and Figure 3.17, respectively.

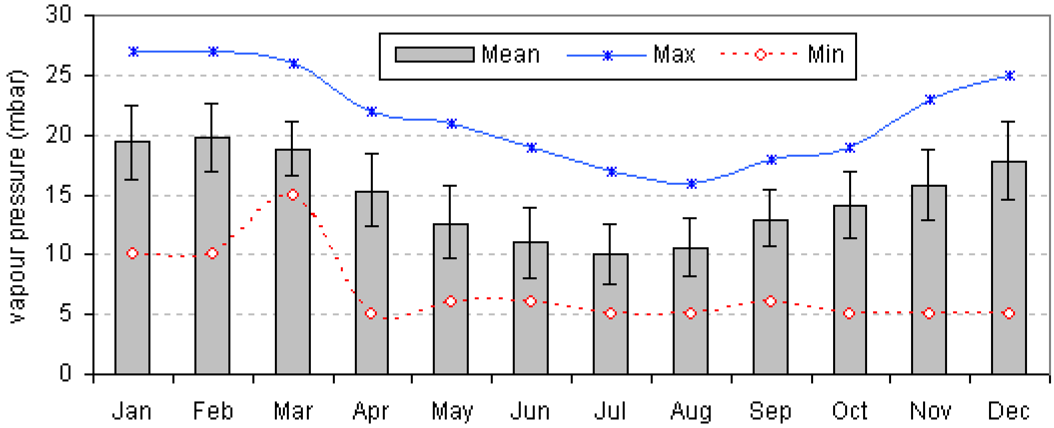



Figure 3.16 Mean daily vapour pressure for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily vapour pressure of Cooby reservoir.

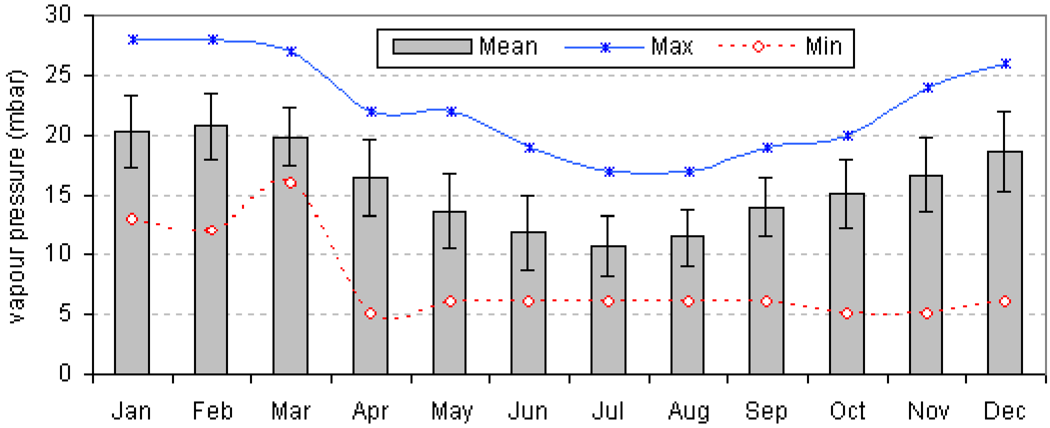



Figure 3.17 Mean daily vapour pressure for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily vapour pressure of Cressbrook reservoir.

3.3.2.7 Evaporation

Daily evaporation data (in mm, ± 0.05 mm) for the dams were recorded by Toowoomba City Council from 1978 to 2003 and made available to this project. Mean monthly evaporation values for each reservoir are presented in Figure 3.18 and Figure 3.19.

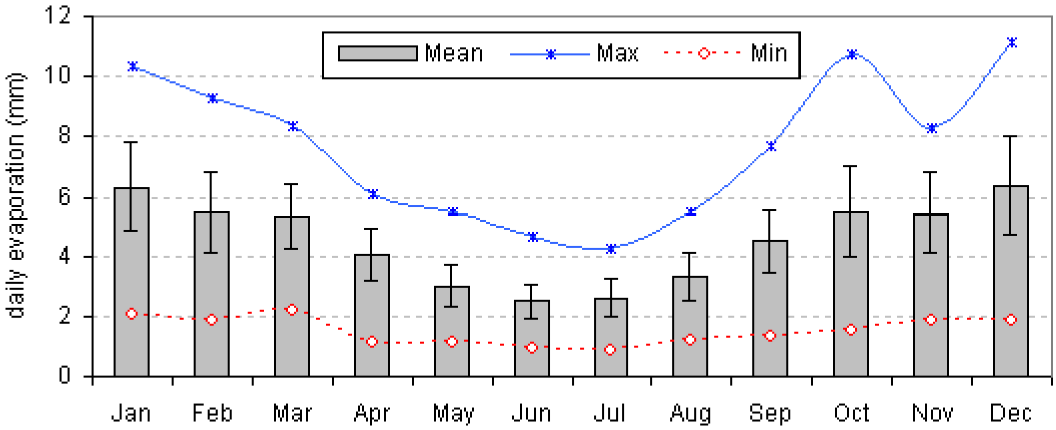



Figure 3.18 Mean daily evaporation for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily evaporation of Cooby reservoir.

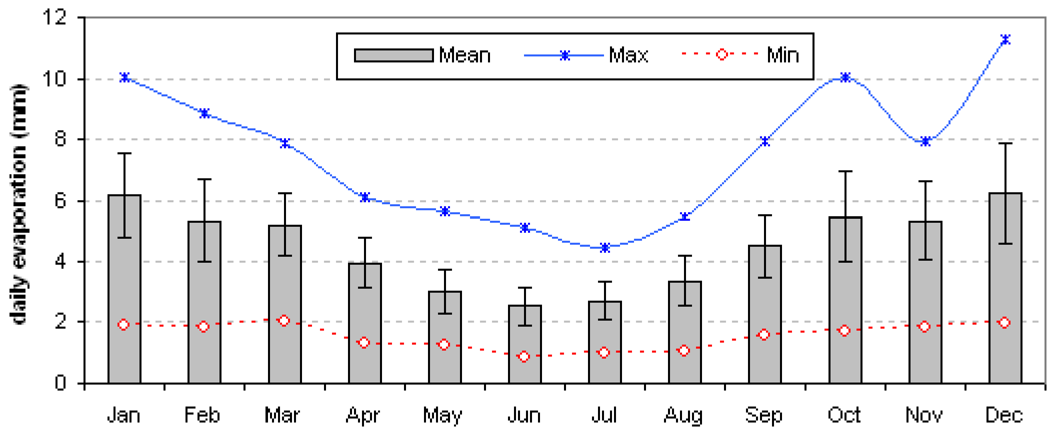



Figure 3.19 Mean daily evaporation for each month (filled bars) with standard deviation interval (line) and mean maximum (cross) and minimum (diamond) daily evaporation of Cressbrook reservoir.

### *3.3.3 Inflow data*

Inflow data were available from two sources - The Queensland Department of Natural Resources, Mines and Water (DNRMW), and from consultant John Macintosh (Boughton, 2002). The DNRMW provides inflow data from October 1935 to January 1940 for Cooby and for 1965-1980 for Cressbrook. The data are presented as mean stream discharge in $m^3 s^{-1}$ with an apparent precision of ± 0.005 $m^3 s^{-1}$. John Macintosh in Boughton (2002) obtained data for Cressbrook in depth units of millimetres for the period 1988 to 1992. These data were used to calibrate the AWBM Version 4 model of Boughton (2002). Using the result of Macintosh's calibration, inflow data were produced for the simulations and supplied to the DYRESM-CAEDYM model.

There is no recorded inflow data for Cooby and Cressbrook reservoirs after the Macintosh study. Then inflows produced by AWBM for the years 1998 – 2002 and 2004 – 2053 were used in the place of recorded values. A set daily temperature inflow was acquired from a moving four-day average of the mean air temperature (Antenucci 2000). Salinity inflow is set to a constant value 0.25 psu and 0.4 psu for Cooby and

Cressbrook, respectively (Kleinschmidt 2003; Merz 2001). The preparation of inflow data is detailed in Chapter 5.

### *3.3.4 Withdrawal data*

The Toowoomba City Council provided daily withdrawal data (± 0.5 $m^3$ $day^{-1}$) for all the reservoirs over the years 1998 to 2003. These data were obtained from the pumping system output ($m^3$ $h^{-1}$) and the daily pumping duration. Figure 3.20 and Figure 3.21 represent the actual daily withdrawal and the surface water elevation of Cooby and Cressbrook Dam, respectively. No withdrawal was made from Cooby reservoir during the period of 1998 because of the occurrence of cyanobacterial blooms.

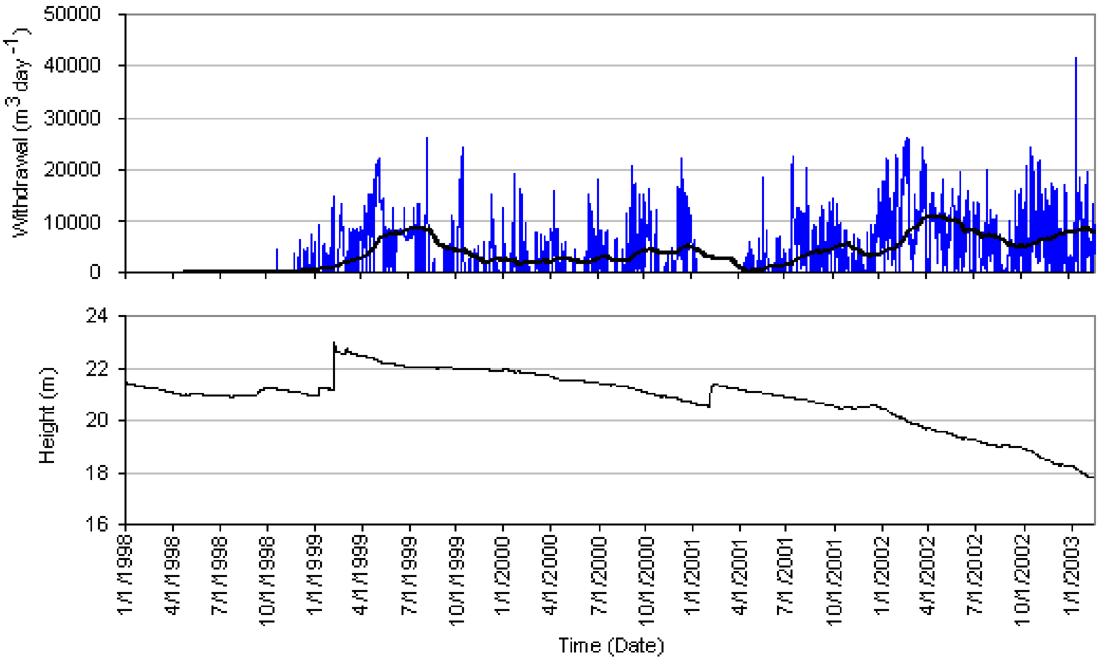



Figure 3.20 Withdrawal (top) and surface water level (down) at Cooby Dam from 1998 to 2003.

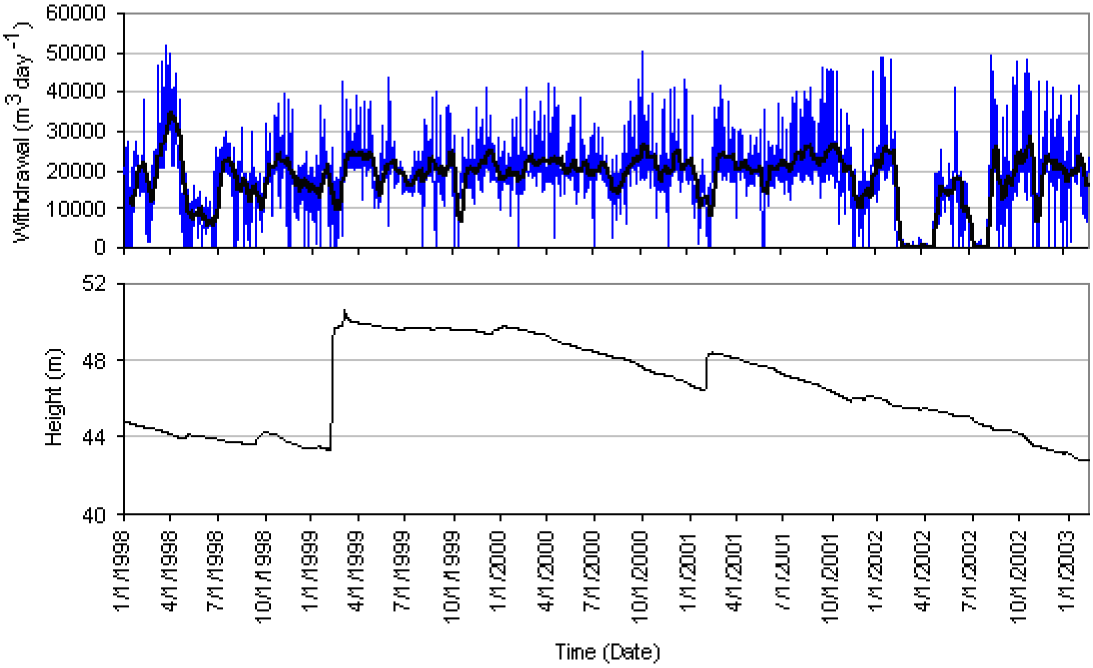



Figure 3.21 Withdrawal (top) and surface water level (down) at Cressbrook Dam from 1998 to 2003.

### *3.3.5 Artificial mixing data*

Operational data for the artificial mixers were provided by the Toowoomba City Council and by the supplier - WEARS P/L. Two WEARS surface mixers type SMDI-5 have operated continuously in Cooby reservoir since 2001. The diameter is 5m and the draft tube length of these mixers is 15m. The average flow rate is $7m^3 s^{-1}$. There is no artificial mixer installed in Cressbrook reservoir, although the Council is considering a future purchase.

### *3.3.6 Water quality data*

Water quality data from 1998 to 2004 were provided by the Water and Waste Operation (WWO) section of the Toowoomba City Council. The physical characteristics (water temperature, salinity, dissolved oxygen, turbidity, and pH) were measured at 1 m layers in the reservoirs using a Yeo-Kal Profiler Model 611. Biological and chemical characteristics (the cyanobacterial cell count, chlorophyll *a*, total phosphorus, nitrate, iron, and manganese concentrations) were sampled at least for the surface, middle, and bottom layers with the samples analysed in the Water and Waste Operation Laboratory at the Mt. Kynoch Water Treatment Centre.

The operational specification for the Yeo-Kal Profiler Model 611 is summarized in Table 3.3.

Table 3.3 General specification of Yeo-Kal Profiler Model 611.

| **Parameters** | **Range** | **Precision** | **Resolution** |
|---|---|---|---|
| Temperature | -5 – 50 $^{o}$C | ± 0.05 $^{o}$C | 0.01 $^{o}$C |
| Conductivity | H 0 – 80 ms/cm<br>L 0 – 800 μs/cm | ± 0.02 ms/cm<br>± 3.0 μs/cm | 0.02 ms/cm<br>2.0 μs/cm |
| Salinity | 0 – 60 ppt | ± 0.05 ppt | 0.02 ppt |
| Turbidity | 0 – 600 NTU | ± 0.2 NTU (0-200 NTU)<br>± 4 NTU (200-600 NTU) | 0.3 NTU |
| pH | 0 – 14 pH | ± 0.03 pH | 0.01 pH |
| ORP | ± 900 mV | ± 2 mV | 1 mV |
| DO | 0 – 200 % sat<br>0 – 20 mg/L | ± 0.5% | 0.1% sat<br>0.1 mg/L |
| Depth | 0 – 100 m | ± 0.5% | 0.1 m |

Detail of the water quality profiles for both Cooby and Cressbrook reservoirs are presented as seasonal behaviour of reservoirs in Chapter 4.

All these hydrological and management data were used in simulations of the reservoirs. The flow of data and the sequence of models is depicted in Figure 3.22.

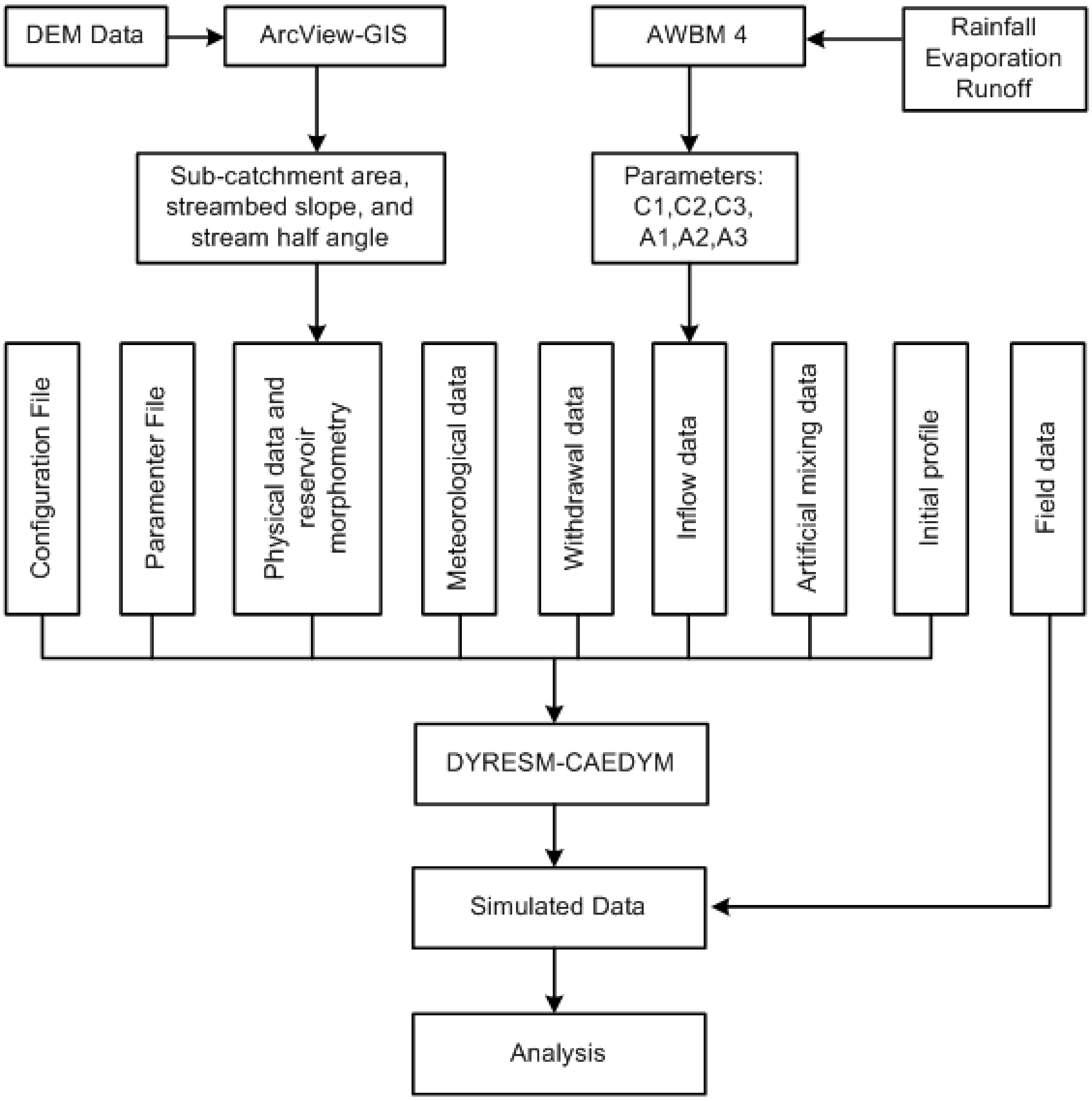



Figure 3.22 Structure and flow of data processing/analysis

# Chapter 4

# SEASONAL BEHAVIOUR OF RESERVOIRS

Some parts of this chapter have been presented and/or published in:

- Achmad, M & Porter, M 2003, '*Evaluating the Effect of Mechanical Destratifiers on Water Quality in Toowoomba's Dams*', 14th Queensland Hydrology Symposium 2003, Nathan, Brisbane, Australia, 22 – 23 July 2003

- Achmad, M & Porter, M 2004, '*Stratification, Artificial Mixing and Water Quality in Cooby Reservoir Toowoomba Australia*', International Conference of Hydro-Science and Engineering VI in Brisbane, Australia, May 31 – June 3, 2004. ISBN 0-937099-12-0 (Book and CD-ROM) or 0-937099-13-9 (CD-ROM only)

## 4.1 Introduction

This chapter investigates and summarises the historical water quality in Cooby and Cressbrook reservoirs. Recorded data from 1998 to 2003 were used to produce line and contour graphs for a better understanding of the seasonal behaviour of selected water quality parameters. Water temperature, dissolved oxygen concentration and cyanobacterial cell count were selected as particularly important seasonal factors.

The variation in concentration of a water quality parameter in a temperate reservoir through the year is strongly affected by the seasonal variation in climatic parameters such as the intensity and duration of sunshine.

As a consequence of this dependence, thermal stratification occurs during warm periods when reservoirs gain energy from long time penetration of solar radiation. In most cases, the reservoir develops a warm top water layer (epilimnion) overlying cold water at the bottom (hypolimnion). The epilimnion releases its energy to the air as the daily average air temperature drops. The reservoirs then become unstratified. Destratification can also occur if sufficient energy from the wind mixes the whole reservoir. Wind energy circulates the epilimnion layer and extends the depth of this layer below the surface.

Seasonal behaviour of reservoirs in this chapter is described by considering the profiles of water temperature, dissolved oxygen and cyanobacterial concentrations over a five-year observation period. The reasons for this are that thermal stratification can be seen through vertical temperature profiles. Dissolved oxygen shows the effect of thermal stratification on the mixing process and the deoxygenation process. As the main and only biological indicator in this project, Cyanobacterial concentration represents the biological aspect of water quality.

## 4.2 Temperature Variation and Stratification Pattern

Water temperature is one of the key bio-physical characteristic parameters in reservoir management. Temperature influences the rate of all nutrient transformation processes. The rate coefficient of most chemical formulations is adjusted as a function of temperature of the environment (Bowie et al 1985).

Spatial and temporal variation of temperature in a water body affects the equilibrium of chemical substances. In a stratified reservoir, for example, chemical transformation models are more complex because water temperatures vary from the surface to the bottom of the reservoir. This profile creates different rate transformations of chemical substances through the vertical layers.

The variation of vertical temperature profiles in Cooby reservoir for each month before the installation of artificial mixers can be seen in Figure 4.1. The reservoir gains heat energy from the sun in late September (spring). The stratification starts in late September (spring) and continues to develop during summer. During October, the metalimnion is clearly seen at a depth of 8-10 metres. The process of natural mixing is supported by the form of the reservoir. With a 22.6-metre depth, the metalimnion is fully developed during the warm period (spring and summer). The combination of wind and radiation forces the metalimnion to dynamically adjust its position.

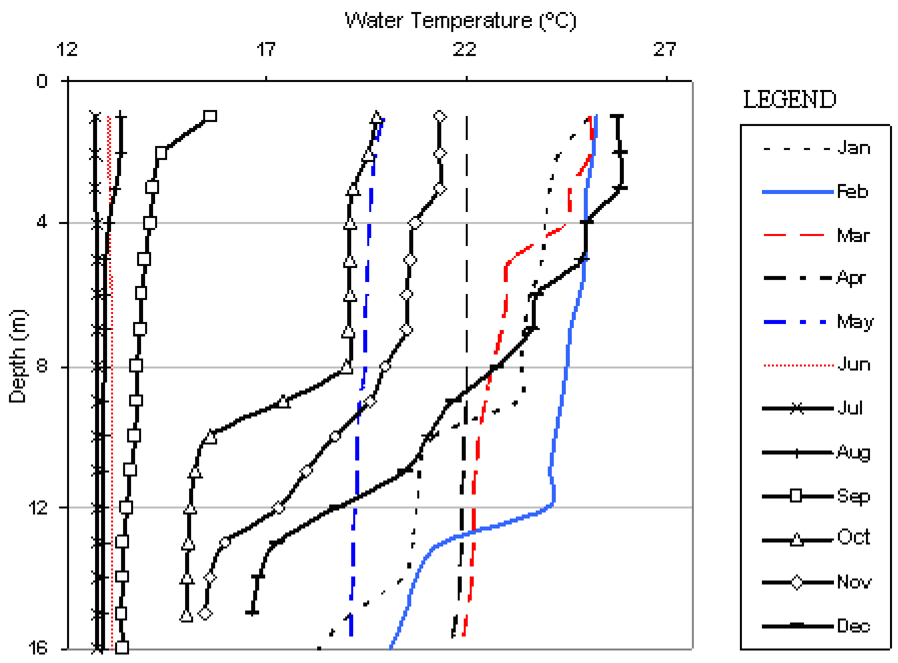



Figure 4.1 Vertical temperature profiles for each month in Cooby reservoir.

Only natural mixing occurred before November 2001, and the vertical thermal stratification in the reservoir recurred reliably each year. Total mixing was achieved in June-July (overturn period) while the maximum stratification occurred during summer. The installation of a couple of surface mixers (mechanical destratifiers) in November 2001 changed this pattern by introducing additional energy and forcing the mixing through the depth of reservoir (Achmad & Porter 2003).

Figure 4.2 shows the contour plot of the water temperature of the reservoir from the period 1998 to 2003. The figure illustrates the effect of artificial mixers on Cooby Dam by comparing the period before (Apr 1998 – Nov 2001) and after (Dec 2001 – Feb 2003) the mixer installation. The artificial mixers change the vertical profile of the reservoir particularly during summer. Warmer water can be found in deeper layers as the effect of destratifiers start to work. The metalimnion layer moves down to a lower level. This leads to the creation of a thicker epilimnion.

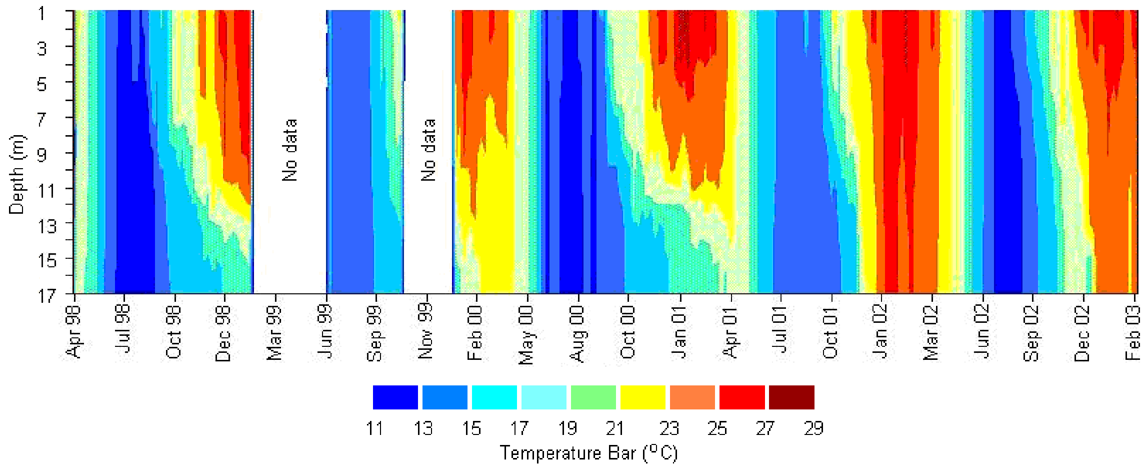



Figure 4.2 Temperature contour plots of observed data of Cooby reservoir before (Apr 1998 – Nov 2001) and after the mixer installation (Dec 2001 – Feb 2003). No available data on January – June 1999 and October 1999 – January 2000.

The degree of stratification was calculated using the Stratification Index (*SI*) as described in Chapter 2 and Chapter 3. The *SI* indicates that strong stratification ($SI > 7$) occurs in the reservoir during the period from September/October to April/May prior to the mixer installation for about seven months. The remaining time after installation shows medium to very weak stratification ($7 > SI > 0$) or unstratified conditions ($SI$ = 0). Details of the stratification level of Cooby reservoir for the period of March 1998 to February 2003 is presented in Figure 4.3.

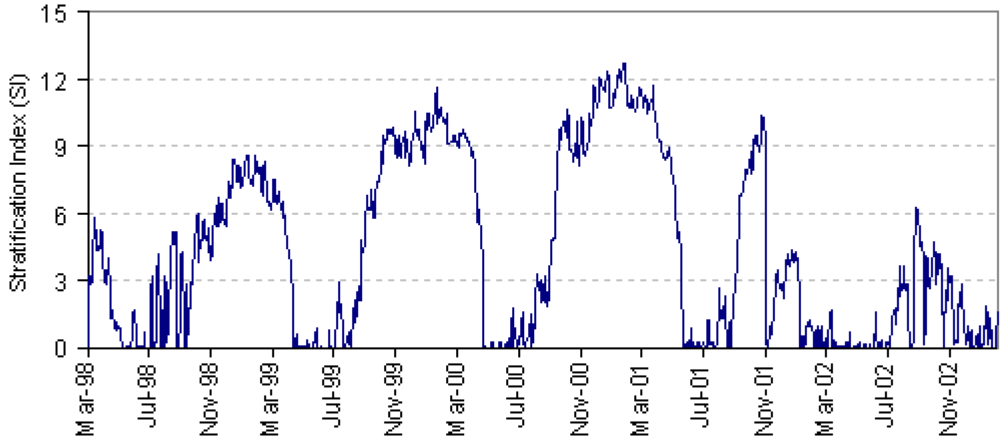



Figure 4.3 Degree of stratification using the Stratification Index ($SI$) for Cooby reservoir before and after the mixer installation period. Interpolated data were used for the period of January – June 1999 and October 1999 – January 2000.

Cressbrook reservoir, which has no artificial mixers on it, has a comprehensible cycle of its thermal profile. The cycle is seasonal. The reservoir gains heat from solar radiation in September. Stratification occurs from October and reaches a peak in December. The stratification persists during summer with a fully developed metalimnion lying at a depth of 7 – 13 m. As a consequence of releasing energy during autumn, the level of stratification decreases until full mixing occurs in June-July (winter). The monthly vertical temperature profiles of Cressbrook reservoir, which indicate the natural processes of gaining and releasing heat (stratification and destratification) in the reservoir, are shown in Figure 4.4.

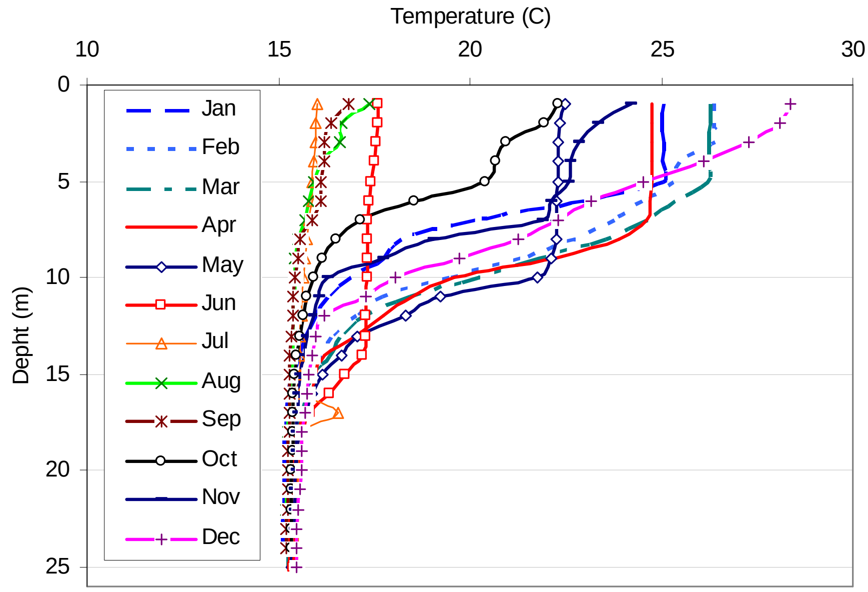



Figure 4.4 Vertical temperature profiles for each month at Cressbrook reservoir.

The temperature contour plots of observed data for Cressbrook reservoir show a clear annual pattern. Figure 4.5 shows the water body in stratified and unstratified conditions. Thermally stratified periods persist longer than unstratified (overturn) periods. Stratification periods can be divided into stages of developing (strengthen), persisting (peak), and releasing (weaken) stratification.

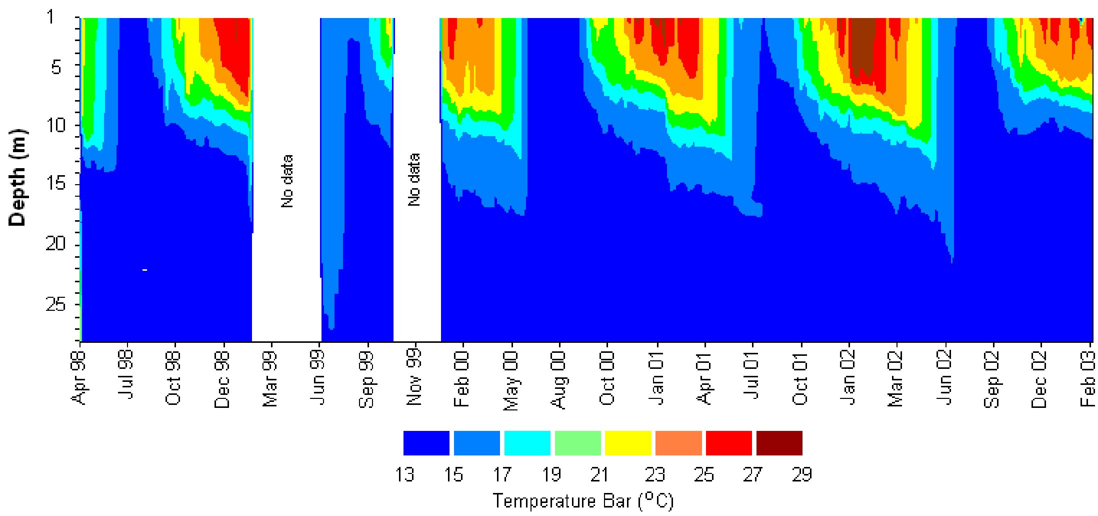



Figure 4.5 Temperature contour plots of observed data of Cressbrook reservoir (Apr 1998 – Feb 2003) from water surface to the depth of 28 m. No available data on January – June 1999 and October 1999 – January 2000. Time step is 90 days

The calculation of stratification index for Cressbrook reservoir is based on temperature difference. The measured temperature was available only from surface to maximum about 35 m depth. Therefore temperatures below the lowest measurement point to the bottom of the reservoir were assumed to be constant. The degree of stratification in Cressbrook reservoir is higher than in Cooby reservoir because of a greater depth and size. The stratification index values of the water body indicate that strong stratification occurs during October – May every year.

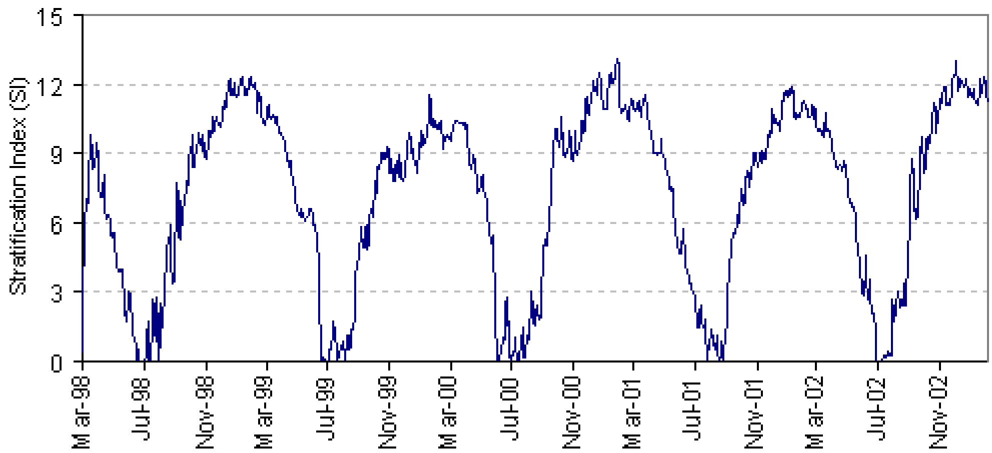



Figure 4.6 Degree of stratification using the Stratification Index (*SI*) for Cressbrook reservoir (Mar 1998 – Feb 2003). Interpolated data were used for the period of January – June 1999 and October 1999 – January 2000.

### 4.3 Dissolved Oxygen Variation

Oxygen diffusion in standing water is very slow compared to that in turbulent flowing water. The vertical distribution of dissolved oxygen in a reservoir works effectively when the energy available for vertical circulation reaches a minimum threshold (Imberger 1982; Imboden & Wüst 1995; Wetzel 2001). The seasonal variation in dissolved oxygen concentrations at the surface is small because the epilimnion is in direct contact with the atmosphere (diffusion process).

The oxygenation process in the hypolimnion layer can only occur effectively if the vertical circulation is able to reach a deeper level in the body of water. In most cases, seasonal variation in dissolved oxygen concentrations at the hypolimnion layer is very sharp and associated with mixing events, particularly in deep reservoirs.

The contour plots of dissolved oxygen concentrations for Cooby reservoir show that a high concentration does exist during the overturn period (Figure 4.7). Once the stratification process starts, the oxygen concentrations decrease in the hypolimnion. The metalimnion layer acts as a barrier between the surface and bottom layers and prevents oxygen transport from the surface. The oxygen concentration in the hypolimnion layer becomes low. In Cooby reservoir, the concentration of oxygen in the hypolimnion layer can be lower than 4 mg $L^{-1}$.

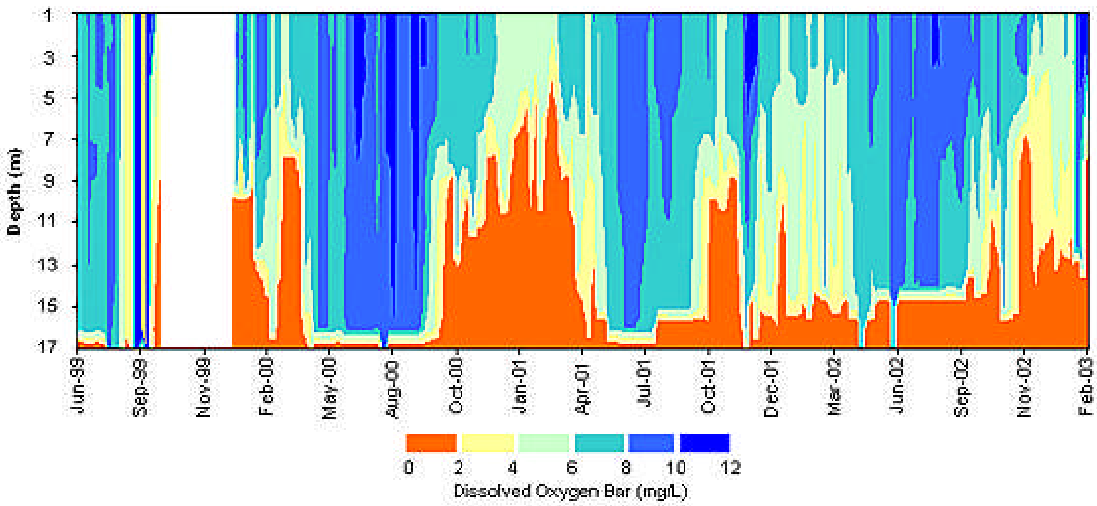



Figure 4.7 Dissolved oxygen contour plots (observed data) of Cooby reservoir (Jun 1999 – Feb 2003). No available data from Oct 1999 to Jan 2000.

Comparing the oxygen concentration in the epilimnion and the hypolimnion layers, it is clear that the vertical profiles of dissolved oxygen concentration in the storage are seasonally different. A better water quality with higher oxygen concentrations is found in the epilimnion than hypolimnion layer through the whole season. The measured difference in dissolved oxygen concentration between epilimnion and hypolimnion was up to 8 mg $L^{-1}$ in November/December 2000, before the mixer installation. In the period June – August 2000, there is no significant difference between dissolved oxygen concentrations in the layers (see Figure 4.8). The initiation of mixers' operation at the end of November 2001 changed the dissolved oxygen characteristics of both layers. The dissolved oxygen concentration in the hypolimnion layer increases during the summer season.

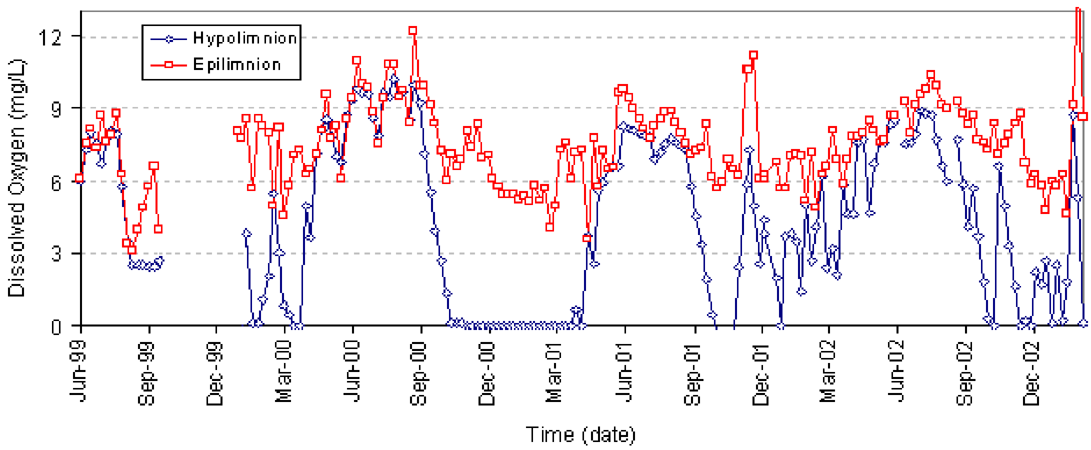



Figure 4.8 Averaged dissolved oxygen concentrations in the epilimnion and the hypolimnion (observed data) of Cooby reservoir (Jun 1999 – February 2003). No available data from Oct 1999 to Jan 2000.

A clear seasonal pattern of dissolved oxygen contour plots for Cressbrook reservoir is shown in Figure 4.9. It indicates that the availability of oxygen in the bottom of the reservoir is limited (the concentration was less than 4 mg $L^{-1}$) during the period of October – June. However, dissolved oxygen concentration is higher (more than 4 mg $L^{-1}$) during the overturn period.

The natural mixing during the stratified period is only able to circulate oxygen to the layer of 7 m below the surface water. The presence of the metalimnion in the layer between 7 and 11 metres below the water surface prevents a deeper circulation in the reservoir. When the thermocline lessens, the wind energy is able to force the water circulation into a deeper layer. The energy circulation changes the position of the thermocline down. If the circulation is strong, it can remove the thermocline and create a single layer of dissolved oxygen concentration in the body of water. A single dissolved oxygen layer in the reservoir can be found for a short term if a complete mixing occurs during the overturn period (mostly in June or July).

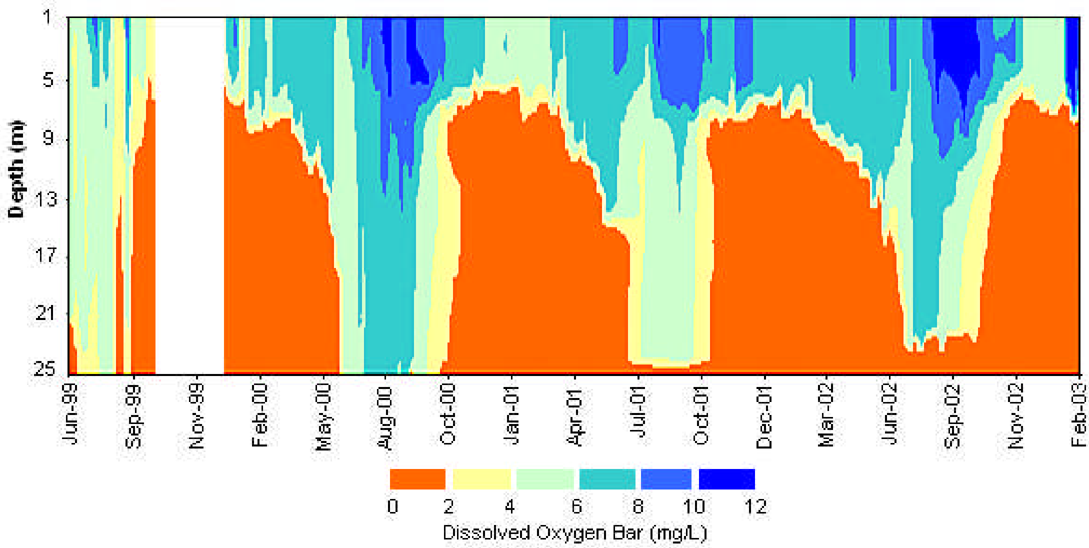



Figure 4.9 Dissolved oxygen contour plots (observed data) of Cressbrook reservoir (Jun 1999 – Feb 2003). No available data from Oct 1999 to Jan 2000.

Because Cressbrook's morphometry is deep and meandering, the period of complete mixing for the whole reservoir's body through the year is limited. Average dissolved oxygen concentration of the epilimnion and hypolimnion layers in the last five years from 1999 to 2003 is about 7 and 2 mg $L^{-1}$, respectively. A comparison value of dissolved oxygen concentrations in the epilimnion and hypolimnion layers can be clearly seen in Figure 4.10. The variation of dissolved oxygen concentrations in the epilimnion layer is in between 2.5 and 13 mg $L^{-1}$. In the hypolimnion layer, the concentration of dissolved oxygen varies from 0 to 7.4 mg $L^{-1}$. The difference of dissolved oxygen concentration of the two layers is up to 9 mg $L^{-1}$. The biggest differentiation occurs during the warm period (summer and spring seasons).

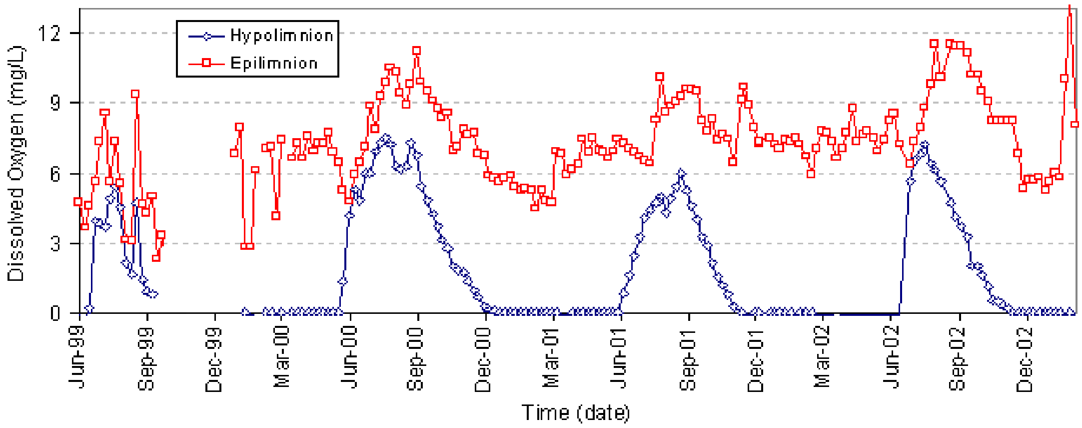



Figure 4.10 The averaged dissolved oxygen concentrations (observed data) of Cressbrook reservoir (Jun 1999 – Feb 2003). No available data from Oct 1999 to Jan 2000.

Anoxic condition in the hypolimnion layer of the reservoir for a long period will affect the living environment of some creatures which normally live in a deeper body of water with sufficient dissolved oxygen. The deficiency of dissolved oxygen in the hypolimnion also affects the transformation of other chemical substances in the layer.

## 4.4 Cyanobacterial Concentration

There are four major cyanobacterial species growing in Toowoomba's reservoirs which are: *Anabaena*; *Mycrocystis*; *Aphanizomenon*; and *Cylindrospermopsin*. All these species are classified as summer bloom species (Steinberg & Gruhl 1992). The total cyanobacterial concentrations of the reservoirs mostly reach a peak during the summer period as the stratification occurs in the reservoirs. The cyanobacterial is recorded as a number of cells per millilitre. The historical record of total cyanobacterial cells is presented for a period of 1998 – 2003 in selected layers based on the decision made by the Water Section of Toowoomba City Council.

In Cooby Dam, it was recorded that the high density of cyanobacteria occurred in the period of January to October 1998. The concentrations reached up to 86400 cells per millilitre and created a 35 record of the alert level 3 (cells count is more than 15000) based on a weekly calculation (the detail alert calculation is presented in Table 2.2 Chapter 2). These blooms stop the dam operation for a long period from activity as a water supplier and for the recreation function.

The period after 1998 shows that a normal pattern of cyanobacterial concentration occurs only during summer season. An exception occurred during the period of 1999 – 2000 where *Anabaena* found a suitable condition for growth during the winter season. As a result, the total cyanobacterial concentrations reached up to 2000 cells per millilitre. The highest cyanobacterial cells are mostly found in the upper layer of the reservoir (surface and 9.14 m layers).

The concentration increased from less than 2000 cells count per millilitre in 1999 to over 10000 cells in summer 2001. Then it decreased again in the period of summer 2002 – 2003. This trend was identified as the effect of the mechanical mixers' work (Clark, *pers. comm.*, 28 August 2002). The detail of total cyanobacterial cells of selected layers in Cooby reservoir during the period of 1998 – 2003 can be seen in Figure 4.11.

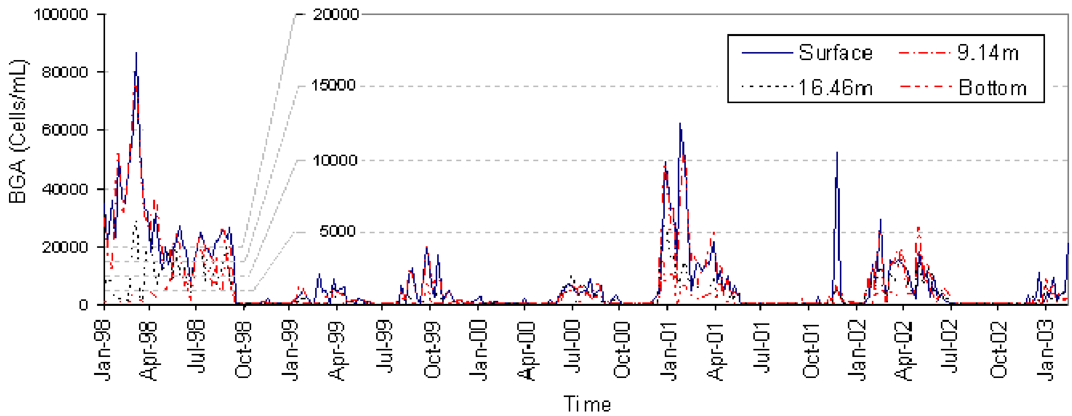



Figure 4.11 Cyanobacterial cell counts in the selected layers (from surface to the bottom) of Cooby reservoir in the period of 1998 – 2003. Rescale on January 1999 to detail the cell counts.

Seasonal pattern of cyanobacterial concentration in the Cressbrook water body is clearly seen in Figure 4.12. The figure shows that the algal cells count dramatically increases during the summer season. In 1998, the cyanobacterial cells reach up to 16000 cells per millilitre, recording seven of algal alert level 3. The concentration decreased in summer one year after (less than 2000 cells per millilitre). The following years shows that the cyanobacterial concentration increased exponentially to over 100000 cells per millilitre in summer 2002 before decreasing again in summer 2003. There was recorded four the algal alert level 3 in the reservoir during summer 2002. On the other hand, the cell counts were very low (classed as safe) for the period of winter.

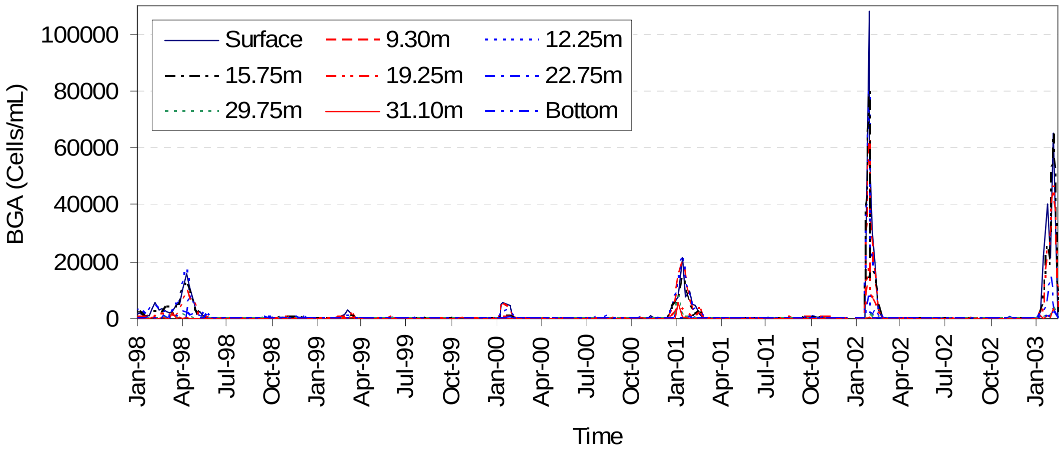



Figure 4.12 Cyanobacterial cell counts in the selected layers (from surface to the bottom) of Cressbrook reservoir in the period of 1998 – 2003.

# Chapter 5

# WATER QUALITY SIMULATIONS

## 5.1 Model Description

Three main software packages were used in this study including DYRESM-CAEDYM, AWBM and ClimGen models. The DYRESM-CAEDYM is for water quality simulation, the AWBM is for inflow preparation, and the ClimGen is to generate 50-year synthetic weather data. The preparation of files and their description is presented in this chapter. The preparation of the files was based on the available measured data, works or research related to this study site and other references related to water quality modelling. Structure and flow of data processing/analysis can be seen in Chapter 3 (Figure 3.22).

### *5.1.1 DYRESM-CAEDYM model*

The DYRESM and CAEDYM models require amount information, which is basic information about the storage (*.stg), initial condition (*.int), DYRESM configuration (*.cfg), CAEDYM configuration (*.con), simulation parameters (*.par), general constants (*.dat), inflow (*.inf), meteorology (*.met), withdraw or outflow (*.wdr), and mixer setting (*.mix) if required. Additionally, the field data (*.fd) can be configured for comparison purposes. To force some parameter values in the simulation, a forcing file (*.for) is needed.

5.1.1.1 General information

General information about the reservoir is presented in storage files. The files are created based on the contour and other physical information of the reservoirs as described in Chapter 3 (part 3.2.1). The configuration of storage files is presented in the *.stg files. The structure of the files consists of generic data about the reservoirs and their inflows. The files also describe the bathymetry of the water bodies.

Table 5.1 presents a general description of the reservoirs including position and elevation of the dams and their outlets, and bathymetry of the reservoirs as described in Chapter 3.

Table 5.1 Basic data for Cooby and Cressbrook reservoirs.

| Subjects | Cooby | Cressbrook |
|---|---|---|
| Latitude ($^o$) | -27.40* | -27.25* |
| Height above sea level (m) | 450 | 230 |
| Crest elevation (m) | 22.6 | 50 |
| Number of outflows | 1 | 1 |
| Outlet elevation (m) | 10.4 | 22 |
| Contour Plot | Fig 3.4 and Fig 3.5 | Fig 3.6 and Fig 3.7 |

* Negative sign means the area is situated in the southern hemisphere.

The lake latitude was used to calculate the declination of the sun. The DYRESM adopts a TVA equation for this calculation.

$$\partial = 23.45\left(\frac{\pi}{180}\right)\cos\left(\frac{2\pi}{365}(172 - D)\right) \quad (5.1)$$

where $D$ is the day of the year (TVA 1972, eq 2.4).

The physical characteristics of the inflows into the reservoir including the names of the inflows and the position of entering the reservoir, the slope of the streambed, half angle of the channel cross section entering the reservoir, and drag coefficient are presented in Table 5.2. The streambed drag coefficient value was assumed to be 0.015 (Antenucci 2000; Antenucci & Imerito 2001) which is slightly lower than 0.016, the value suggested by Fisher et al. (1979). The slope of the streambed was determined using the distance of two contour lines which are (i) maximum water elevation of the reservoir body and (ii) closest contour lines from the reservoir. The different elevation of the two contour lines is five metres.

Table 5.2 Physical characteristics of inflow of Cooby and Cressbrook reservoir.

| Reservoir Inflow | Position | Half angle | Slope | Drag Coefficient* |
|---|---|---|---|---|
| Cooby | | | | |
| - Geham Creek | Surface | 87 | 0.350 | 0.015 |
| - Cooby Creek | Surface | 89 | 0.160 | 0.015 |
| Cressbrook | | | | |
| - Cressbrook Creek | Surface | 77 | 0.496 | 0.015 |
| - Little Oaky Creek | Surface | 78 | 0.573 | 0.015 |

* the values are adopted from Antenucci, 2000.

#### 5.1.1.2 Initial condition

There are two simulation settings in this study. The calibration and validation period is from March 1998 to February 2003, and the prediction period is from January 2004 to December 2053. Each simulation setting used different initial conditions taken from the measured data of the beginning simulation time.

#### 5.1.1.3 DYRESM- CAEDYM configuration

All DYRESM simulations coupled with CAEDYM ecological models were set to the time step of 360 minutes with a weekly output basis. The length of simulation is 1343 days for calibration and validation, and 18263 days for future prediction.

Minimum and maximum permissible layer thicknesses ($PLT_{max}$ and $PLT_{min}$) were set to 0.5 and 3.0 m, respectively (Antenucci & Imerito 2001). This combination complies with the rule $PLT_{max} > 2\ PLT_{min}$. It also gives the best results for other users. The destratification system was set to FALSE if the simulation was running for a natural setting (no artificial mixers). Otherwise it was set to TRUE if the mixers were set on the operation.

The atmospheric stability was set to a neutral condition to accommodate the use of interpolated wind speed data from different elevations of stations around the reservoirs. The simulations were assumed as a closed system where there is no open boundary. Sediment nutrient flux is calculated with a consideration of vertical diffusion using an oxygen and pH regression for the flux (Herzfeld & Hamilton 2000).

5.1.1.4 Hydrodynamic parameters

General parameters for DYRESM-CAEDYM consist of 13 coefficients for hydrodynamic computation in the storages. Fischer et al. (1979) suggested an appropriate value for a bulk aerodynamic transfer coefficient for neutral atmospheric stability condition to be $1.3\ 10^{-3}$. This coefficient is required to determine the wind stress exerted on the water surface from air density and wind speed. The mean albedo of water surface was set to be 0.08 as the representation of the reflection coefficient of the incident short wave radiation (Antenucci & Imerito 2001). Imberger & Patterson (1981 p. 316) give the value of emissivity of the water surface as 0.96.

Wind speed can stir a significant horizontal mixing in the water surface if the speed is equal to or bigger than the critical wind speed. Therefore the critical wind speed is needed to determine the initiation of mixing process in the reservoirs. Antenucci and Imerito (2001) used the value of 3.0 m $s^{-1}$ as the critical speed. This value was adopted in this research.

The entrainment coefficient and bubbler entrainment coefficient were 0.002 and 0.012, respectively. Antenucci and Imerito (2001) experimentally found that 0.083 was the optimal value of a buoyant plume entrainment coefficient.

The other value of parameters are adopted from DYRESM default values including shear production efficiency (= 0.080), potential energy mixing efficiency (= 0.20), wind stirring efficiency (= 0.06), effective surface area coefficient (= 1.0 x$10^7$), and vertical mixing coefficient (= 200) (Antenucci 2000; Imberger 1982; Imberger & Patterson 1981).

The time for output was set to ten hours (= 36000 seconds) from midnight as the time of observations in the dams. The summary of generic parameters in DYRESM can be seen in Table 5.3.

Table 5.3 General hydrodynamic parameters in water surface.

| Parameters/Coefficients | Unit | Value |
|---|---|---|
| Bulk aerodynamic transport coefficient | ND | 1.3 $10^{-3}$ |
| Mean albedo of water surface | ND | 0.080 |
| Emissivity of water surface | ND | 0.960 |
| Critical wind speed | m $s^{-1}$ | 3.000 |
| Time of day for output (in seconds from midnight) | s | 36000 |
| Entrainment coefficient constant | ND | 0.002 |
| Bubbler entrainment coefficient | ND | 0.012 |
| Buoyant plume entrainment coefficient | ND | 0.083 |
| Shear production efficiency | ND | 0.080 |
| Potential energy mixing efficiency | ND | 0.200 |
| Wind stirring efficiency | ND | 0.060 |
| Effective surface area coefficient | ND | 1.0 $10^7$ |
| Vertical mixing coefficient | ND | 200 |

Note: ND = non dimensional

5.1.1.5 General water quality constants

Most values of general constants in the water quality model are validated from others water bodies in Australia (Antenucci 2000). Hamilton and Zohary (1999) modified some values of water quality parameters based on the dominant species in the storage. These values were adopted for DYRESM-CAEDYM simulation in Cooby and Cressbrook reservoirs with some modifications. For instance, cyanobacterial growth rate for freshwater in DYRESM is set to 0.9 $day^{-1}$ as the default value. Hamilton and Zohary (1999) suggested 0.46 $day^{-1}$ for a reservoir and 0.37 $day^{-1}$ for a river dominated by Anabaena (http://www.cwr.uwa.edu.au/~yeates/). Some maximum growth rates of cyanobacterial species which are existing in Toowoomba's storages from various observation are presented in Table 5.4 (Robarts & Zohary 1987).

Table 5.4 Maximum growth rates of some Cyanobacterial species.

| Species | Maximum growth rate, $\mu_{max}$ ($day^{-1}$) | References |
|---|---|---|
| *Anabaena* | 0.40 | Konopka & Brock 1978 |
| *Anabaena oscillarioides* | 0.80 | Vincent & Silvester 1979 |
| *Anabaena spiroides* | 0.90 | Seki et al. 1981 |
| *Anabaena variabilis* | 1.10 | Collins & Boylen 1982 |
| *Aphanizomenon* | 0.18 | Konopka & Brock 1978 |
| *Aphanizomenon flos-aquae* | 1.20 | Uehlinger 1981 |
| *Microcystis* | 0.50 | Konopka & Brock 1978 |
| *Microcystis aeruginosa* | 0.80 | Nicklish & Kohl 1983 |
| *Microcystis aeruginosa* | 0.59 | Watanabe & Oishi 1985 |
| *Microcystis aeruginosa* | 0.81 | Van der Westhuizen & Eloff 1985 |
| *Microcystis* sp. | 0.25 – 0.30 | Krüger & Eloff 1978 |

Source: Modified from Robarts & Zohary 1987, p 395.

In the period 1998 – 2003, *Anabaena*, *Microcystis* and *Cylindropermopsin* were the dominant species in Cooby storage. Unlike in Cooby, *Cylindropermopsin* was not found in Cressbrook. *Anabaena* and *Microcystis aeruginosa* were dominant species for the period 1998 – 2001. Since 2002, a new species (*Aphanizomenon flos aqua*) has been found in high counts and has replaced the domination of *Anabaena* species. The growth rate values were determined based on the trend of cyanobacterial growth in both reservoirs. The growth rates were set to 0.46 day$^{-1}$ and 0.50 day$^{-1}$ for Cooby and Cressbrook storages, respectively. These values have given a better result for total Cyanobacteria in both reservoirs. Based on the trial and error simulation for some selected data in both reservoirs.

The light extinction coefficient is strongly affected by the suspended particulates and dissolved organic matter in the water column including chlorophyll-*a* particulates. The light extinction coefficient (ε) was calculated using modification of the Lambert-Beer's equation (Bowie et al. 1985 Eq. 6-33; Eurolakes 2003 Eq. 3.4).

$$\varepsilon = \varepsilon_o + k_{chl} * c_{chl} \qquad (5.2)$$

where $\varepsilon_o$ is the light extinction coefficient for freshwater with all particulates and dissolved organic matter without *chlorophyll*-a component (= 0.27 m$^{-1}$), $k_{chl}$ is a coefficient relating the *chlorophyll*-a concentration, $c_{chl}$ to the corresponding light extinction coefficient for *chlorophyll*-a (= 0.015 m$^2$ mg chl-*a*$^{-1}$), and $c_{chl}$ is *chlorophyll*-a concentration (mg chl-*a* m$^{-3}$).

The variation of light extinction coefficients in Cooby and Cressbrook storages can be seen in Figure 5.1 and 5.2. The coefficient is fluctuated from 0.2775 m$^{-1}$ to 1.185 m$^{-1}$ for Cooby reservoir and from 0.2775 m$^{-1}$ to 1.443 m$^{-1}$ for Cressbrook reservoir. The average value of the coefficient for Cooby and Cressbrook storages are 0.39 m$^{-1}$ and 0.35 m$^{-1}$, respectively.

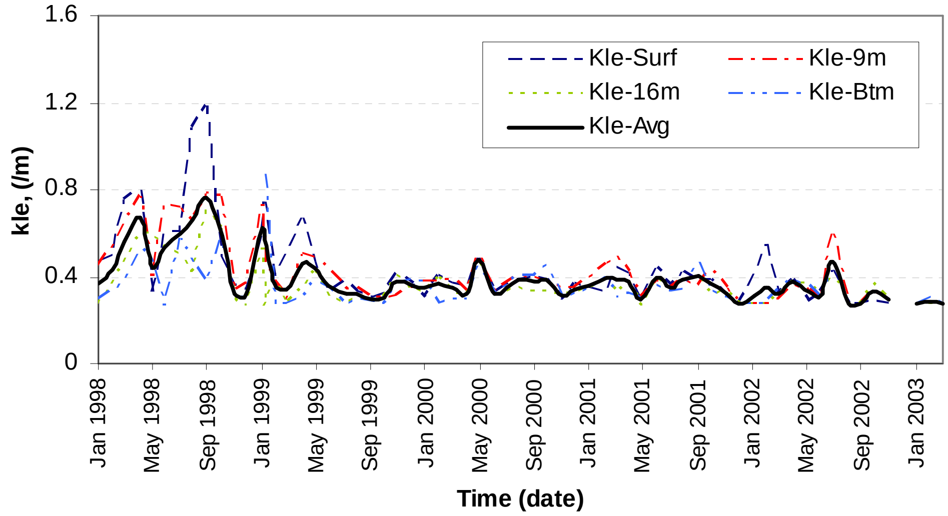



Figure 5.1 Variation of the light extinction coefficient in Cooby storage from the surface to the bottom of the reservoir (selected layers). The average value is added and marked as a bold line.

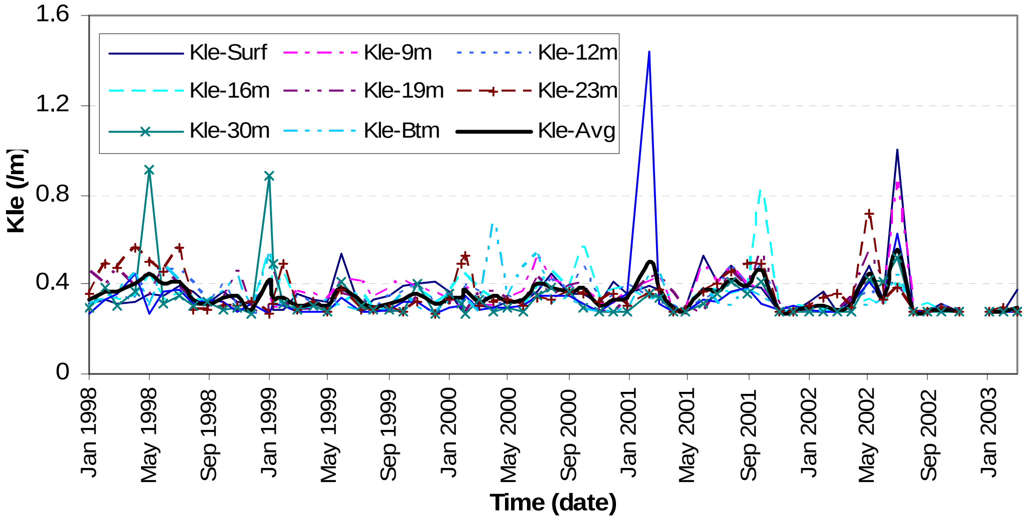



Figure 5.2 Variation of the light extinction coefficient in Cressbrook storage from the surface to the bottom of the reservoir. The average value is added and marked as a bold line.

5.1.1.6 Meteorology data

Meteorology data for the period of 1998 – 2004 were provided by the Queensland Bureau of Meteorology while data for a 50 year future prediction period (2004 – 2053) were generated using the ClimGen climate generator. The detail of synthetic data is presented in section 5.1.3.

5.1.1.7 Withdrawal data

Outflow of the reservoirs were provided by the Toowoomba City Council during the period 1998 – 2004. For future prediction, withdrawal data were assumed constant, based on the average outflow during normal operation of the dam from 1993 to 2001/2002. This assumption is based on the consideration of maximum support of the reservoirs. Increasing water demand in the City will not increase pumping water from the dams (Clark 2003). The deficit water supply is supplemented from ground water sources.

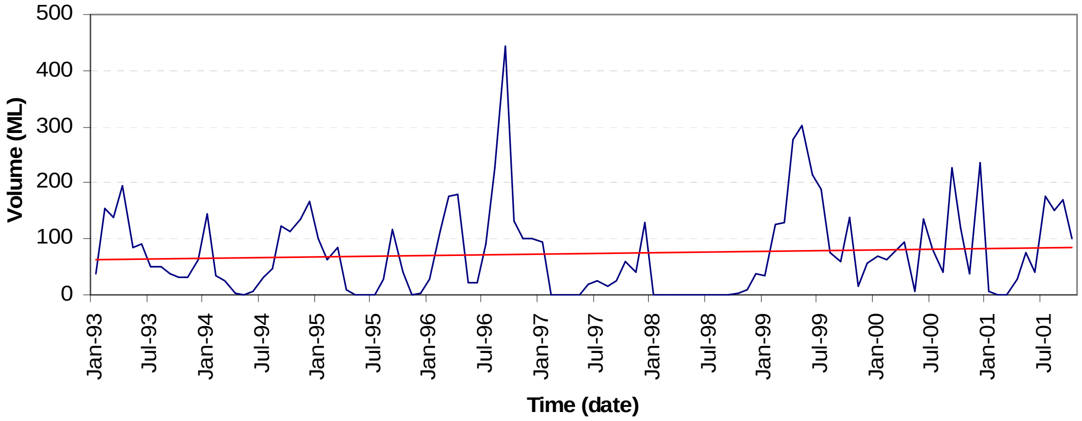



Figure 5.3 Monthly withdrawal of Cooby reservoir in the period of 1993 – 2001.

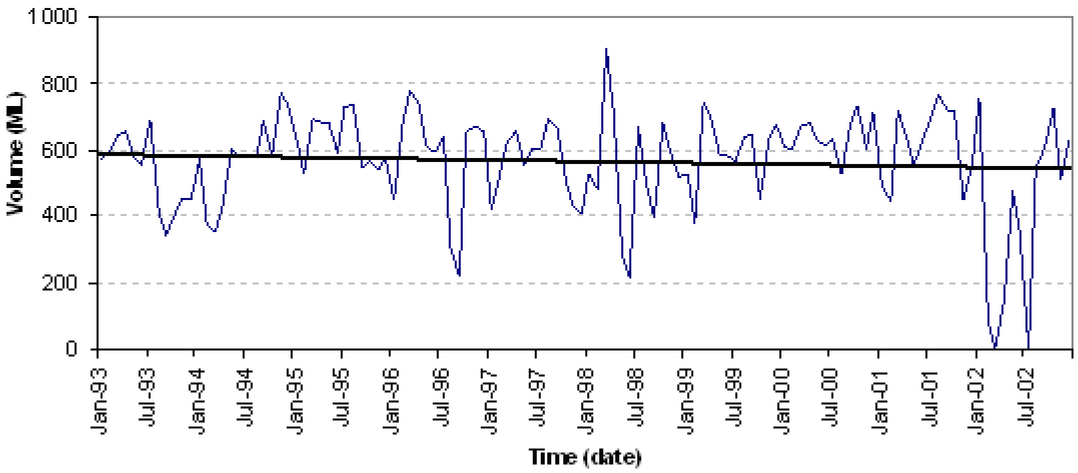



Figure 5.4 Monthly withdrawal of Cressbrook reservoir in the period of 1993 – 2002.

The monthly averaged pumped water from Cooby and Cressbrook dams in the period 1993 – 2002 are 60.9 ML (equivalent to 2000 $m^3$ $day^{-1}$) and 560 ML (equivalent to 18805 $m^3$ $day^{-1}$), respectively. Sequential daily withdrawal/pumped data are presented in Section 3.2.4.

5.1.1.8 Mixers setting

The configuration of mixers for Cooby reservoir was set to continuous operation with dual mixers based on the real mixers installed on November 2001. Specification of the mixers is impeller type SMDI-5 with a draft tube which is manufactured by WEARS Company.

Mixing process in a water body can effectively work if the capacity of the mixer is able to circulate water at least five per cent of the average volume per day (Burns & Powling 1981; Elliott & Morgan 2002). Mixer configuration for Cressbrook reservoir was set based on this requirement. Therefore, the reservoir needs a mixer capacity of 3100 ML $day^{-1}$ or equivalent to 35.9 $m^3$ $s^{-1}$. It was assumed that the SMDI-5s are used for Cressbrook, so the reservoir needs six mixers.

### *5.1.2 AWBM hydrological model*

Since there is no recorded daily inflow for both reservoirs (1998 – 2003), the inflow files therefore (*.inf) were prepared using the AWBM hydrological model. Preparation of the inflow file is presented in this section.

The AWBM hydrological model was used to produce the quantity of inflow. Simulation parameters for the reservoirs' catchments were adopted from Loxton's works (see also Section 3.3). The preparation of inflow for Cooby and Cressbrook is in Section 5.2.

The comparison of measured and simulated inflow using the AWBM hydrologic model of Cressbrook reservoir, for example, was given by Loxton (1999) and Macintosh (2002). Figure 5.5 represents time series of measured and simulated inflow (1988 – 1992) in the reservoir's catchment and Figure 5.6 shows the correlation plot of measured and simulated data. The graphs show the accuracy of the AWBM hydrologic model for Cressbrook Dam.

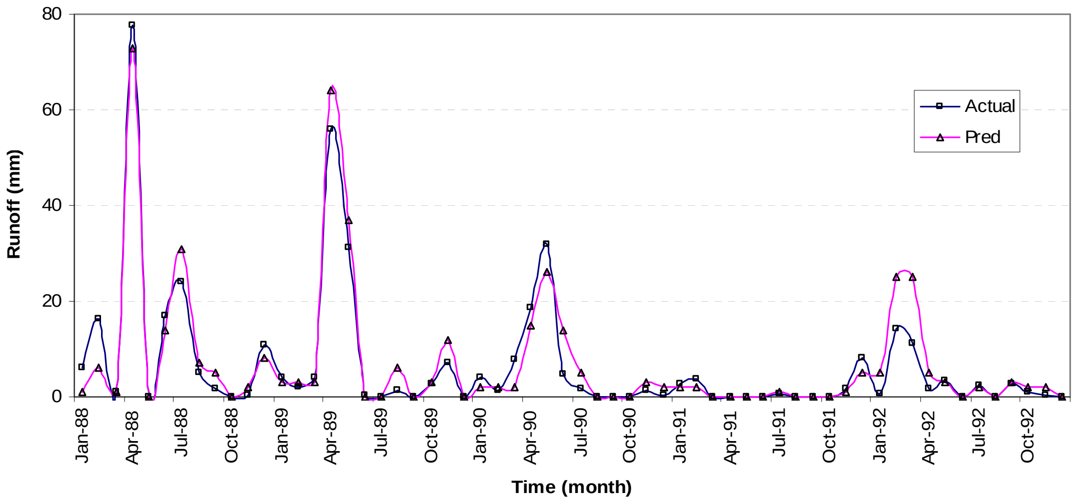



Figure 5.5 Time series of simulated and measured inflow of Cressbrook reservoir in the period of 1988 – 1992 (data adopted from Loxton 1999).

The AWBM model gave a 0.92 correlation coefficient between measured and simulated data (detail verification and validation AWBM model for Cooby and Cressbrook catchments can be seen in Loxton (1999)). This result can produce valid inflow data for hydrodynamic simulation in the reservoir.

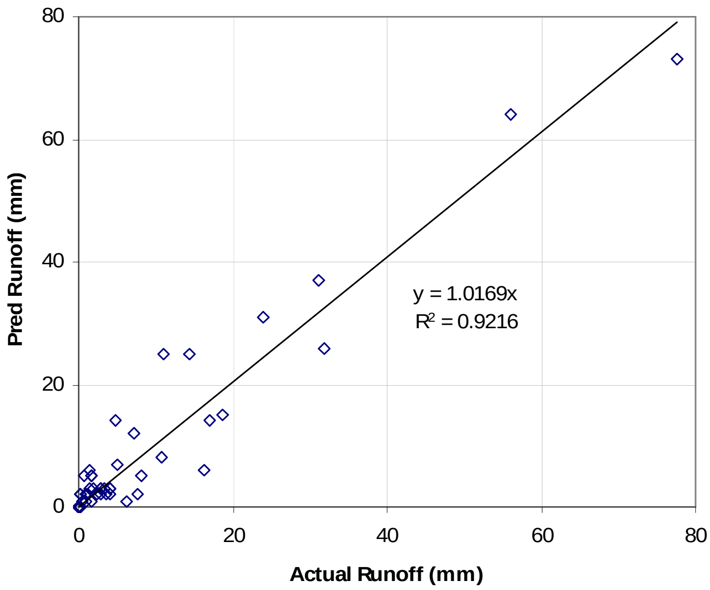



Figure 5.6 Correlation plot of simulated and measured inflow of Cressbrook reservoir in the period of 1988 –1992 (data adopted from Loxton 1999 & Macintosh 2002).

The AWBM simulation has given a similar result for Cooby reservoir with a reduction of the total area fraction. Therefore, the model parameters for the reservoir's catchments were adopted to simulate inflow for the period of 1998 – 2003 and of 2004 – 2053 for both reservoirs. The value of eight basic parameters for both reservoirs' catchments is presented in Section 3.3.3.

The AWBM model acquires two types of input which are monthly evaporation and daily rainfall and the adopted parameters to produce inflow data. For period of 1998 – 2003, the input data were provided by the Toowoomba City Council while for the future prediction (2004 – 2053), data were generated using the ClimGen weather generator.

### *5.1.3 ClimGen*

#### 5.1.3.1 Configuration of the ClimGen

Data generation is developed based on the Weibull distribution function as previously described on Section 2.5. This distribution is sampled for each day of weather generation using the inverse method. All values of general parameters were calculated automatically in the ClimGen using historical data. Clear sky transmission coefficient and B value for solar radiation are the parameters for generating short wave radiation from temperatures when using the Simple ET Model. The parameters are the function of latitude. The Priestley-Taylor constant (usual range = 1.2 – 1.3) is needed to compensate for the elimination of the aerodynamic component of the Penman-Monteith model. The simple ET model is useful to produce evapotranspiration data to generate inflow with the AWBM model (see also Section 5.1.2). A summary of basic parameters for weather generation for Cooby and Cressbrook catchments is presented in Table 5.5.

Table 5.5 General parameters of the weather generator for Cooby and Cressbrook dams.

| Parameters | Cooby | Cressbrook |
|---|---|---|
| Clear sky transmission coefficient | 0.75645 | 0.75478 |
| Fitted B solar radiation | 0.39797 | 0.39839 |
| Priestley-Taylor Constant | 1.26000 | 1.26000 |
| Aridity factor for VPD ($kPa^{-1}$) | 0.03000 | 0.03000 |
| Aridity factor: - Non summer | -13.48640 | -0.03967 |
| - Summer | -5.97222 | -0.00697 |
| VPD Slope: - Non summer | 1.00000 | 0.98685 |
| - Summer | 0.99132 | 0.99768 |
| VPD Intercept: - Non summer | 0.00000 | 0.00000 |
| - Summer | 0.00000 | 0.00000 |
| Dew Point Slope: - Non summer | 0.28194 | 1.04249 |
| - Summer | -0.21327 | 0.91723 |
| Dew Point Intercept: - Non summer | -7.66587 | -2.51988 |
| - Summer | 11.69529 | 0.67822 |

Based on these parameters, the position of both reservoirs was classified as dry land area (Nelson 2002). This class was determined using automatic calculations in the ClimGen model. The vapour pressure deficit was very small which is indicated by the slope values around one and nil interception value.

Rainfall occurrences were predicted based on the probability of a wet day followed by a wet or dry day on a monthly basis. In general, the probability occurrence of precipitation in a dry day was less than 20 per cent while in a wet day was about 50 per cent. The probability of occurrences of a rainfall event for Cooby dam is slightly higher than Cressbrook dam in both wet and dry day situations. The detailed probability occurrence of precipitation in wet and dry days is shown in Table 5.6.

In relation to the Weibull distribution of precipitation, two parameters (α and β) of the monthly distribution were determined for generation purposes. The values of α and β for Cooby and Cressbrook reservoir which were used to generate weather data in the ClimGen version 4.1.05 are presented in Table 5.7.

Table 5.6 Precipitation probability for the next day in wet and dry conditions of Cooby and Cressbrook reservoirs.

| Month | Cooby precipitation probability | | Cressbrook precipitation probability | |
|---|---|---|---|---|
| | *P*(w/w)* | *P*(w/d)** | *P*(w/w)* | *P*(w/d)** |
| January | 0.61333 | 0.15818 | 0.55000 | 0.15652 |
| February | 0.59274 | 0.22052 | 0.57778 | 0.19792 |
| March | 0.51235 | 0.12887 | 0.51852 | 0.10156 |
| April | 0.55189 | 0.17658 | 0.50000 | 0.13559 |
| May | 0.47236 | 0.18229 | 0.50000 | 0.16239 |
| June | 0.50549 | 0.15845 | 0.46667 | 0.13333 |
| July | 0.50758 | 0.10109 | 0.36000 | 0.12308 |
| August | 0.53889 | 0.13950 | 0.57692 | 0.08527 |
| September | 0.53333 | 0.13162 | 0.40741 | 0.13008 |
| October | 0.33520 | 0.19966 | 0.42857 | 0.12598 |
| November | 0.59295 | 0.28995 | 0.48889 | 0.21905 |
| December | 0.59216 | 0.20000 | 0.56098 | 0.15789 |

* *P(w|w)* is the probability of a wet day given a previous wet day.
** *P(w|d)* is the probability of a wet day given a previous dry day.

Table 5.7 The values of α and β for Weibull distribution of precipitation in Cooby and Cressbrook reservoirs.

| Month | Cooby precipitation (mm) | | Cressbrook precipitation (mm) | |
|---|---|---|---|---|
| | α (Alfa) | β (Beta) | α (Alfa) | β (Beta) |
| January | 0.81580 | 5.84897 | 0.84088 | 7.22903 |
| February | 0.66251 | 7.73065 | 0.68743 | 12.14603 |
| March | 0.75020 | 6.06559 | 0.88247 | 9.81893 |
| April | 0.83075 | 2.71203 | 1.06453 | 6.95065 |
| May | 0.77766 | 3.69461 | 0.80458 | 6.54786 |
| June | 0.71389 | 3.25441 | 0.95470 | 5.00798 |
| July | 0.85950 | 5.14338 | 0.87659 | 5.83349 |
| August | 0.79762 | 3.80178 | 0.99450 | 5.97592 |
| September | 0.80113 | 4.45057 | 0.78805 | 6.87175 |
| October | 0.77980 | 6.83038 | 0.97016 | 7.49426 |
| November | 0.77648 | 5.16341 | 0.88704 | 7.52487 |
| December | 0.78584 | 8.11119 | 0.98105 | 14.21472 |

With the same procedure for determination of precipitation parameters, the values of α and β for wind speed distributions were also determined for Cooby and Cressbrook reservoirs as presented in Table 5.8.

Table 5.8 The values of α and β for Weibull distribution of wind speed in Cooby and Cressbrook reservoirs.

| Month | Cooby wind speed (m/day) | | Cressbrook wind speed (m/day) | |
|---|---|---|---|---|
| | α (Alfa) | β (Beta) | α (Alfa) | β (Beta) |
| January | 4.75237 | 608669.18750 | 4.75232 | 608668.62500 |
| February | 3.87310 | 610219.06250 | 3.67015 | 606294.62500 |
| March | 3.99521 | 571014.43750 | 4.01258 | 570765.93750 |
| April | 3.86748 | 552092.18750 | 3.86464 | 552134.43750 |
| May | 2.96362 | 492336.87500 | 2.97053 | 492853.37500 |
| June | 2.85857 | 498540.68750 | 2.85598 | 497563.75000 |
| July | 3.22959 | 454246.34375 | 3.23310 | 453874.25000 |
| August | 3.00611 | 528313.18750 | 3.00715 | 527950.18750 |
| September | 3.57080 | 520608.00000 | 3.56732 | 521127.40625 |
| October | 3.54159 | 546585.37500 | 3.54562 | 546559.00000 |
| November | 4.05293 | 566228.87500 | 4.03960 | 565405.50000 |
| December | 4.27646 | 580039.25000 | 4.28278 | 581915.56250 |

5.1.3.2 Accuracy of data generation

A 50-year daily weather data set was generated using 25-year measured data of precipitation and 5-year measured data of solar radiation, wind speed, average temperature, relative humidity and vapour pressure. The accuracy of the prediction was analysed using the probability of exceedence of generated parameters. A comparison of measured and generated data for each parameter in Cooby catchment is presented in Figure 5.7.

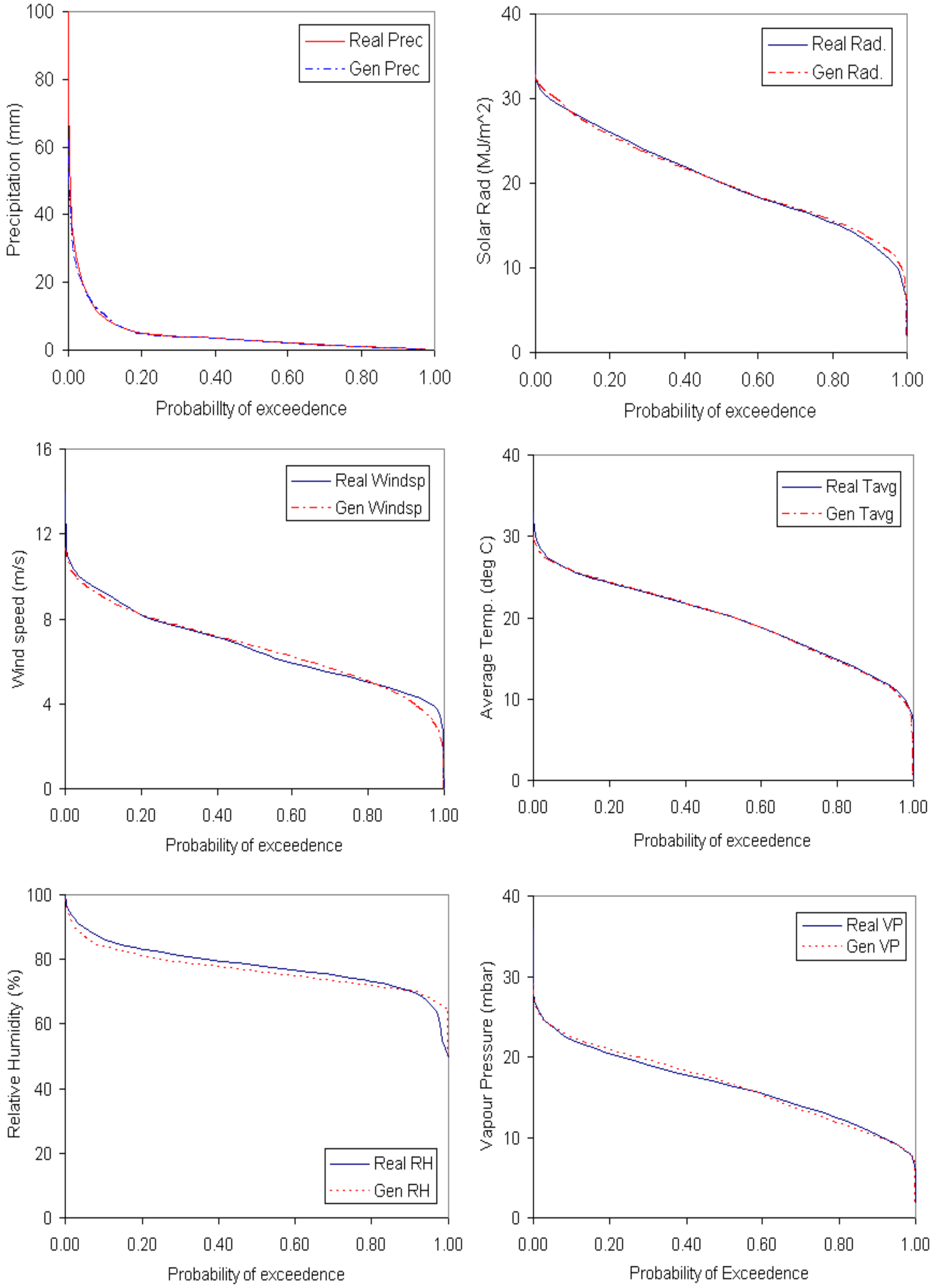



Figure 5.7 Probability of exceedence of measured and generated weather parameters of Cooby reservoir. Measured data are from 1978 to 2002 for precipitation and from 1998 to 2002 for solar radiation, wind speed, average temperature, relative humidity and vapour pressure. Generated data are from 2004 to 2053.

The probability of exceedence of the 50-year sequences synthetic data in Cooby areas has a similar pattern to the probability of exceedence of the historical data. Some differences for historic and generic data are found in the lowest values for wind speed, relative humidity and solar radiation and in the highest values of precipitation. The extreme values of these parameters are below 5 m $s^{-1}$, 15 MJ $m^{-2}$ and 70 per cent, for wind speed, solar radiation and relative humidity, respectively. The extreme value of rainfall is the event over 70 mm per day.

Probability of exceedence of weather parameters in the Cressbrook region is also presented by comparing the measured and generated data. The comparison of probability of exceedence measured and generated data of Cressbrook reservoir is presented in Figure 5.8. The figure shows that the sequences of generated data for all parameters of Cressbrook catchment have a probability of exceedence with a similar pattern to the observed data. However, generated values of rainfall over 70 mm per day, solar radiation over 28 MJ $m^{-2}$, wind speed below 5 m $s^{-1}$ and relative humidity below 70 per cent give a slightly different result to the probability of exceedence of the measured data. These differences mostly occur in the extreme data range as can be clearly seen at the values of probability of exceedence below 0.1 and above 0.9. Water volume in the dam is directly affected by rainfall extreme data. However, rainfall data generation show not much different at the values of probability of exceedence below 0.1 and above 0.9

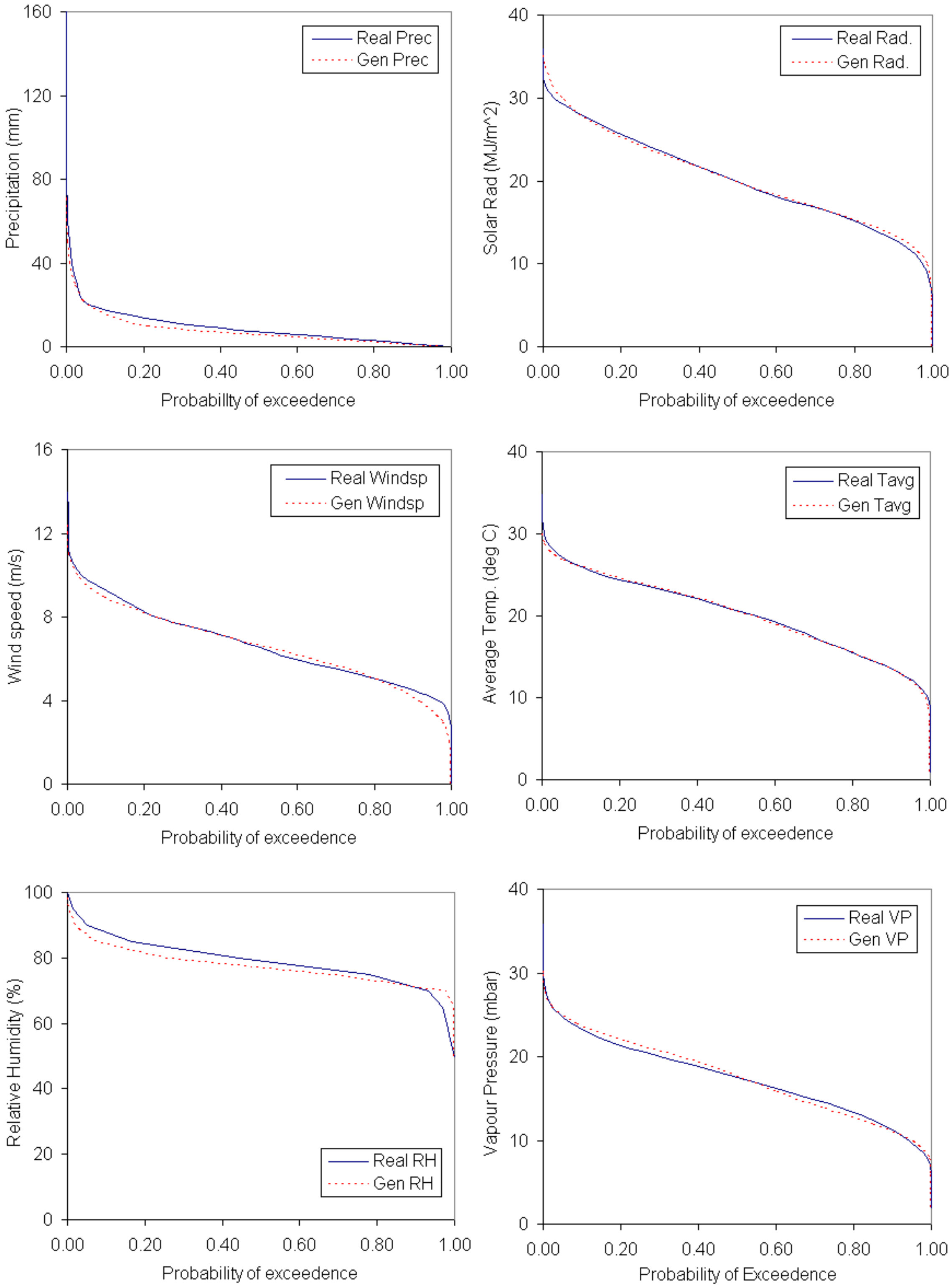



Figure 5.8 Probability of exceedence of measured and generated weather parameters of Cressbrook reservoir. Measured data are from 1978 to 2002 for precipitation and from 1998 to 2002 for solar radiation, wind speed, average temperature, relative humidity and vapour pressure. Generated data are from 2004 to 2053.

## 5.2 Preparation of Inflow

### *5.2.1 Inflow for period 1998 – 2003*

The quantity of inflow for all creeks in Cooby and Cressbrook were simulated using the AWBM model. The accuracy of the simulations was tested by comparison against water surface elevation data for the dams. The simulation accuracy was above 90 per cent with regression coefficients of 0.92 and 0.97 respectively as shown in Figure 5.10 and 5.12. The inflow simulations were assumed to be valid and were used in the DYRESM-CAEDYM water quality modelling work.

A sequential data of simulated inflow into Cooby reservoir is presented in Figure 5.9.

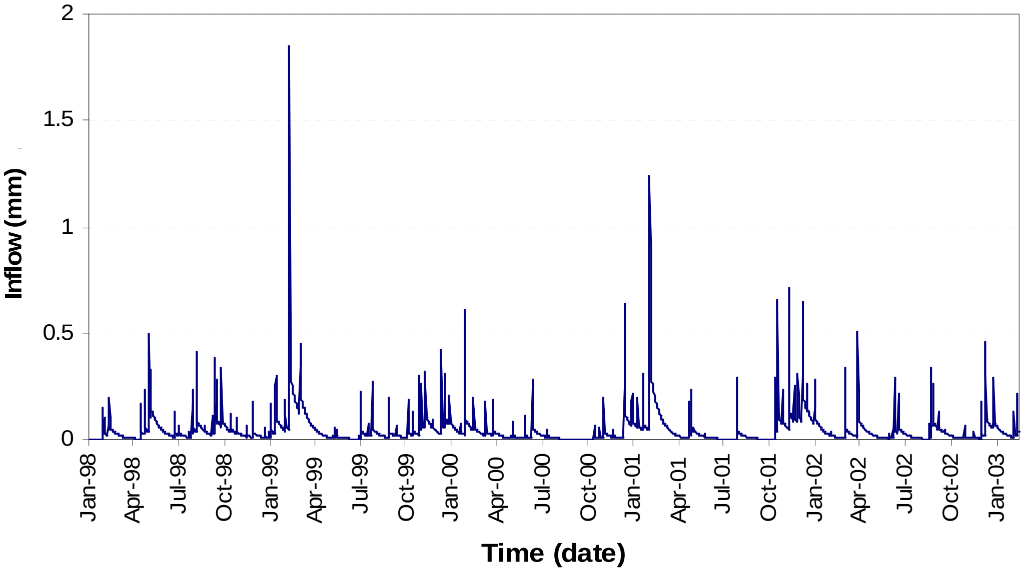



Figure 5.9 Time series simulated inflow for Cooby reservoir (in mm depth) in the period from 1998 to 2003.

The depth of inflows was multiplied by the sub-catchment areas to produce volume inflow data for each creek.

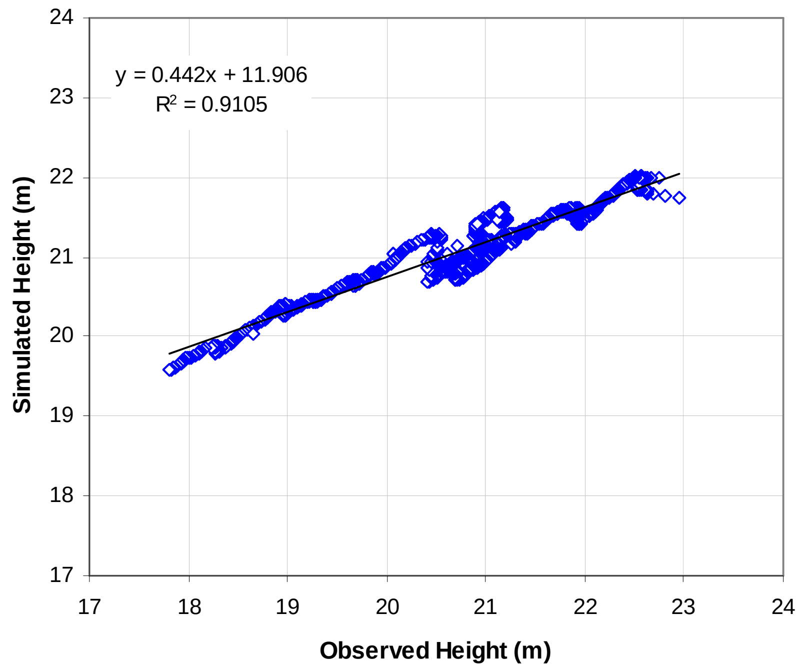



Figure 5.10 Correlation between measured and simulated water surface elevation data in Cooby reservoir in the period between Mar 1998 and Feb 2003 (1434 days).

Inflow into Cressbrook dam is intermittent as shown in Figure 5.11. This creek is ephemeral, and only flows during the wet season. It dries up when there is no significant rainfall event.

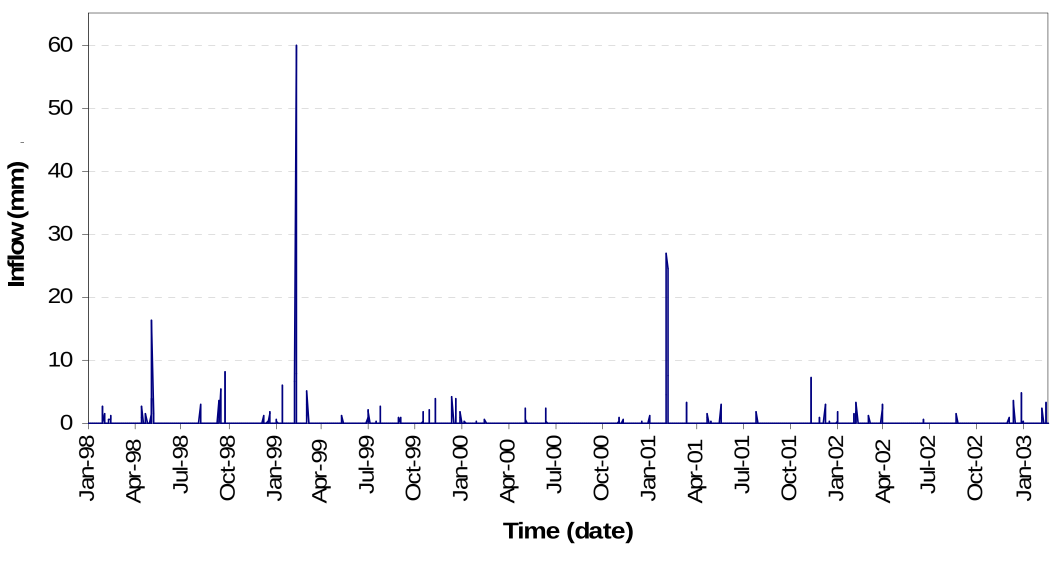



Figure 5.11 Time series simulated inflow of Cressbrook reservoir in the period from Jan 1998 to Feb 2003.

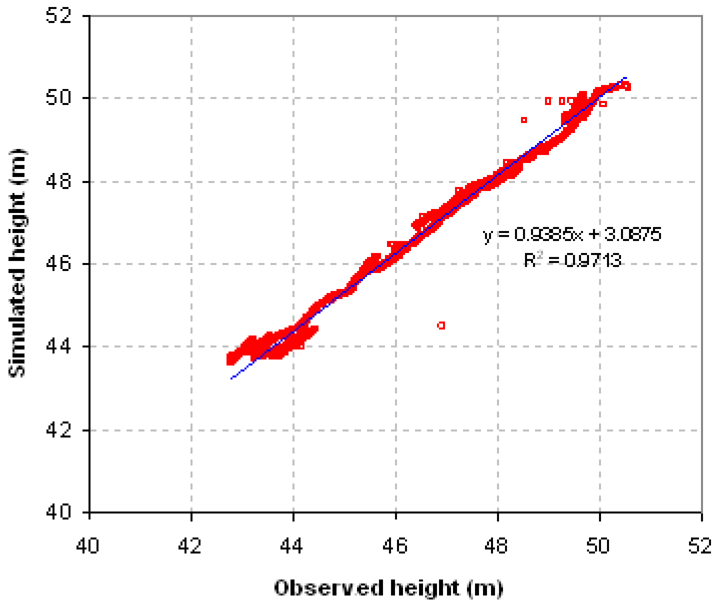



Figure 5.12 Correlation between measured and simulated water surface elevation data in Cressbrook reservoir for the period of Mar 1998 – Feb 2003.

### *5.2.2 Inflow for the period 2004 – 2053*

The quantity of inflow for a 50 year period was simulated using the AWBM hydrologic model and labelled as 2004 – 2053 data for convenience. The parameters for both catchments were held unchanged for this simulation, effectively freezing the catchment condition for the study including land use and soil conservation practices.

A series of daily rainfall values was taken directly from the ClimGen simulation (synthetic/generated data) while monthly evaporation data were calculated from the synthetic weather data using the modified Penman-Monteith approach before being exported to the AWBM model. The 50-year inflow series was successfully simulated from these two data sets. The 50-year period of synthetic inflows of Cooby and Cressbrook catchments are shown in Figure 5.13 and 5.14. The average inflow for the catchments is 0.046mm for Cooby and 0.115 mm for Cressbrook. The inflow values for both reservoirs show a negative trend with time. A similar trend was observed in water surface elevation in the dams. Surface inflows are the main water source for the reservoirs.

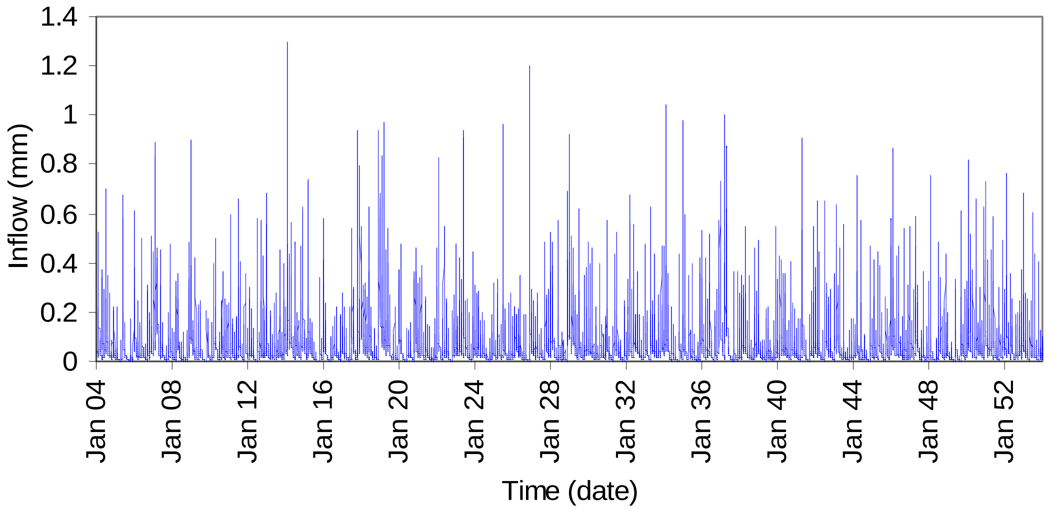



Figure 5.13 Time series of synthetic inflow of Cooby's creeks for the period of 2004 – 2053 (Inflow in mm depth).

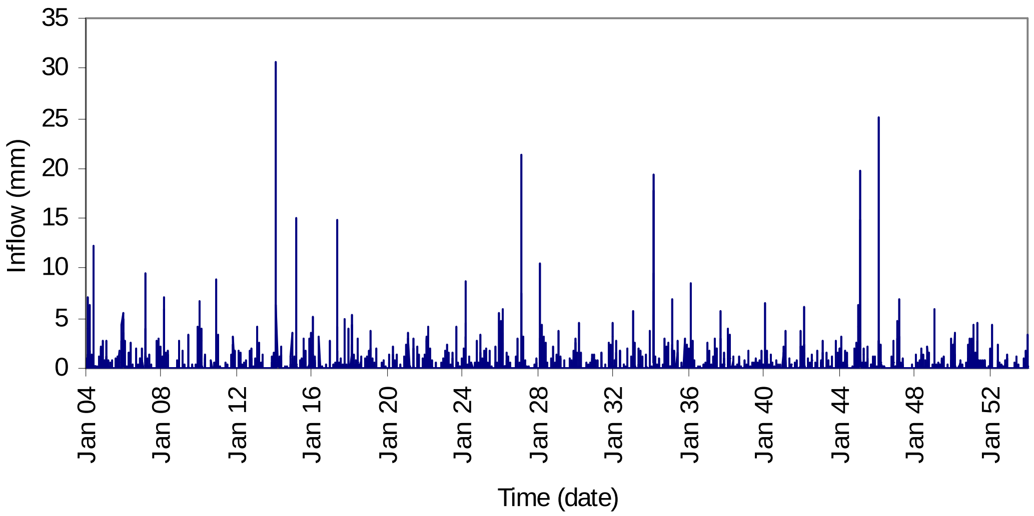



Figure 5.14 Time series of synthetic inflow of Cressbrook's creeks for the period of 2004 – 2053 (Inflow in mm depth).

The 50 year period of synthetic inflows to the dams provides a basis for predictions of future dam behaviour. Sensitivity analyses of inflow to variations in rainfall and solar radiation are provided in Chapter 6.

Information on inflow water quality was a limitation in this project since there were no recording stations on the creeks for either flow rates or quality. Quality data for inflows was adapted from other related studies (Merz 2001; Sanders & Porter 1994; Titmarsh et al. 1997). The data was taken as lumped values dependent on land use, with no temporal variation. Therefore, the quality of inflows was assumed constant during the simulation period.

Cyanobacterial concentrations in all creeks (Cooby, Geham, Little Oaky, and Cressbrook creeks) were assumed to be insignificant. This assumption was based on the variable nature of the inflows, which are associated with rainfall events. Temperatures of inflow were determined as a function of the 4-day moving average of air temperature (Antenucci 2000). Salinity concentrations of the inflows were very small (0.05 psu for Cooby and 0.10 psu for Cressbrook). The dissolved oxygen concentrations of inflow was set to 5.68 mg $L^{-1}$ in accordance with Queensland Department of Natural Resources and Mines (2002).

## 5.3 Model Validation

Model validation focused on selected parameters of importance: water temperature, dissolved oxygen, nitrogen and phosphorus, and cyanobacterial concentrations. These parameters have a major impact on water quality dynamics in the reservoirs. Three of the parameters also have shown variability in the reservoirs during the year (see chapter 4). The simulated values of these parameters were validated by comparisons with available measured data. A full discussion on water quality validation follows:

### *5.3.1 Validation of water temperature*

The results of water temperature simulation in Cooby reservoir were validated by comparing simulated values at selected layers with the measured data. The correlation coefficient of these paired data is used to quantify the level of acceptability of the simulations.

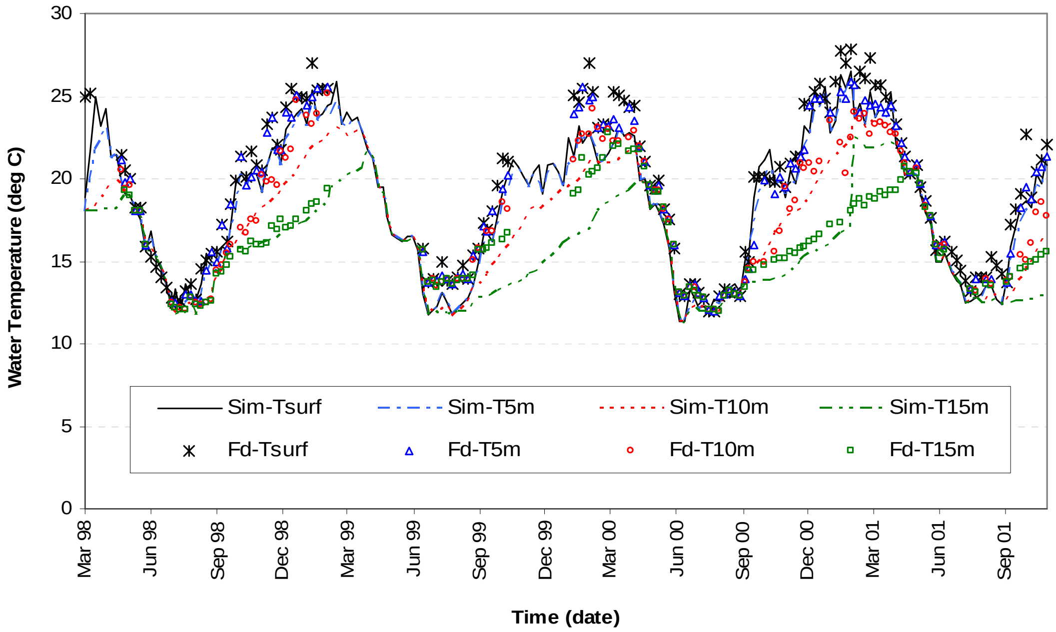



Figure 5.15 Time series of measured and simulated water temperature at selected depths (water surface, 5 m, 10 m and 15 m depths) of Cooby reservoir for the period 1998 – 2001 (no artificial mixer).

Figure 5.15 shows the time series of water temperatures in selected layers before the mixer installation was computed. A good correlation coefficient was obtained between measured and simulated water temperatures in these layers. The correlation coefficient for all selected layer data in Cooby Dam before mixers installation can be seen in Figure 5.16.

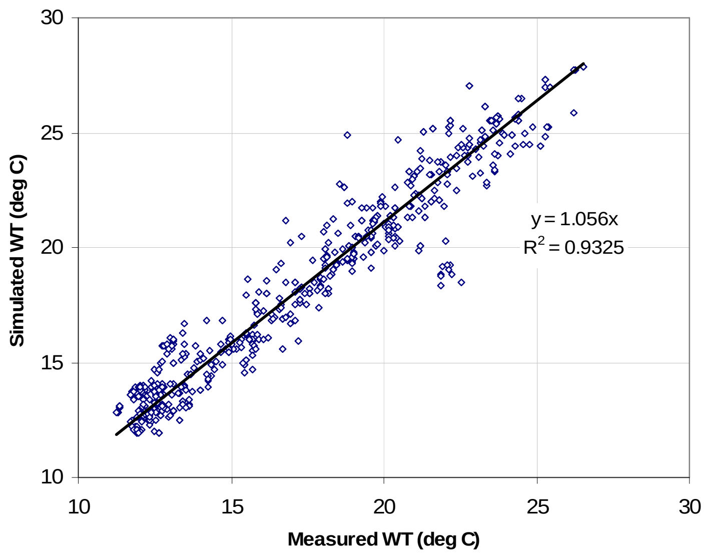



Figure 5.16 Correlation between measured and simulated water temperature for selected depths in Cooby Dam from 1998 to 2001 (no artificial mixer).

Figure 5.16 indicates the accuracy of the water temperature simulations without mixers in the storage. The correlation coefficient is 0.93 and the gradient for the regression line is 1.056 ($n$ = 336). These values indicate that predictions of water temperature without mixers in Cooby Dam can be accepted as providing a close match to actual values.

Water temperature simulation with artificial mixers was also validated using data from the period 2001 –2003. The results give a close correlation between the measured and simulated values as shown in Figure 5.17. The associated regression coefficient was 0.92 with regression line slope of 0.96. This value indicates similar accuracy of simulation to that found without mixers (see Figure 5.18). The regression line gradient for the period 1998 – 2001 shows that the water temperature simulation without mixers is slightly higher than the observed values. Conversely, the simulations for the period 2001 – 2003 with mixers indicated lower values than measured.

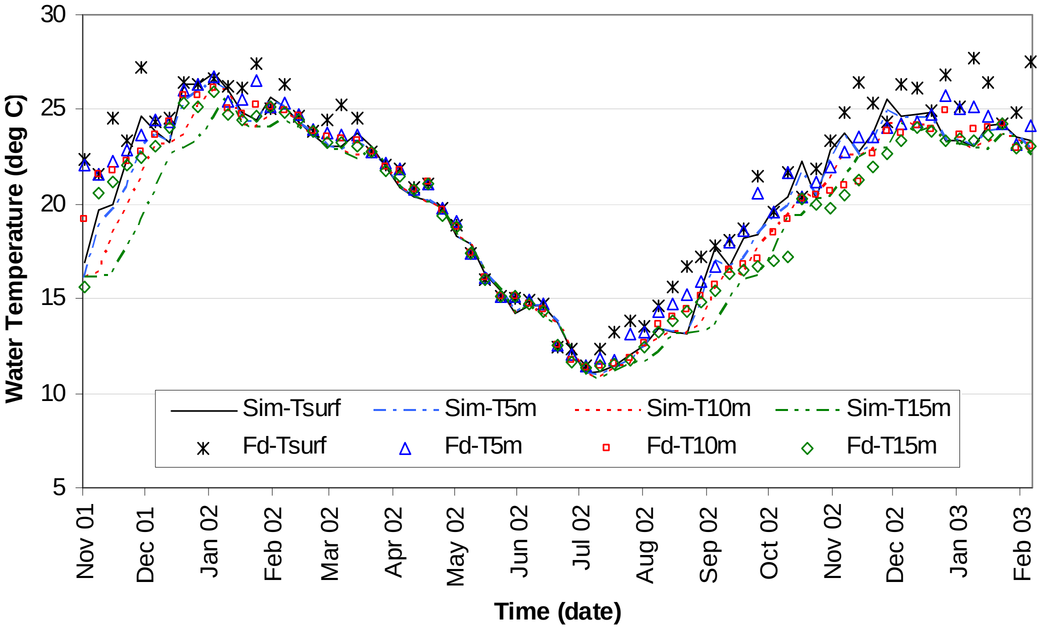



Figure 5.17 Time series of measured and simulated water temperature at selected depths (water surface, 5 m, 10 m and 15 m depths) of Cooby reservoir for the period 2001 – 2003 (with a couple of artificial mixers).

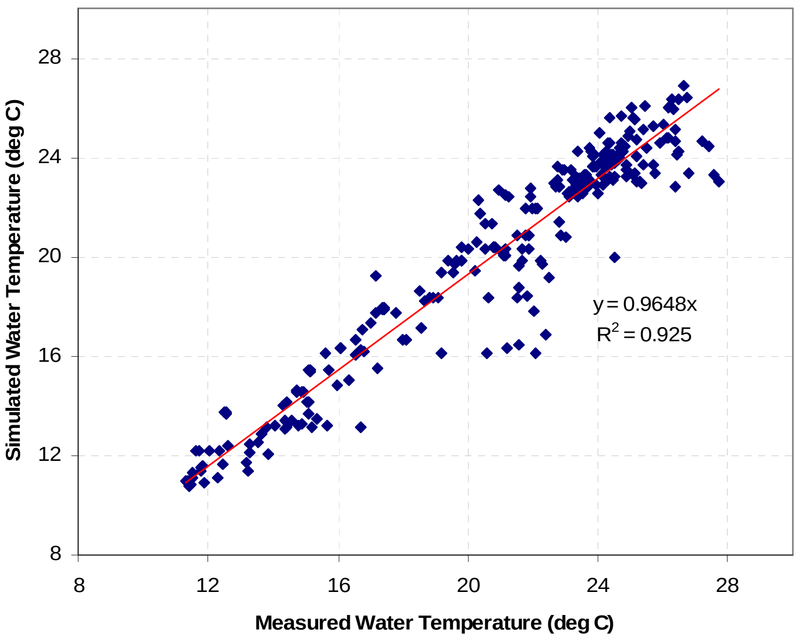



Figure 5.18 Correlation between measured and simulated water temperature for selected depths in Cooby Dam from 2001 to 2003 (with a couple of artificial mixers).

Validation of water temperature simulations in Cressbrook reservoir can only be done without artificial mixers (there has been no mixer installation in this dam).

Nevertheless, comparison of simulated and measured water temperatures in Cressbrook storage indicated that the simulations were accurate. The comparison are presented in Figure 5.19 and 5.20 for this storage.

Simulated water temperatures show vertical stratification occurring during the warm periods between the unstratified cold periods. Some extreme conditions of water temperatures level at the surface layer and the layer below the thermocline (15 metres below the water surface) create a small variation between measured and simulated data but the correlation coefficient between measured and simulated data is still 0.98 for all selected layers. The lowest value of the correlation coefficient for selected layers is 0.79 at 15 metres below the water surface.

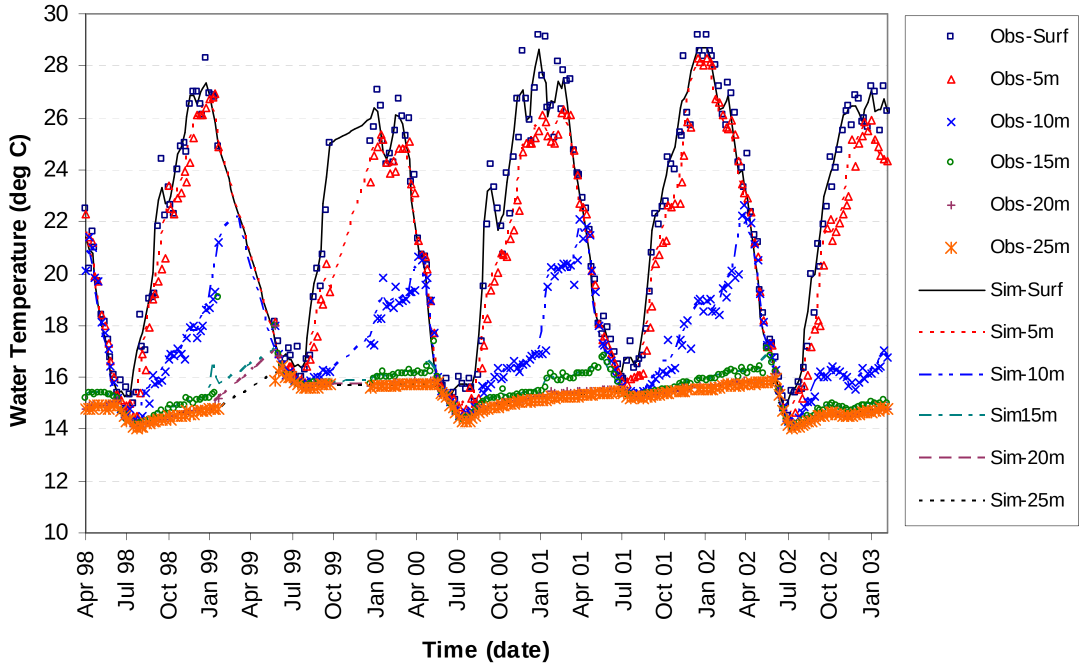



Figure 5.19 Time series of measured and simulated water temperature at selected depths (water surface, 5 m, 10 m and 15 m depths) of Cressbrook reservoir for the period 1998 – 2003.

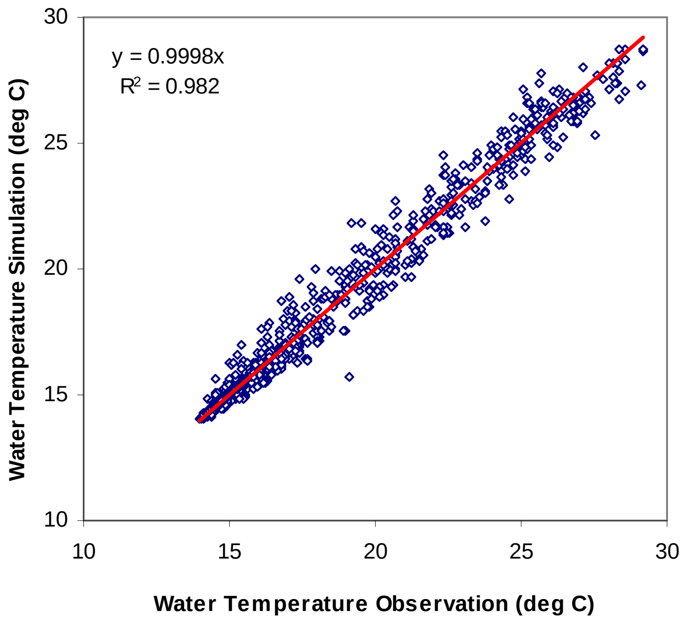



Figure 5.20 Correlation between measured and simulated water temperature for selected depths in Cressbrook Dam from 1998 to 2003.

### *5.3.2 Validation of dissolved oxygen*

Validation of dissolved oxygen concentrations encountered difficulties from suspect measured data. The comparison of measured and simulated values in Figure 5.21 shows considerable variation between the series, with measured values frequently approaching zero. In the period June – December 1998, the measured data from the surface to the 10 m layer below the surface showed over or super saturated values. Yet the dissolved oxygen concentrations were very low to a minimal value (zero) in the surface layer during stratified periods.

Investigations confirmed that the instrument (sensor) was not calibrated before use in the three different storages in Toowoomba and the differences in site conditions have rendered the data suspect.

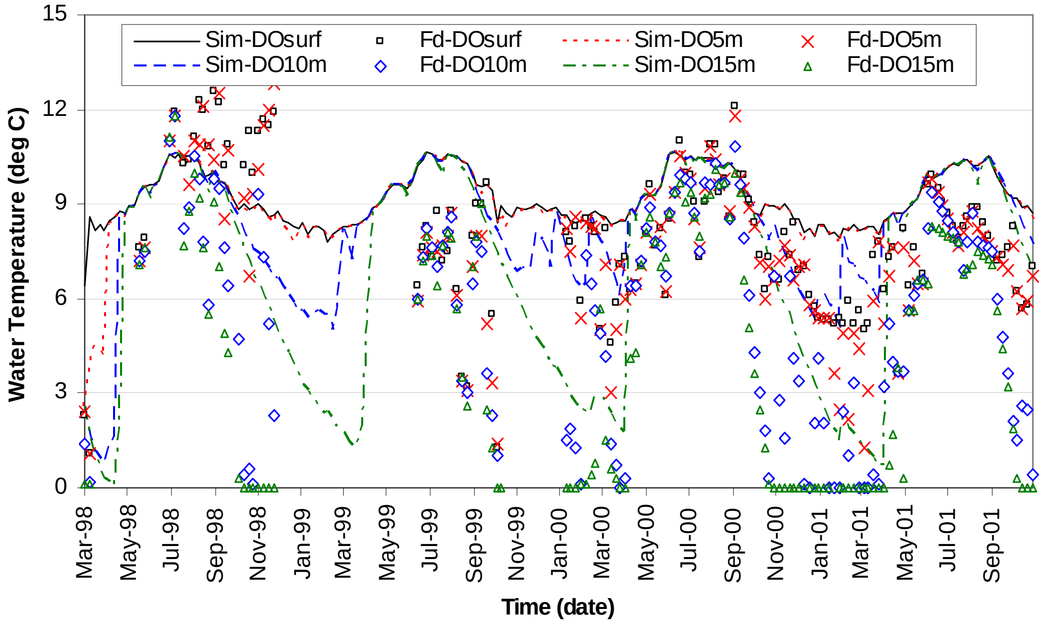



Figure 5.21 Time series of measured and simulated dissolved oxygen at selected depths (water surface, 5 m, 10 m and 15 m depths) of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

The simulation result shows the expected seasonal pattern in the storage as shown in Figure 5.21. The concentration in the surface layer is close to saturation while concentrations the layers below the surface decrease gradually with depth and distance from the atmosphere.

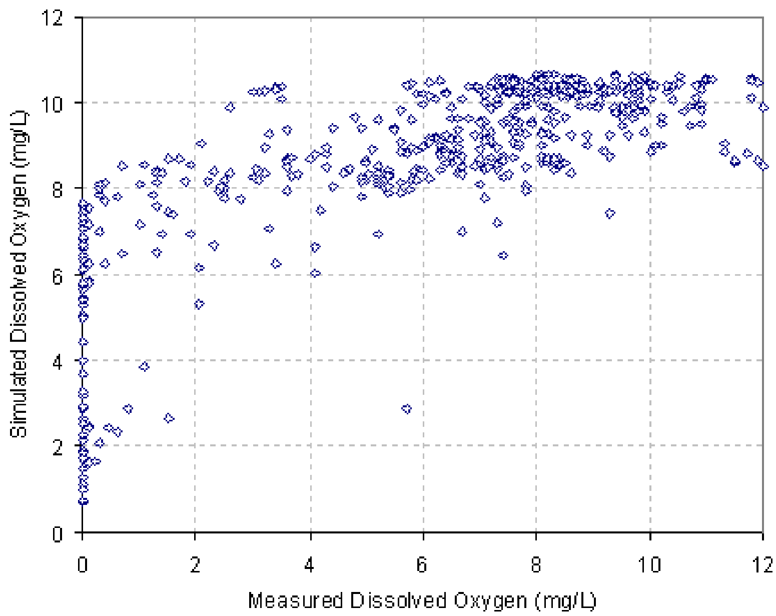



Figure 5.22 Correlation between measured and simulated dissolved oxygen for selected depths in Cooby Dam from 1998 to 2001 (without artificial mixers). Measured data which are higher than 12 mg $L^{-1}$ are not presented.

Figure 5.22 compares the measured and simulated values. It shows the large number of recorded dissolved oxygen concentrations with zero value. The difference between measured and simulated dissolved oxygen in this value can be up to 7.8 mg $L^{-1}$. The simulated values range between 0.5 and 10.5 mg $L^{-1}$ while the measured values are in between 0 and 14 mg $L^{-1}$. The patterns of simulated dissolved oxygen at all selected layers are more rational than those found in the measured data. It is concluded that the dissolved oxygen simulations are probably working well, but it is not possible to prove this.

The measured dissolved oxygen concentrations after mixer installation also give some low (zero) records of dissolved oxygen at 10 metres and 15 metres below the water surface (see Figure 5.23) with no observable pattern in their occurrence. In general, the simulated values are higher than the measured data. The simulation result shows that the oxygen concentrations moderately change (increase or decrease) with time while the measured data drop and increase irregularly over the same time period.

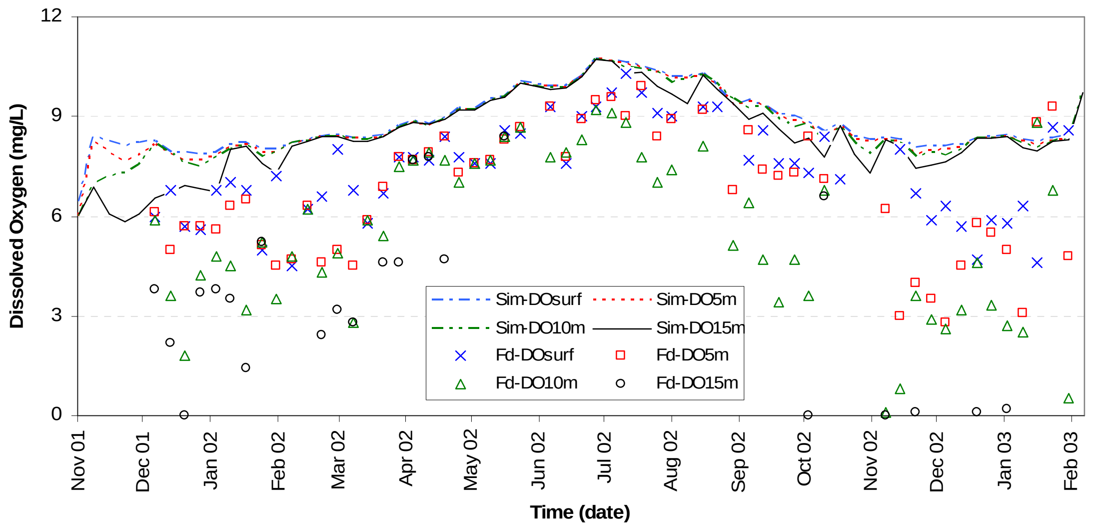



Figure 5.23 Time series of measured and simulated dissolved oxygen at selected depths (water surface, 5 m, 10 m and 15 m depths) of Cooby reservoir for the period 2001 – 2003 (with two artificial mixers).

Comparisons between measured and simulated dissolved oxygen concentrations in Cooby dam after the installation of mixers gives a similar result to the validation without artificial mixers (see Figure 5.24).

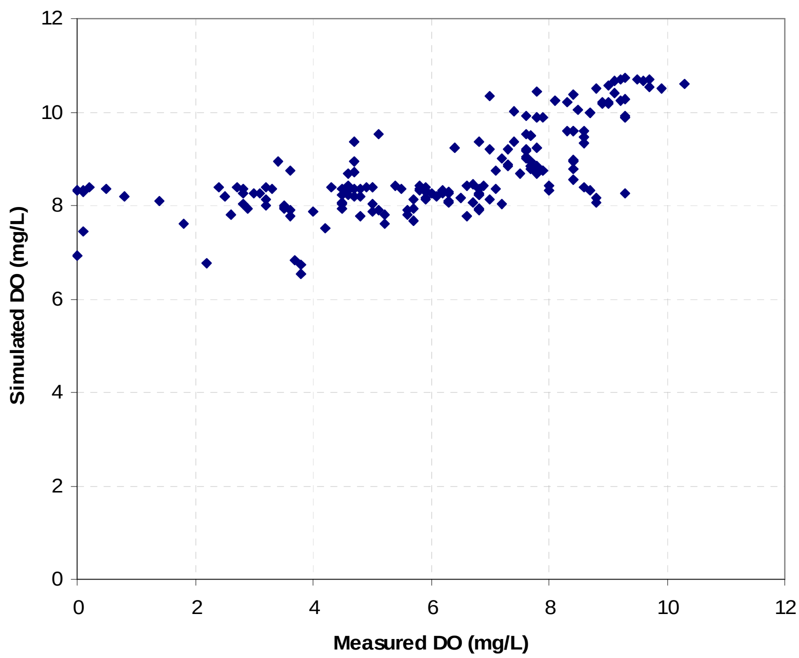



Figure 5.24 Correlation between measured and simulated dissolved oxygen for selected depths in Cooby Dam from 2001 to 2003 (with a couple of artificial mixers).

It was observed that some early values of dissolved oxygen lower than zero were recorded during the warm period in particular. These were modified to zero as negative values of dissolved oxygen are impossible. Most measured dissolved oxygen values below 10 m depth during the warm period were recorded as zero while the simulations gave values above 6 mg $L^{-1}$. This further reinforced the doubtfulness of the recorded values.

Model verification of the DO concentration in Cressbrook Dam had similar problems as Cooby Dam. A comparison of measured and simulated data in Cressbrook is presented in Figure 5.25 and 5.26.

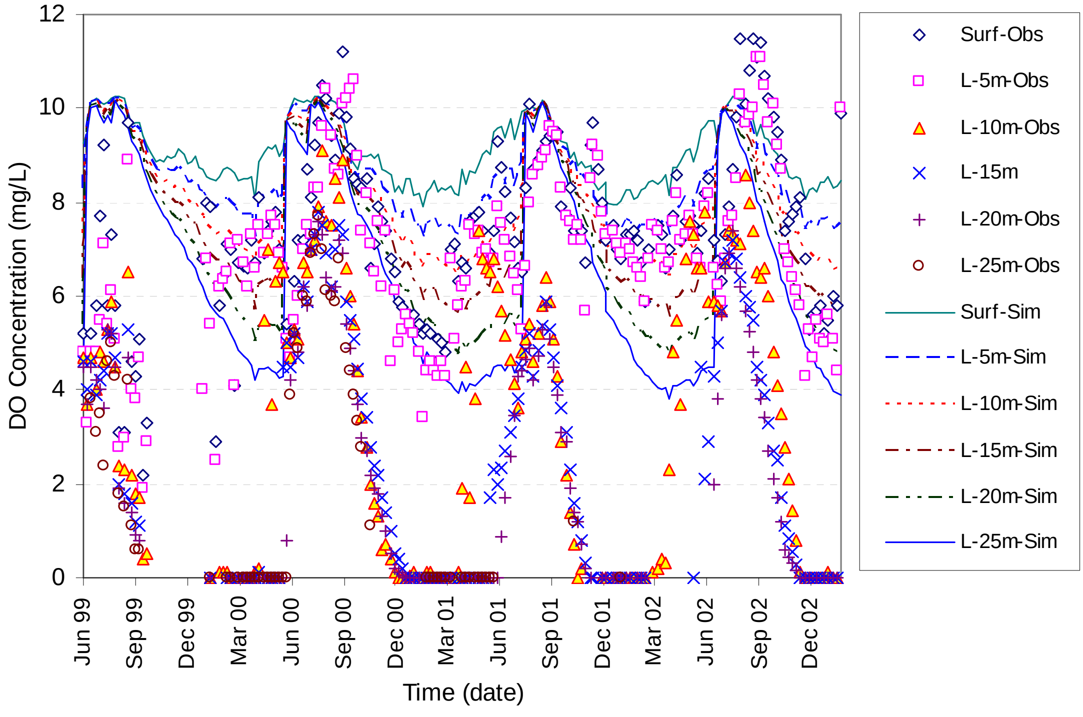



Figure 5.25 Time series of measured and simulated dissolved oxygen at selected depths (water surface, 5 m, 10 m, 15 m, 20 m and 25 m depths) of Cressbrook reservoir for the period 1999 – 2003 (with two unit artificial mixers).

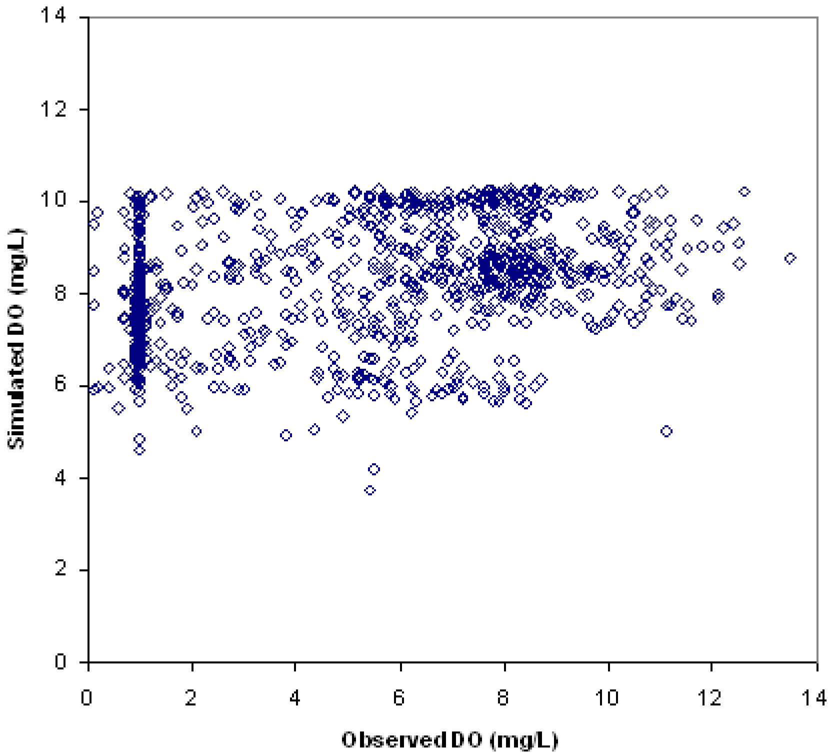



Figure 5.26 Correlation between measured and simulated dissolved oxygen for selected depths in Cooby Dam from 2001 to 2003 (without a couple of artificial mixers).

### *5.3.3 Validation of total phosphorus*

Validation of simulated total phosphorus concentrations also proved difficult because the available measured data were recorded in ranges. Most simulated values were less than 0.1 mg $L^{-1}$ with only a few values above this point. Comparison of the recorded and simulated values in selected layers can be seen in Figures 5.27 to 5.30.

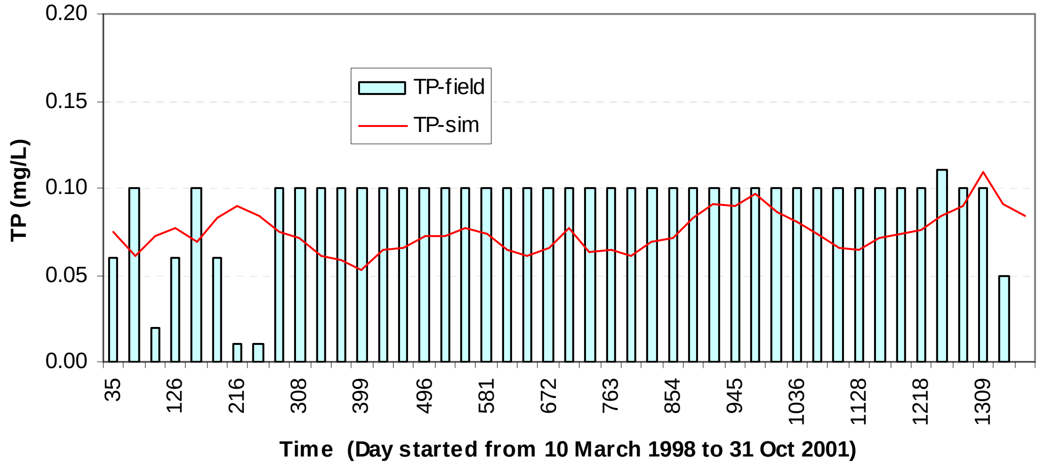



Figure 5.27 Time series of measured and simulated total phosphorus at the water surface of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

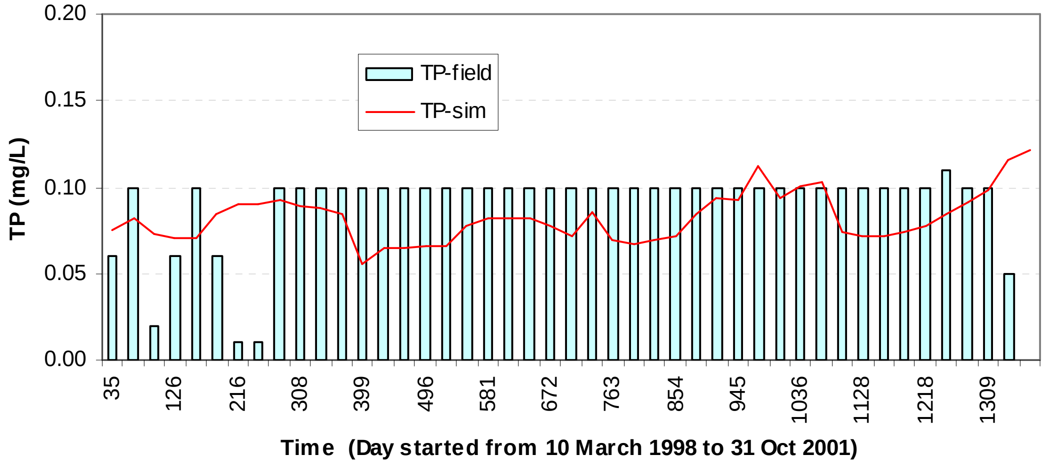



Figure 5.28 Time series of measured and simulated total phosphorus at the 9.14 m depth of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

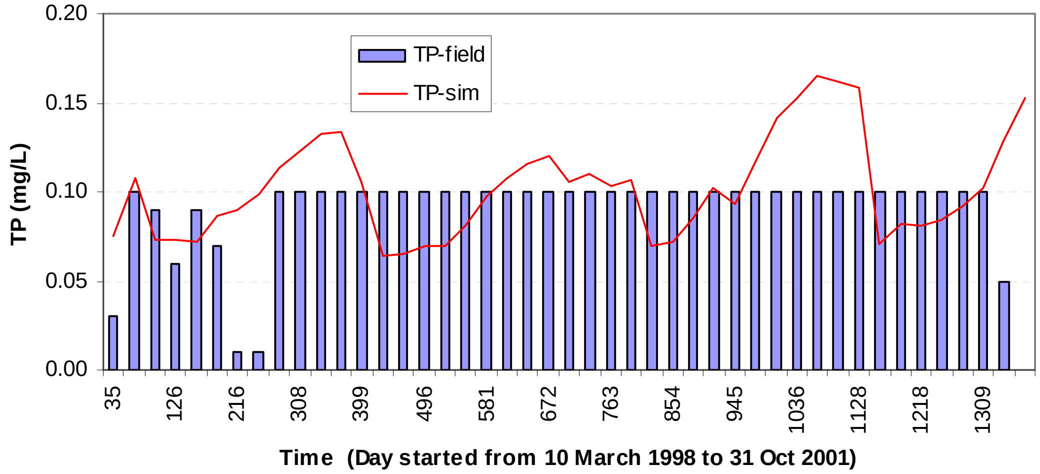


Figure 5.29 Time series of measured and simulated total phosphorus at the 16.46 m depth of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

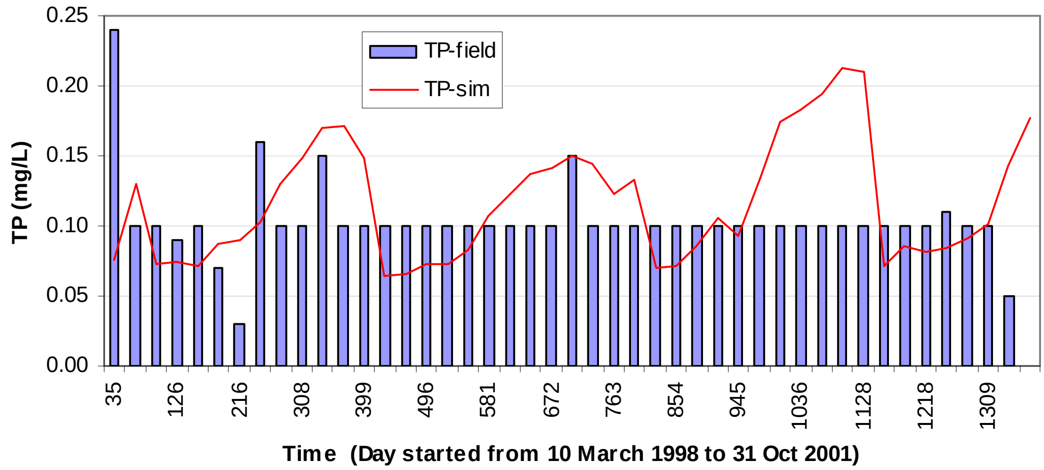



Figure 5.30 Time series of measured and simulated total phosphorus at the bottom of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

Figures 5.27 to 5.30 give comparisons but do not allow the degree of correlation to be calculated. It is clear that the simulation results from the surface to 16.46 m depth are mostly in the measured range which is indicated by the bars on the figures. Seventy six per cent simulated values are within the bars representing the range of measured values (139 from 184 measured data). In the absence of more detailed data, it is assumed that the simulation result is valid and suitable for predicting future water quality.

A double unit artificial surface mixer was operating in the dam for the period December 2001 to Feb 2003. The simulated total phosphorus concentrations become uniform from the water surface to the bottom of reservoir for this period with an average concentration about 0.1 mg $L^{-1}$. The simulated depth average values lie mostly in the range of measured data, confirming the model results during mixing.

Validation of total phosphorus in Cressbrook reservoir provides the same difficulties as was found with Cooby Dam. Most values of total phosphorus available to check the simulation are in a range form. A time series of measured and simulated data for selected individual layers (the water surface and depths of 12.25m, 19.25m and 29.75m, as well as the bottom of the reservoir) in Cressbrook storage are presented in Figure 5.31 – 5.35.

The simulated total phosphorus values for the period March 1998 to February 2003 are relatively higher than the observated values in all layers. In most cases, the concentration of observed total phosphorus increases when the surface inflow fills up the reservoir and is then constant. This can be seen during overflow in 1998/1999, where the concentration range increases from 0.05 to 0.1 mg $L^{-1}$ in Figures 5.31 to 5.32.

In the lower levels the simulated total phosphorus values appear to follow an annual cycle from July to June

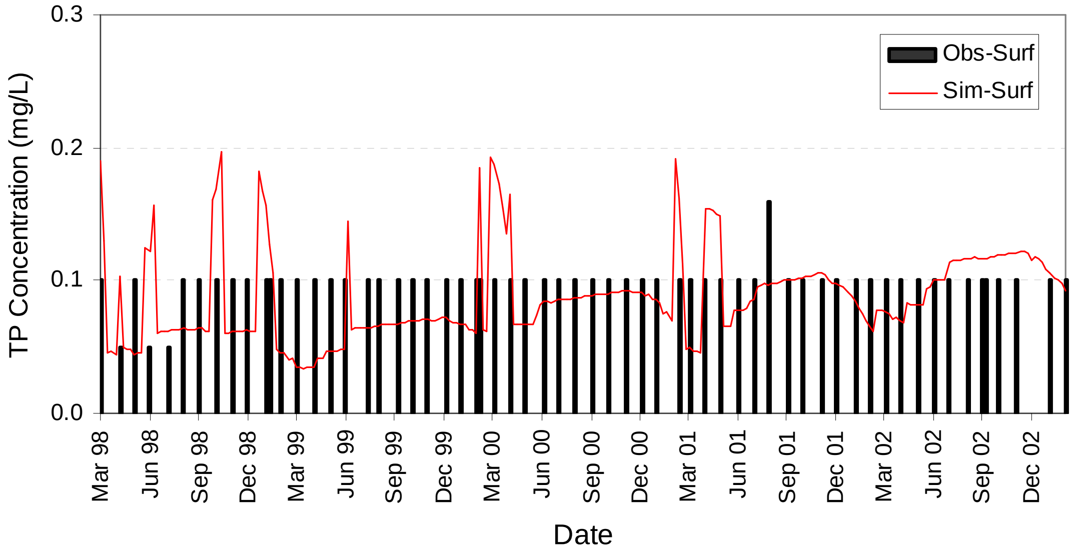



Figure 5.31 Time series of measured and simulated total phosphorus at the water surface of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

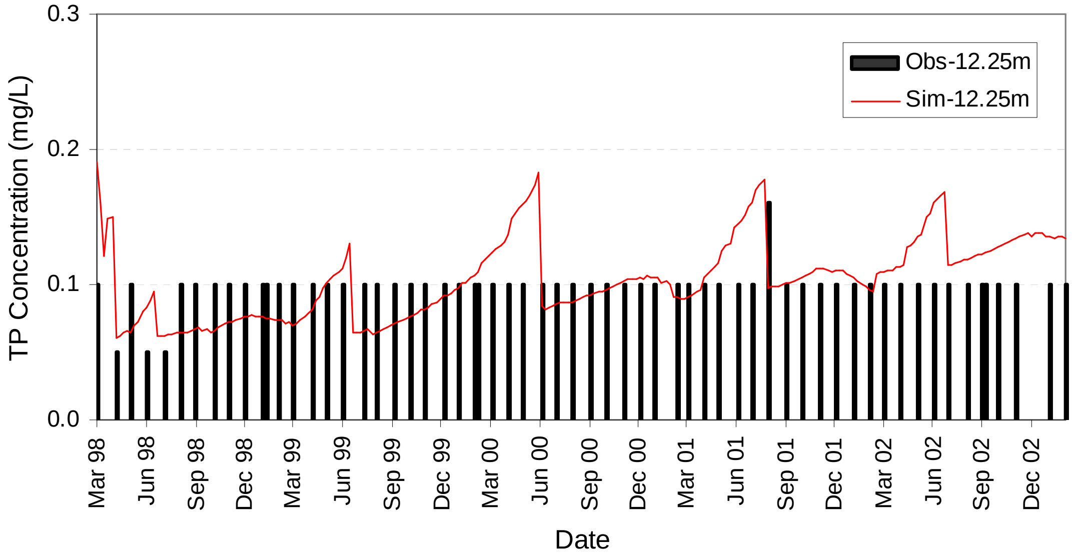



Figure 5.32 Time series of measured and simulated total phosphorus at the 12.25 m depth of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

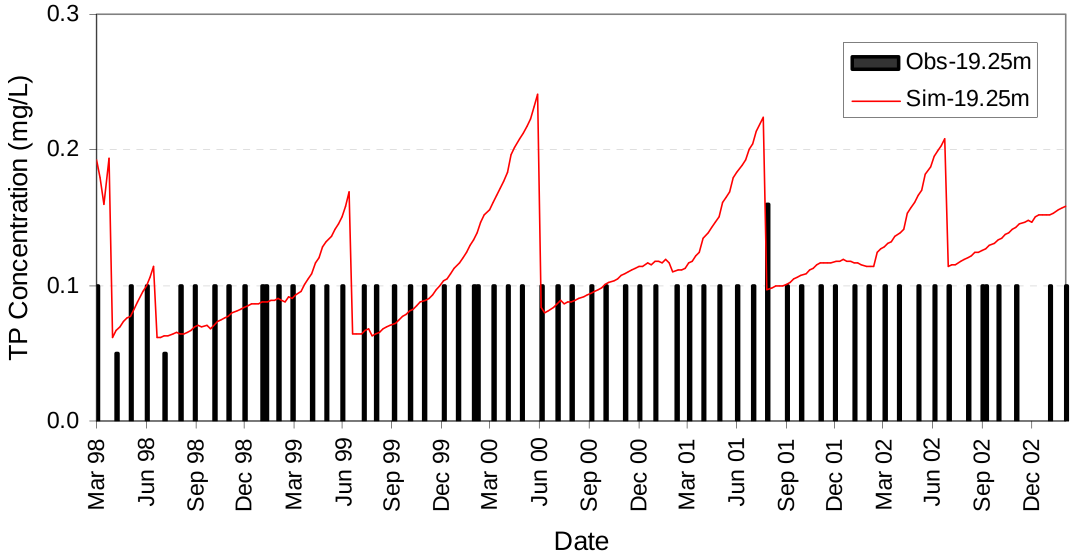



Figure 5.33 Time series of measured and simulated total phosphorus at the 19.25 m depth of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

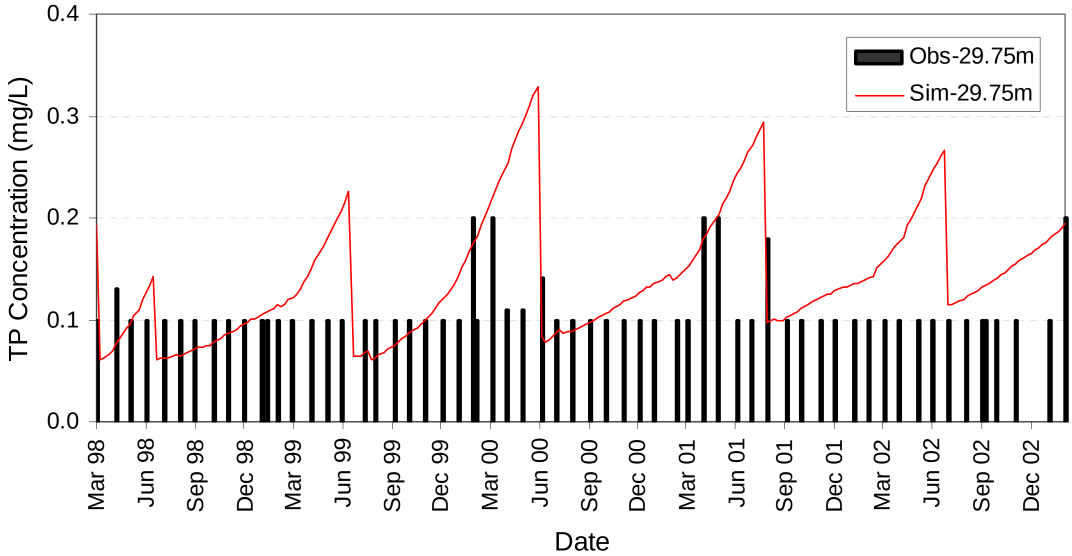



Figure 5.34 Time series of measured and simulated total phosphorus at the 29.75 m depth of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

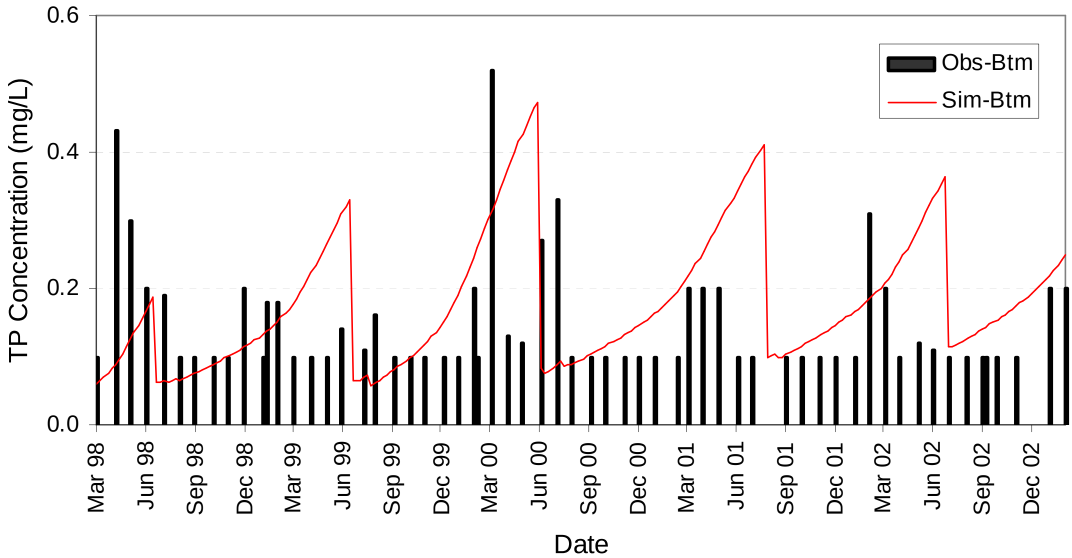



Figure 5.35 Time series of measured and simulated total phosphorus at the bottom of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

Other nutrient components of water quality including nitrate, total iron, and total manganese in both reservoirs also face a similar problem to total phosphorus for model validation because of the recording of data in a range of values.

### *5.3.4 Validation of Cyanobacteria*

Cyanobacterial concentrations are notoriously, difficult to measure, requiring specialist sampling and laboratory techniques which were not available to this project.

Simulated cyanobacterial concentrations were therefore compared to derived chlorophyll_*a* concentration data. Recorded cell counts were converted to chlorophyll_*a* concentration (mg chl_*a* $m^{-3}$) using an empirical relationship. The derived values are not as accurate as actual observations but sufficient for the purposes of this thesis. The conversion process does not accommodate the varying sizes of cell, gyres or filaments of Cyanobacteria, nor the variability of chlorophyll_*a* concentrations with species, location and time (*pers*. *comm*., Sutherland, 23 September 2003).

The validation of cyanobacterial concentrations in Cooby Dam was done by comparing derived data with simulation results at the water surface and depths of 9.14m and 16.46m as well as the bottom of the reservoir.

A time series of the derived and simulated data before the mixers installation (Mar 1998 – Nov 2001) are presented in Figures 5.36 to 5.39. The simulated results follow similar trend and pattern to the derived actual values although the degree of correlation is lower than 50 per cent for all layers. Cyanobacterial blooms (cyanobacterial concentrations in excess of 3.5 mg $m^{-3}$) in early 1998 closed the storage for water supply and recreation purposes because of the high risks for the community.

The simulations indicated that the maximum primary productivity layers for Cyanobacteria were located at 1.5 m to 6.5 m depth while the reservoir was stratified and slightly lower between 2.5 and 6 m depth when unstratified. However, recorded data are not available at these depths to validate this simulated result.

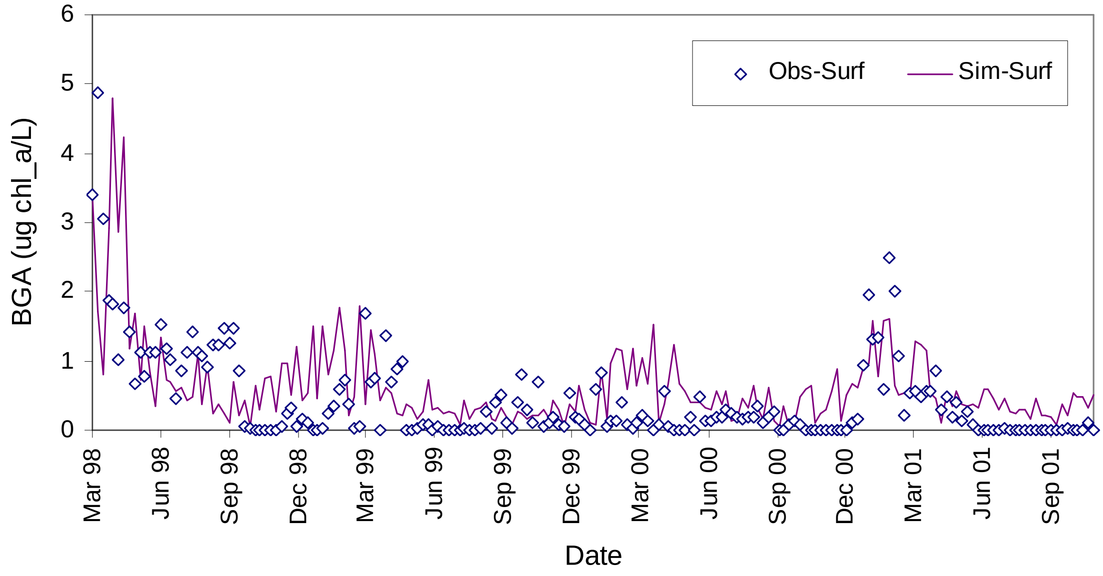



Figure 5.36 Time series of measured and simulated Cyanobacteria at the water surface of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

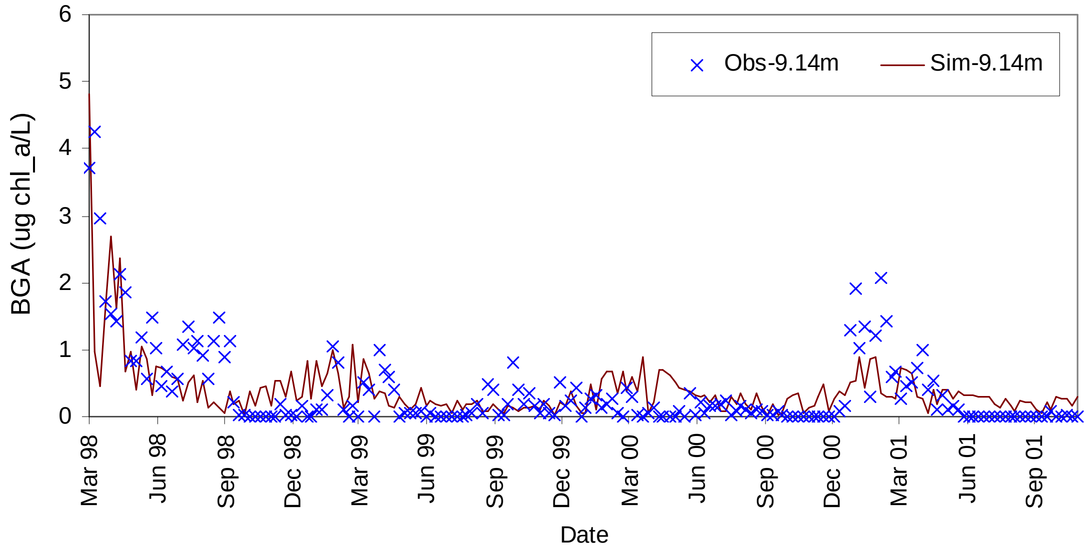



Figure 5.37 Time series of measured and simulated Cyanobacteria at the 9.14 m depth of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

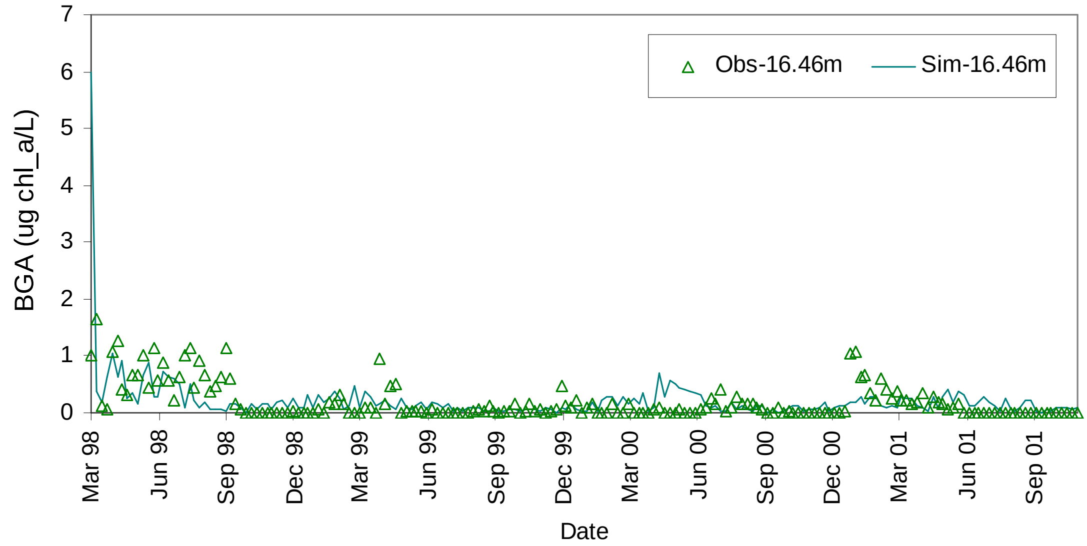



Figure 5.38 Time series of measured and simulated Cyanobacteria at the 16.46 m depth of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

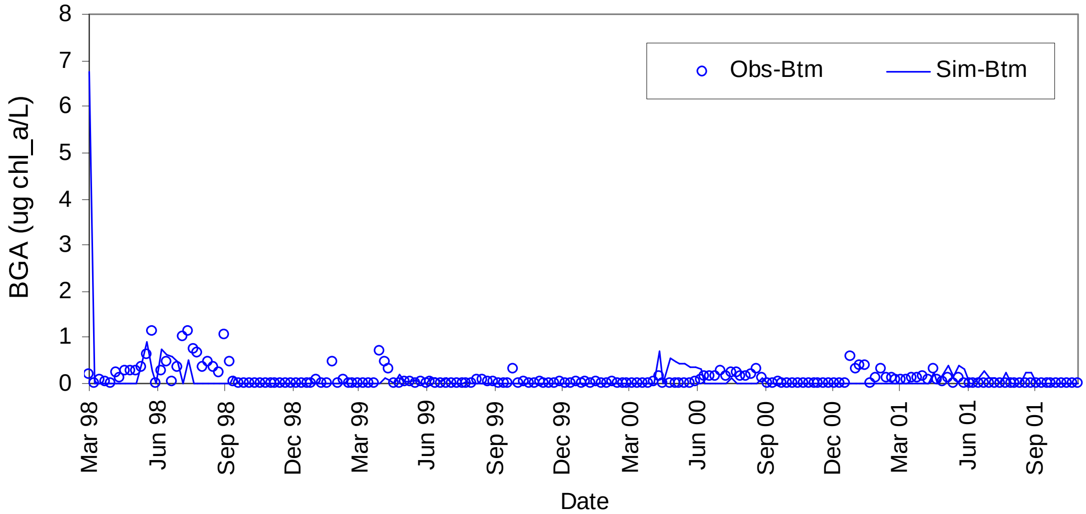



Figure 5.39 Time series of measured and simulated Cyanobacteria at the bottom of Cooby reservoir for the period 1998 – 2001 (without artificial mixers).

The DYRESM-CAEDYM model is able to simulate the operation of surface mixers in a dam. The mixers were moduled in Cooby Dam for the period 2001 – 2003. A comparison of derived values and simulated results for this period is shown in Figure 5.40 to 5.43.

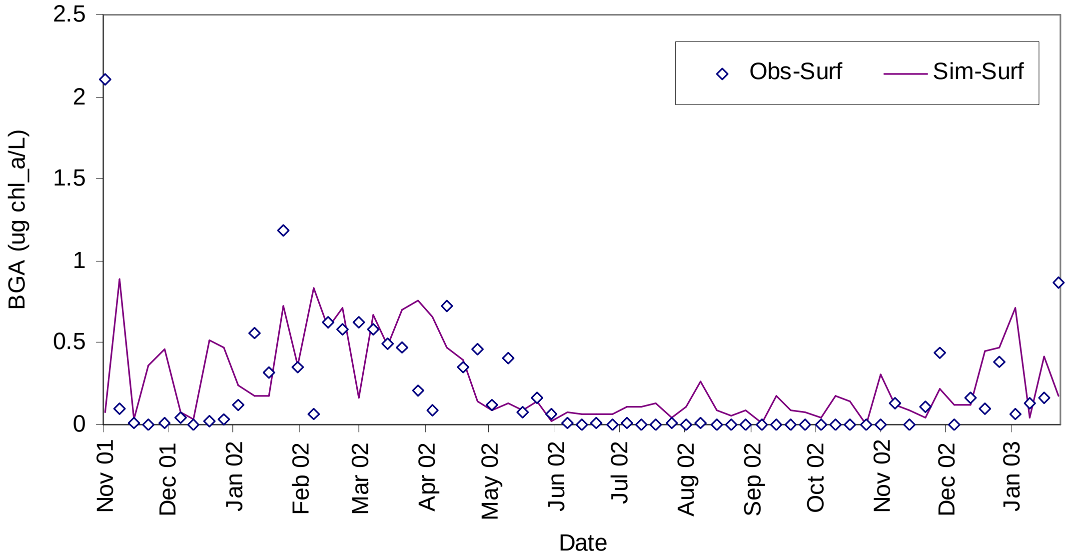



Figure 5.40 Time series of measured and simulated Cyanobacteria at the water surface of Cooby reservoir for the period 2001 – 2003 (with artificial mixers).

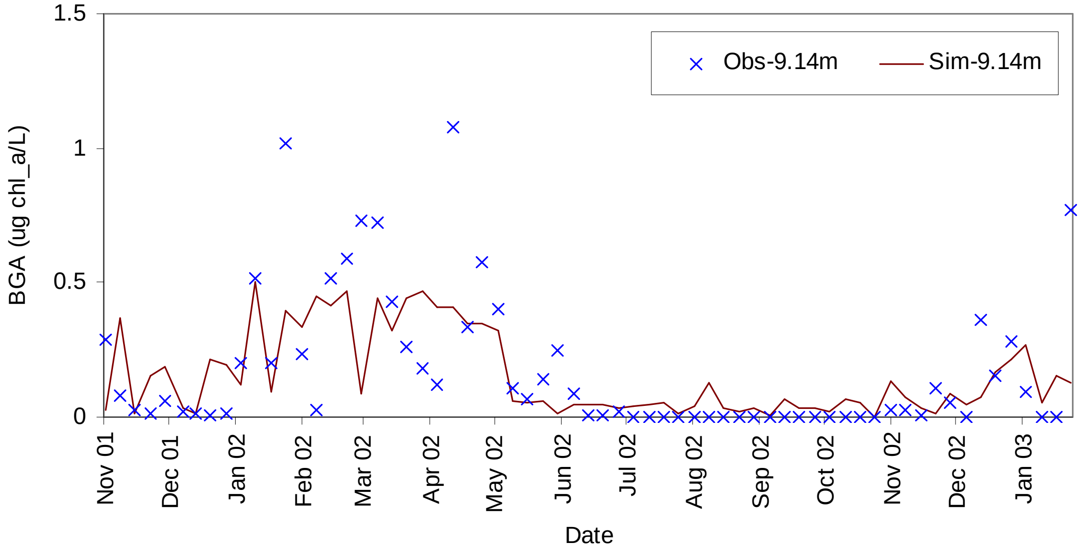



Figure 5.41 Time series of measured and simulated Cyanobacteria at the 9.14 m depth of Cooby reservoir for the period 2001 – 2003 (with artificial mixers).

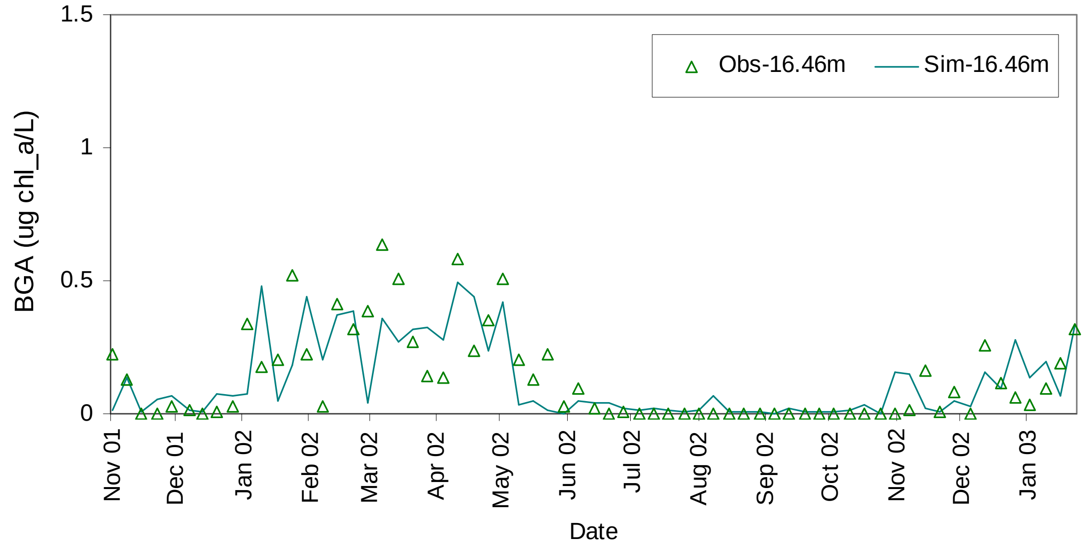



Figure 5.42 Time series of measured and simulated Cyanobacteria at the 16.46 m depth of Cooby reservoir for the period 2001 – 2003 (with artificial mixers).

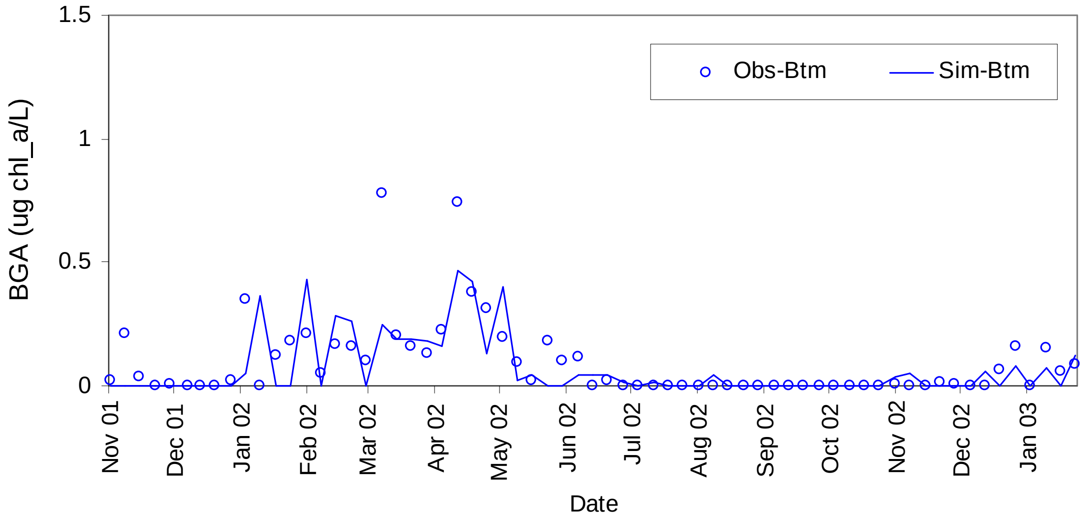



Figure 5.43 Time series of measured and simulated Cyanobacteria at the bottom of Cooby reservoir for the period 2001 – 2003 (with artificial mixers).

Validation of simulated Cyanobacterial concentrations in Cressbrook storage was attempted in a similar way by comparing the derived values and the simulation results in selected layers. The time series of measured and simulated data is presented in Figures 5.44 to 5.47. The comparisons show that the model is capable of providing acceptable simulation of Cyanobacteria in the storage.

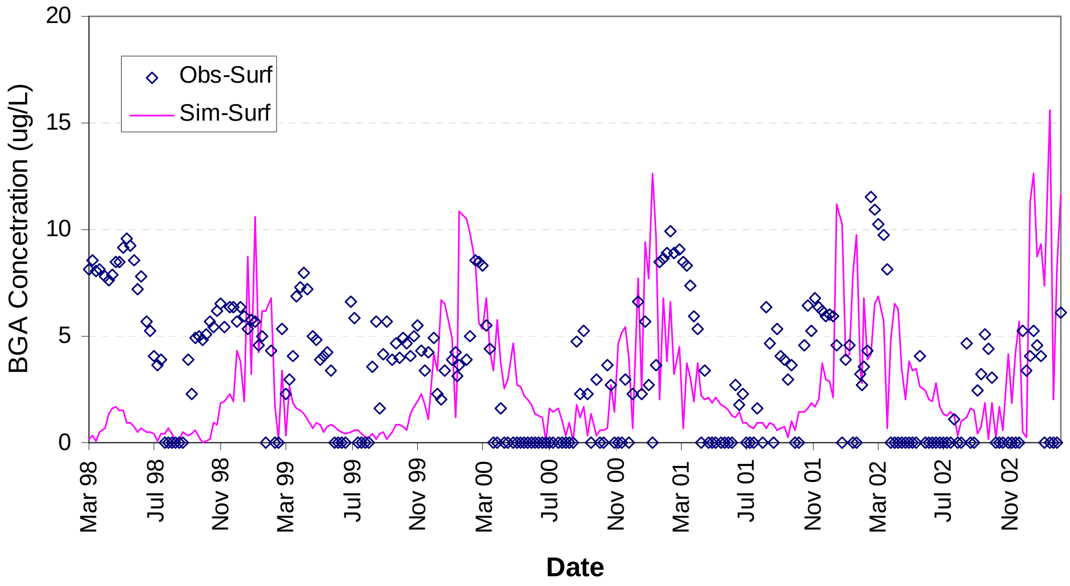



Figure 5.44 Time series of measured and simulated Cyanobacteria at the surface of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

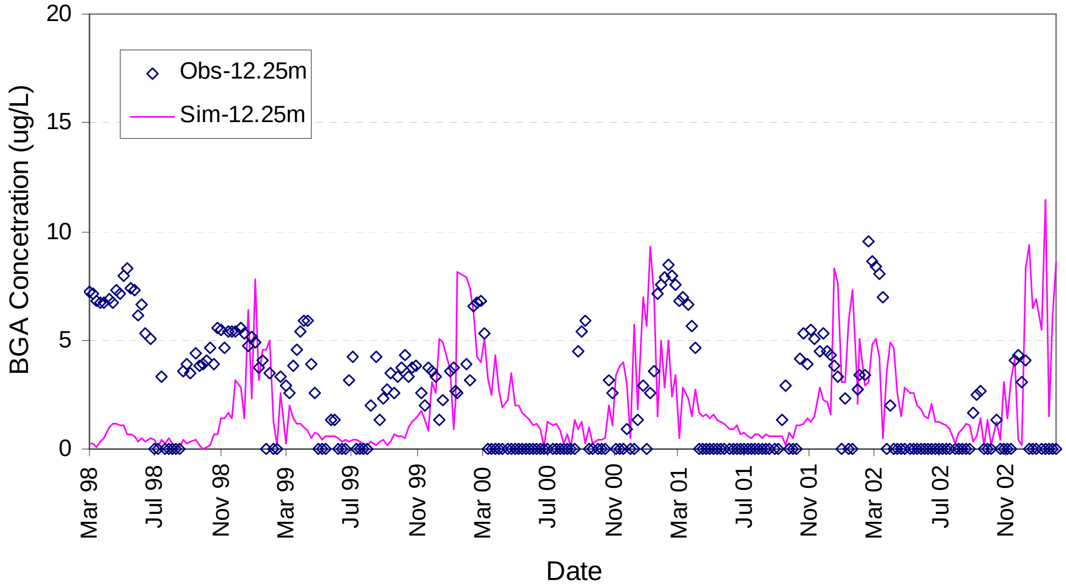



Figure 5.45 Time series of measured and simulated Cyanobacteria at the 12.25m depth of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

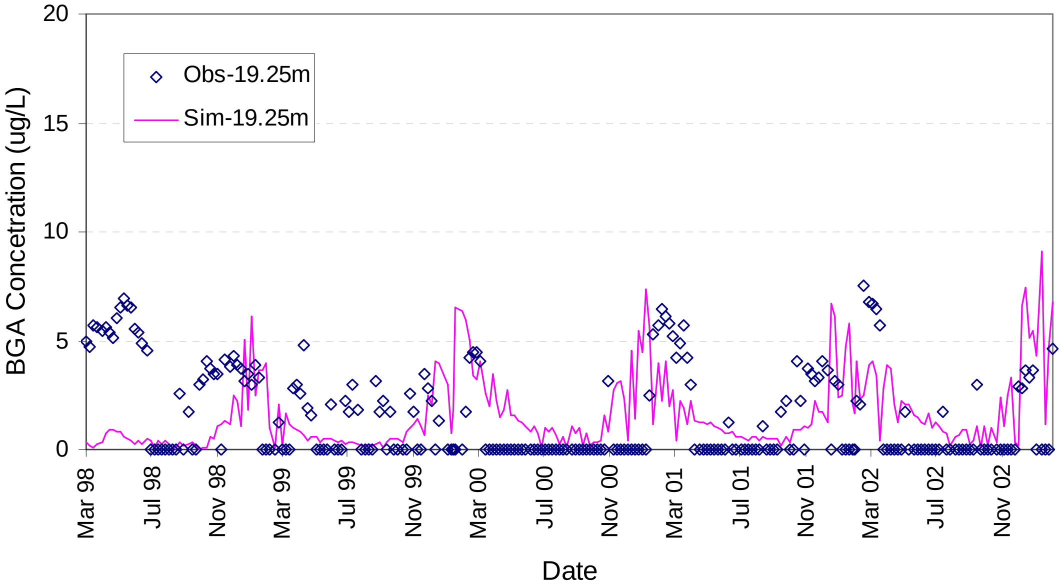



Figure 5.46 Time series of measured and simulated Cyanobacteria at the 19.25m depth of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

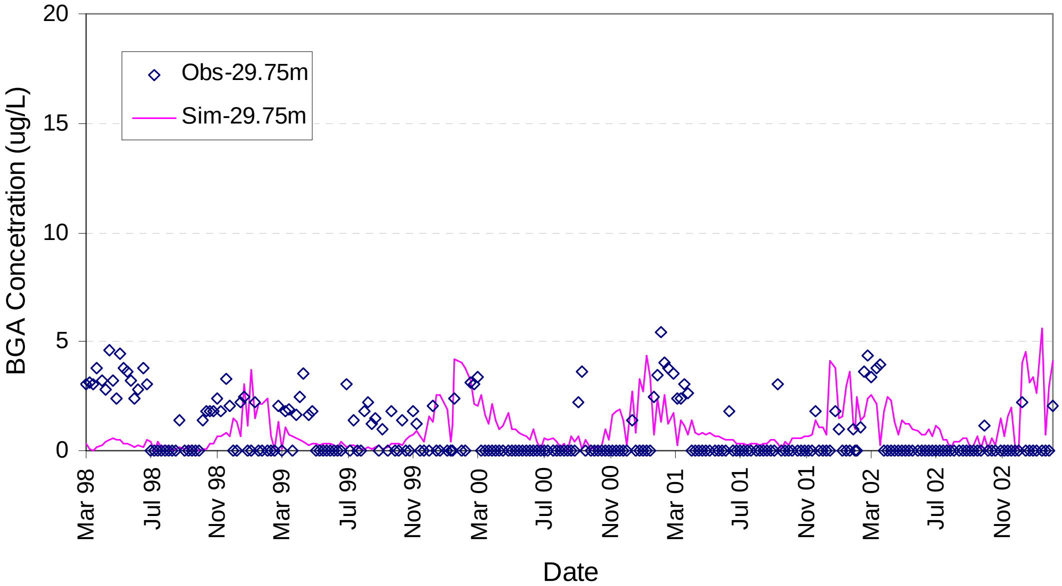



Figure 5.47 Time series of measured and simulated Cyanobacteria at the 29.75m depth of Cressbrook reservoir for the period 1998 – 2003 (without artificial mixers).

It is concluded from this analysis that the model can be used for water quality prediction in both storages to assess the risks of blooms in the reservoirs.

# Chapter 6

# ANALYSIS OF BEHAVIOUR OVER A 50 YEAR PERIOD

Some of the materials in this chapter was presented and/or published in:

- Porter, M., Brodie, I., Achmad, M. & Aravinthan, V. 2005 "*Researching sustainable future urban water supplies*" Southern Engineering Conference 2005 – Managing Resources for a Sustainable Future in Toowoomba, Australia, September 31, 2005.

The acceptability of water quality can be defined in terms of the suitability of water bodies for various uses such as a water supply source, recreation or the protection of aquatic life (Loucks & Gladwell 1999). The level of water quality is definitely affected by water abstractions, by pollution loads from human activities and by climate and weather (Kaczmarek et al. 1996; McMahon & Mein 1978; Votruba & Broza 1989). An increase in intensity of human activities in a catchment commonly degrades water quality inflow to a reservoir. At the same time, the impact of climate change is to decrease the total volume of rainfall and increase the level of evaporation from a catchment (Toowoomba City Council 2001). These factors work to reduce the sustainability of reservoirs.

Time series of water quantity and quality data are presented in this chapter. Quantity is presented as the water surface level and volume of the dams while the water quality data are presented in the form of water quality index (WQI). The indices are presented for two layers (the surface and pumping layers), and as an average value of all layers for simulated water quality parameters. The surface layer was chosen for its association with recreation purposes in the dams, swimming in particular. The pumping elevation layer was analysed as for water supply purposes raw water for the Mt. Kynoch water treatment plant is drawn from this part of the reservoir. The average of all layers was assumed to reflect the ecological aspect of the reservoirs.

A 50-year period of simulation represents the minimal time requirement for sustainability analysis in water resources system (Loucks 1997; Loucks & Gladwell 1999). Sustainability of the reservoirs is assessed in the three sequences water quality data on a weekly basis. Weighting of the parameters was based on the local management of the reservoirs. The analyses were made to compare the condition of water quality in the reservoirs with and without artificial mixers over the 50 year period.

## 6.1 Surface Water Level and Storage Volume of the Dams

### *6.1.1 Cooby reservoir*

The water elevation is used to assess the physical sustainability of the reservoirs. The reduction of inflow to water supply dams is a major issue for inland storages (Votruba & Broza 1989), with global warming implying future water scarcity. The simulated surface water elevation of the two dams is compared for various conditions of rainfall and solar radiation.

The simulation results indicate that under current conditions the surface level of Cooby dam will decrease over a 50 year period. Assuming no land use change, and no climate change, the storage volume will decrease by 4548 ML over a 50-year period as shown in Figure 6.1. The water surface elevation decreases by about 91 ML per year on average, equivalent to about 0.028 m per year. If water elevation alone is used as a criterion for physical sustainability, then Cooby reservoir is barely sustainable under current withdrawal rates. It will eventually fail as the storage level trends downward, but it will last a long time before failure occurs.

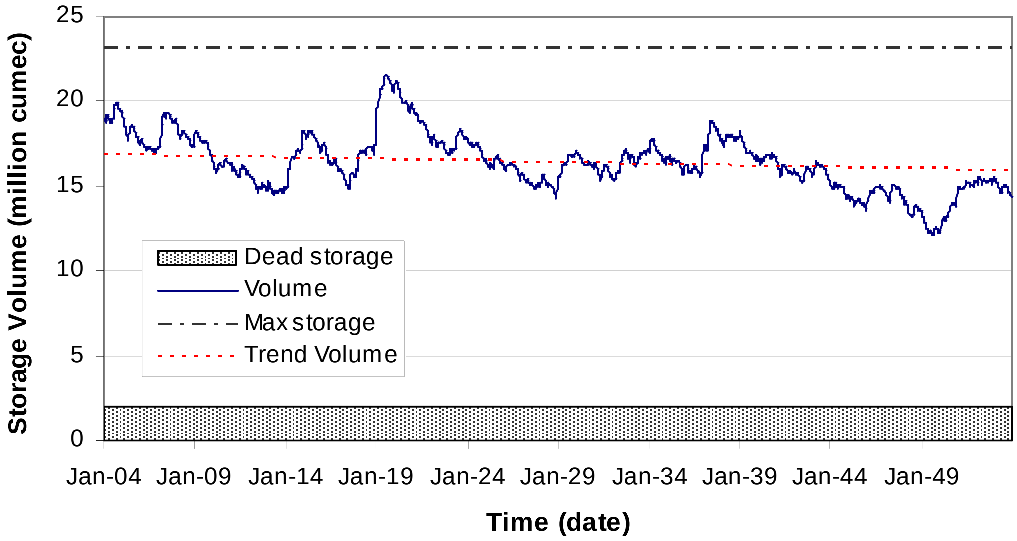



Figure 6.1 Prediction of the volume changes in Cooby storage over 50 years.

Simulations with varied rainfall scenarios indicated that the storage could be sustainable if rainfall inputs were five per cent greater than that adopted for the model (see Figure 6.2 and 6.4). However if actual rainfall amounts are 10 per cent lower than modelled conditions, the storage will fail as the water level drops below dead storage in the next 23 years (year of 2027). The simulated performance of the dam had no water available for pumping in 2027.

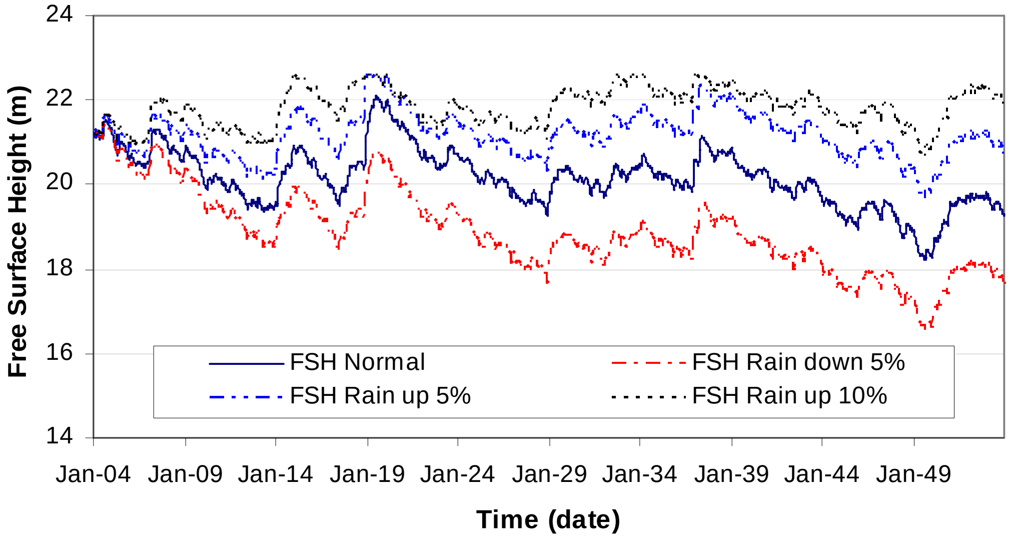



Figure 6.2 A 50-year period of the free surface height of Cooby Dam showing the impact of varying rainfall conditions. Simulation starting date is January 1st, 2004.

The water surface elevation was found to be sensitive to radiation intensity. A one per cent increase in solar radiation resulted in 0.7-cm drop of water elevation per year because of the extra evaporation. However, the reduction in evaporation will make Cooby reservoir sustainable if the actual solar radiation decreses at least 5.7 per cent less than the estimated current conditions.

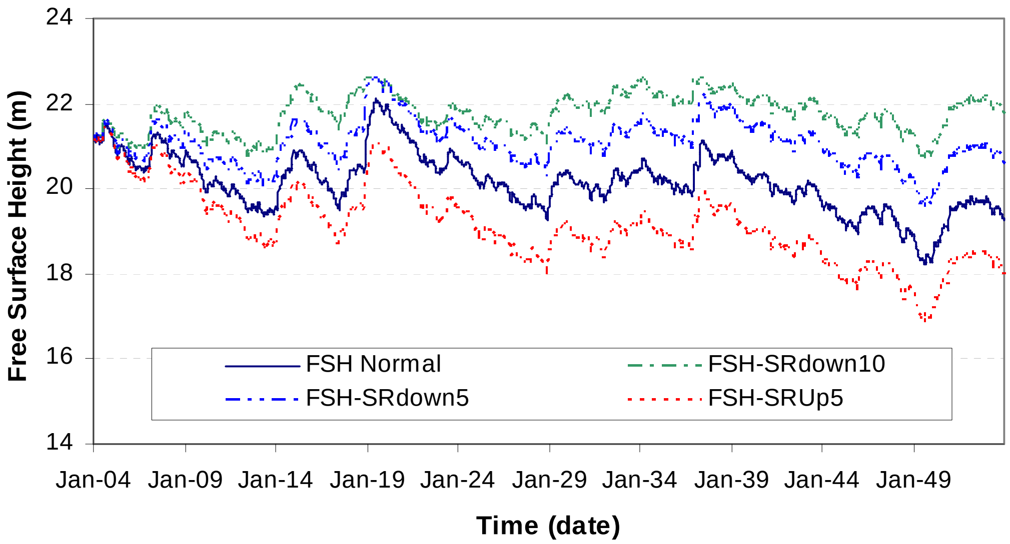



Figure 6.3 A 50-year period of the free surface height of Cooby Dam showing the impact of varying solar radiation conditions. Simulation starting date is January 1st, 2004.

Figure 6.4 summarises the modelled sensitivity of the water surface to rainfall and radiation.

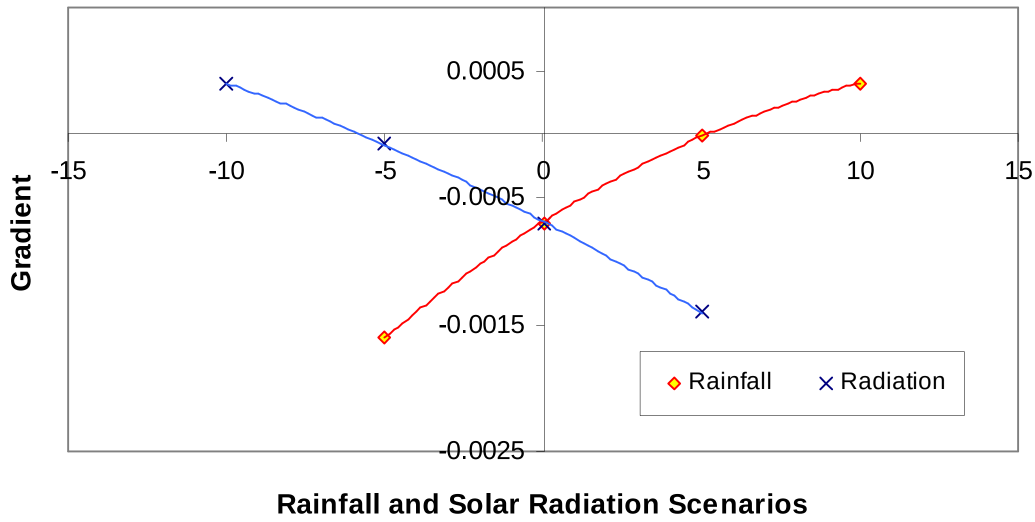



Figure 6.4 Sensitivity of rainfall amounts and solar radiation values indicated by the gradient of the trend of free surface water height in Cooby reservoir.

### *6.1.2 Cressbrook reservoir*

Based on available rainfall records, the volume of storage in Cressbrook Dam will decrease by 858 ML per year, or about 43,000 ML over a 50 year period. By the synthetic year 2030, the volume of Cressbrook dam will be less than 20 per cent of the maximum storage volume and trigger Level 5 water restrictions. This restriction is predicted to occur three times (2030s, 2040s, and 2050s) within the 50 years period. There will be no water available for releasing downstream (environment) to sustain the ecological system.

The volume of the storage shows a dramatic drop from about 57,000 ML in 2004 to about 14,000 ML in 2053. A trend line can be fitted to the result in Figure 6.5 as shown in Equation 6.1.

$$Volume(t_y) = 57.895 - \left( \frac{0.0152}{wk} \times \frac{52wk}{year} \right) t_y \qquad (6.1)$$

At the time ($t_{DS}$) when the dam reaches the dead storage level, Equation 6.1 becomes:

$$t_{DS} = \frac{57.895 - Volume(t_{DS})}{0.7904} \tag{6.2}$$

$$t_{DS} = 66.4 \text{ years}$$

where $Volume(t_y)$ and $Volume(t_{DS})$ are the volume of storage at $t_y$ and at $t_{DS}$; $t_y$ is time in year from the year of 2004 and $t_{DS}$ is time where the dam reaches the dead storage volume.

Equation 6.2 is the simulation trend equation (from Equation 6.1) to extrapolate the result further. It indicates that the storage volume will drop to the dead storage value of 5400 ML before the year of 2070 (66.4 years from the start of the simulation).

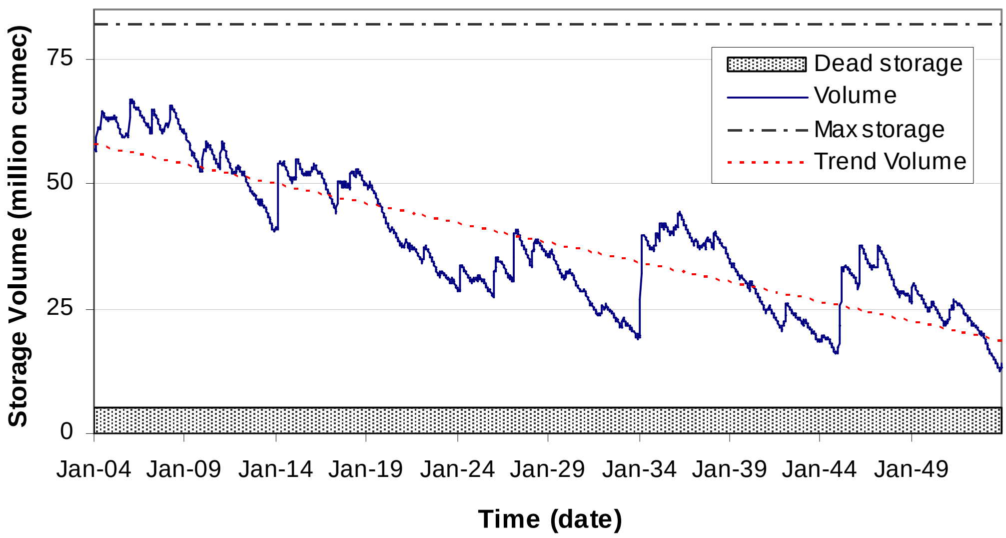



Figure 6.5 Prediction of the volume of Cressbrook storage in the years 2004 - 2053.

These simulated results are again sensitive to the input parameters used by the model. If the volume of rainfall events decreases by 5 per cent, then the reservoir will reach the dead storage level about 28 years into the simulation period. On the other hand, the reservoir would be sustainable if the quantity of rainfall increases by at least 6.7 per cent. This result is based on the trend slope of surface height for various rainfall levels. The storage volume is most sensitive to rainfall. Its effect on the changes in water level in the dam can be seen in Figure 6.6. The water surface of the dam decreases by about 3.7 centimetres per year for each 1 per cent decrease in rainfall amount.

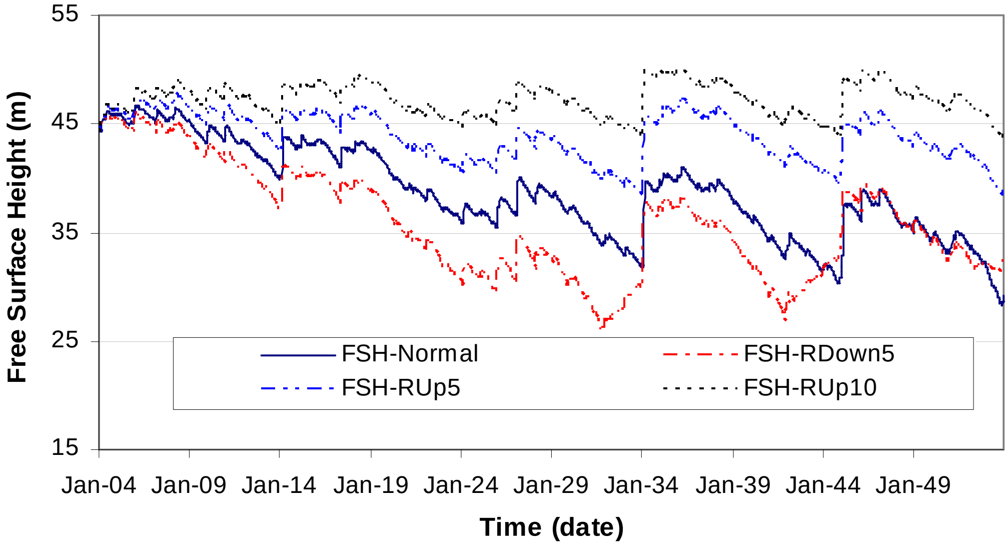



Figure 6.6 A 50-year period of the free surface height of Cressbrook Dam in various rainfall conditions.

The level of solar radiation also creates variations in the storage volume. This is because solar radiation is a major factor in evaporation. A high evaporation level reduces total inflow to the reservoir. It also increases evaporation level from the surface of the reservoir. The sensitivity level of water level in the reservoir to solar radiation is lower than to rainfall. If the intensity of solar radiation increases by 1 per cent from that modelled, then the surface water height will decrease by 2.08 centimetres per year. The effect of different solar radiation scenarios on water surface are shown in Figure 6.7.

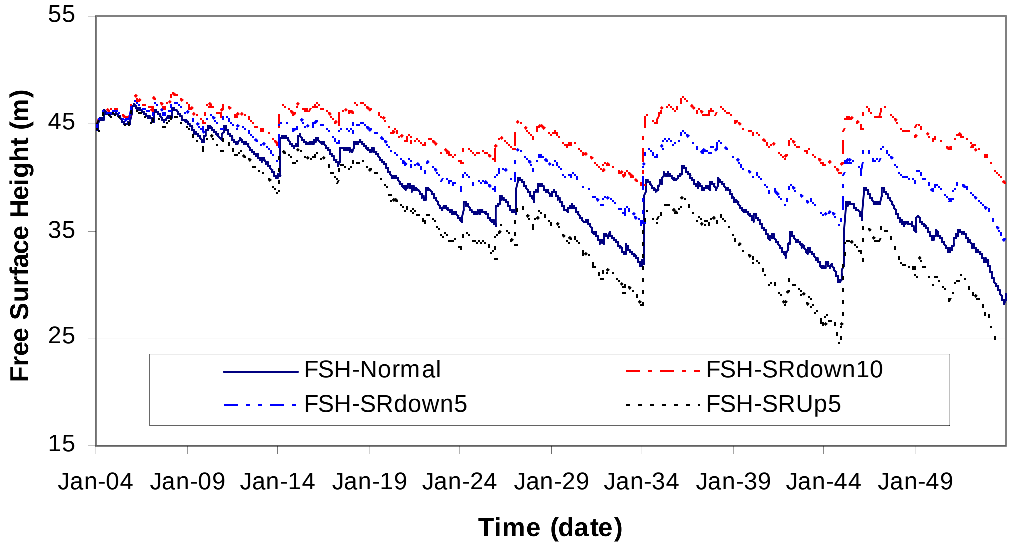



Figure 6.7 A 50-year period of the free surface height of Cressbrook Dam showing the impact of varying solar radiation conditions.

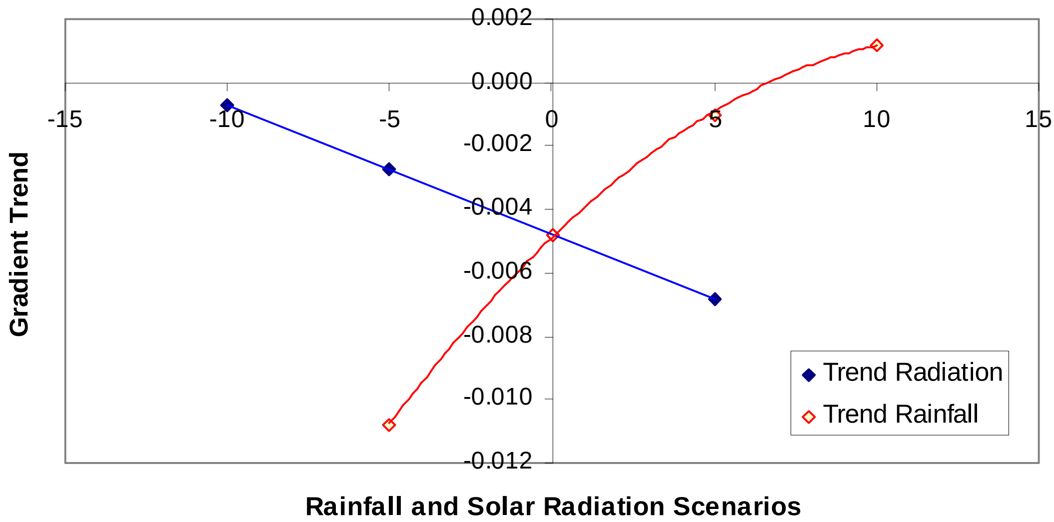



Figure 6.8 Sensitivity of rainfall amounts and solar radiation values indicated by the gradient of the trend of free surface water height in Cressbrook reservoir.

## 6.2 Water Quality and the Effect of Artificial Mixers

Fifty years of averaged water quality condition for the full depth of the reservoirs and the condition of two selected layers (surface and pumping layers) were used to quantify the effects of artificial mixers in the reservoirs, in both cold and warm periods. The data were into four categories, cold and warm periods, with and without mixers for each water quality parameter.

The depth averaged values of each parameter are presented in box plots in the following sections. The box on the plots depicts median of the average values with the lower (25$^{th}$) and upper (75$^{th}$) quartiles, minimum and maximum values, and outliers. Values under three IQRs (Inter Quartile Ranges) from the 25$^{th}$ to 75$^{th}$ percentiles (or the first to the third quartiles) are called mild outliers and values above the three IQRs are called severe outliers.

### *6.2.1 Cyanobacteria*

A major objective of this dissertation is to establish the impacts of mechanical mixing on algal blooms in the reservoirs. Cyanobacterial concentration can be used as a biological indicator of water quality in most multi purpose reservoirs including Cooby and Cressbrook Dams. The average cyanobacterial concentration through the water column was used to compare the four data sets corresponding to the warm period with and without artificial mixers, and the cold period with and without artificial mixers.

In Cooby Dam during the warm period, cyanobacterial data range from 0.25 to 3.30 μg $L^{-1}$ with a mean, first and third quartile values of about 1.60, 1.20 and 2.00 μg $L^{-1}$, respectively. The use of mechanical mixers widens the range to 0.20 – 4.10 μg$L^{-1}$. As a result, the median increases to approximately 1.8 μg $L^{-1}$ and the third quartile data increases to 2.5 μg $L^{-1}$ as shown in Figure 6.9 (see variables Warm and Warm Mixers). However, the mixers' operation decreases the median value of average cyanobacterial concentrations by about 0.2 μg $L^{-1}$ (from 0.9 μg $L^{-1}$ to 0.7 μg $L^{-1}$) in the cold period as shown in Figure 6.9 (see variables Cold and Cold Mixers). The data range suggests that this change is not significant.

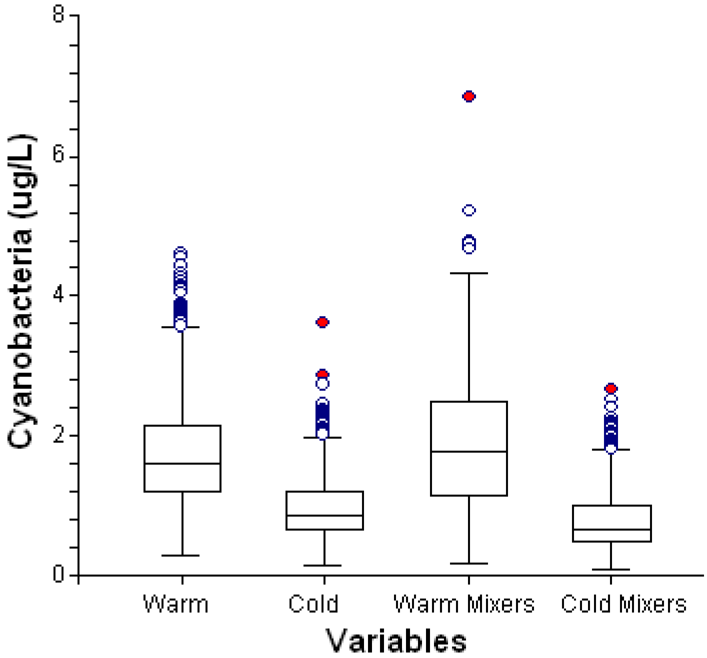



Figure 6.9 Box plots of the average cyanobacterial concentrations of Cooby reservoir.

Figure 6.9 indicates that the surface mixers in the reservoir have no significant effect on cyanobacterial concentration (slightly decrease) during the cold period. However, the surface mixers increase the median, first and third quartile of cyanobacterial concentrations in Cooby storage during the warm period.

The percentile patterns of Cyanobacteria in Cressbrook storage are similar to that in Cooby. However, the concentrations of Cyanobacteria in the Cressbrook storage are relatively higher than the concentrations in Cooby. The detailed box plots of average value of Cyanobacteria in Cressbrook storage for each category are presented in Figure 6.10.

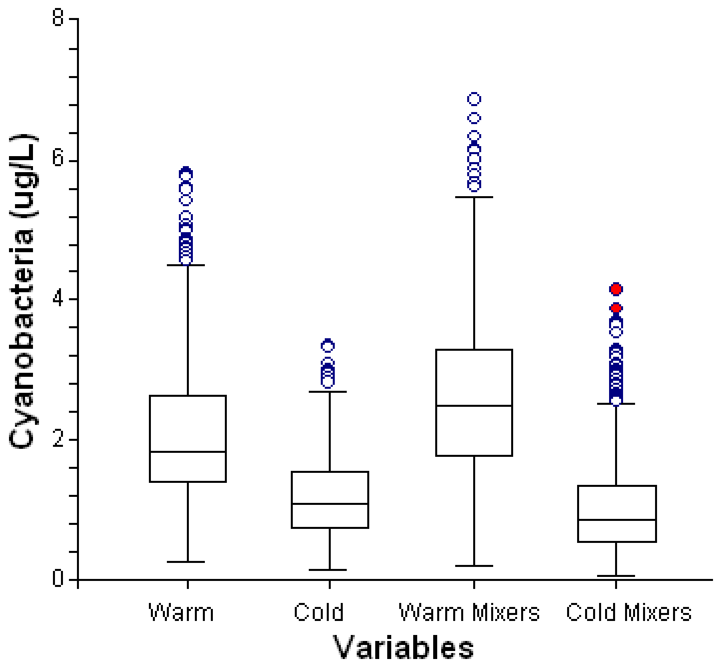



Figure 6.10 Box plots of the average cyanobacterial concentrations of Cressbrook reservoir.

The box plots indicate that the use of artificial mixers during the warm period of the year will raise the median, first and third quartiles of Cyanobacterial concentration by 0.67, 0.35, and 0.64 µg $L^{-1}$, respectively. Conversely, the value of these parameters decreases during the cold period from 1.12 to 0.90 µg $L^{-1}$, 0.75 to 0.56 µg $L^{-1}$, and 1.56 to 1.35 µg $L^{-1}$, respectively.

The artificial mixing impact in Cressbrook Dam is similar to that in Cooby storage. Cyanobacteria in the water column respond differently to the mixing action depending on the weather. The mixers widen the habitat zone of Cyanobacteria in the warm period. However, the reservoir still experiences a possible reduction of cyanobacterial concentration during the cold period.

### *6.2.2 Dissolved oxygen*

Dissolved oxygen concentrations in the water column are determined by aeration processes at the surface. A good aeration system results in high oxygen concentrations deeper in the water column. Dissolved oxygen concentration is a parameter which is greatly affected by artificial mixers. Some reservoir managers installed artificial mixers in their reservoir simply to improve the dissolved oxygen concentration in the hypolimnion layer.

Average dissolved oxygen concentrations in the water column of Cooby dam during the warm period is improved by the use of artificial mixers. The average DO concentration can be improved from 6.5 mg $L^{-1}$ (range 3.2 – 10 mg $L^{-1}$) to 8.4 mg $L^{-1}$ (range 6.4 – 9.3 mg $L^{-1}$). However, no significant difference in DO concentrations occurs during the cold period with and without the use of artificial mixers in the storage. If the mixers are operated continuously during this period, the outliers can be removed and the lower data range of average DO concentrations is improved to 8 mg $L^{-1}$. Detailed box plots of average DO concentrations in Cooby Dam are presented in Figure 6.11.

Generally, mechanical surface mixers improve average DO concentrations during the warm period because the mixers transport the rich oxygen surface water to the anoxic hypolimnion layer. This result represents an improvement in quality. However, the growth rate of Cyanobacteria consequently increases as dissolved oxygen becomes accessible throughout the water column. This is why cyanobacterial concentrations in the water column are increased during the warm period when the mixers are continuously operated.

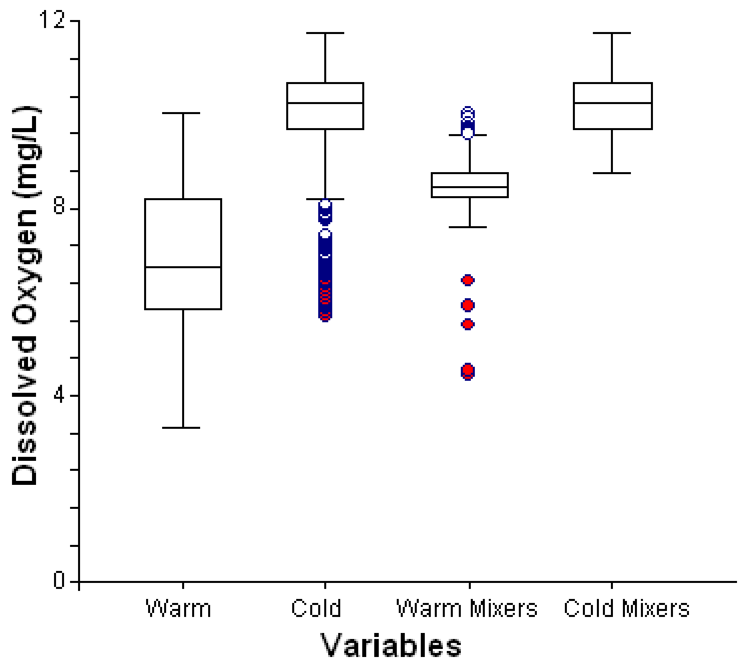



Figure 6.11 Box plots of the average dissolved oxygen concentrations of Cooby reservoir.

The average DO concentration in Cressbrook storage during the warm period has a median of about 5.1 mg $L^{-1}$ with a range from 2.0 to 8.8 mg $L^{-1}$. The use of artificial mixers in the storage during this period increases the median, the first and the third quartiles of average DO concentrations in all layers by 0.9, 1.2 and 0.7 mg $L^{-1}$, respectively.

Generally, the average DO concentration during the cold period is relatively higher than the values occurring during the warm period. The use of the artificial mixers significantly increases the first quartile from 6.6 to 9.2 mg $L^{-1}$. The mixers improve the range of DO concentrations from 2.0 – 11.6 mg $L^{-1}$ to 7.6 – 11.6 mg $L^{-1}$. There are some severe outliers of DO data (from 2.0 to 6.0 mg $L^{-1}$) during the cold period with the operation of the artificial mixers. A detailed box plot of average DO concentrations in Cressbrook storage can be seen in Figure 6.12.

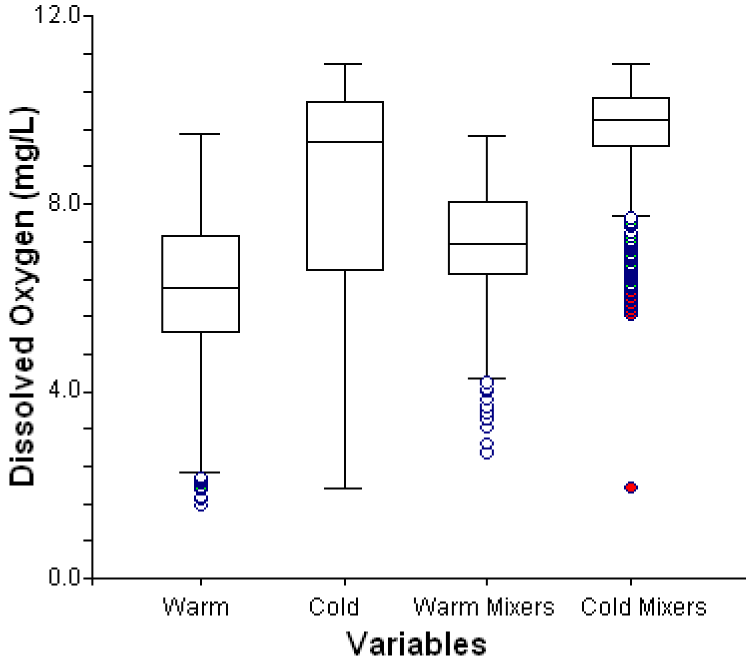



Figure 6.12 Box plots of the average dissolved oxygen concentrations of Cressbrook reservoir.

In both storages, an improvement of the average DO concentrations in the water column can be achieved by forcing vertical circulation through the use of mechanical destratifiers.

### *6.2.3 Water temperature*

The simulated water temperatures also show stratification in the water column during the warm period. This is consistent with historical behaviour as described in the calibration part of Chapter 5. The average temperatures for the water column are used to describe the distribution of the 50-year synthetic data set in Cooby and Cressbrook reservoirs during the warm and the cold periods in this chapter. The vertical differences caused by thermal stratification during the warm period are further discussed in Chapter 7 (Section 7.2.3) with the probability of occurrences of water temperature levels through the water column.

The average water temperature in Cooby storage during the warm period ranges from 13.0°C to 21°C with a median of 17.5°C. The surface mixers introduce warmer water to deeper in the column and so increase the water temperature range to 16 – 25.5°C with a median of 22°C.

During the cold period, average water temperature has a distribution from 7°C to 19°C with a median of 13°C. The operation of mechanical mixers changes the upper data range and the third quartile by only about 1°C. Statistically, there is no significant difference of water temperature in the storage with and without the use of artificial mixers during the cold period. The average water temperature distribution in Cooby Dam is summarised as box plots in Figure 6.13.

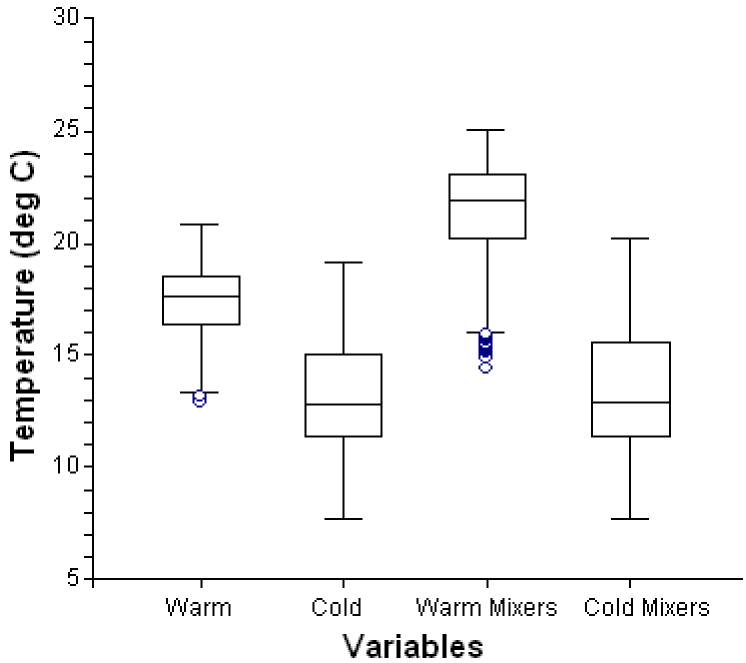



Figure 6.13 Box plots of the average water temperatures of Cooby reservoir.

The average water temperatures of Cressbrook storage during the warm period range from 13 to 17.5°C with a median value of 15°C. This range is smaller than that at Cooby and the median is also lower. A deep, colder hypolimnion layer in Cressbrook results in a lower average water temperature during the warm period. The use of the mixer in the storage can increase the epilimnion size in the top layer of reservoir. As a result, the average water temperature increases significantly, with a range from 14 to 24$^{o}$C and a median of 18$^{o}$C.

The range of average water temperatures during the cold period is about 2$^{o}$C lower than during the warm period. Artificial mixing of the vertical profile during the cold period results in a larger range of average water temperatures in the storage (from 10 – 16.5$^{o}$C to 10 – 20.5$^{o}$C). A comparison of average water temperature behaviour for both periods with and without the artificial mixers in Cressbrook Dam is presented in Figure 6.14.

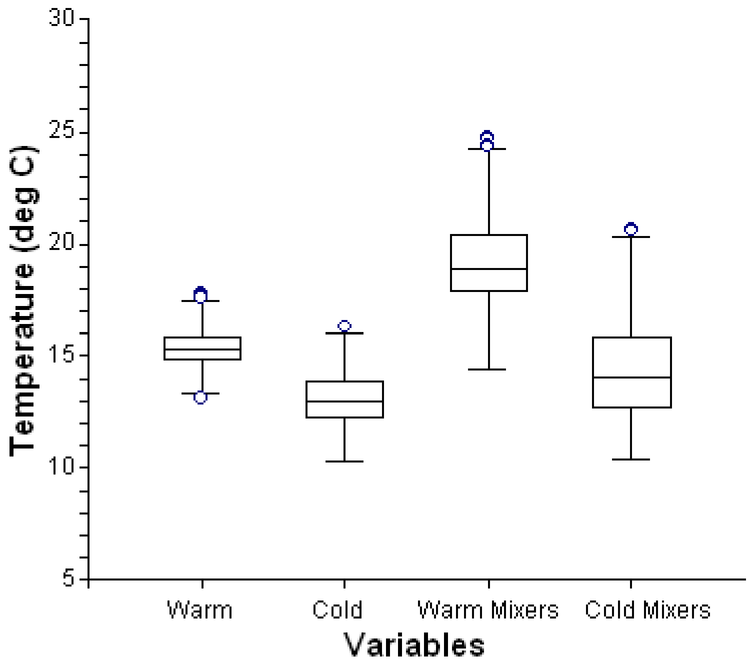



Figure 6.14 Box plots of the average water temperatures of Cressbrook reservoir.

In summary, appropriate vertical circulation in both storages can introduce warmer water through the water column and change water quality. A change in water temperature will affect the reduction-oxidation processes controlling most chemical substances in the storages.

### *6.2.4 Nitrate ($NO_3$)*

Nitrate is one form taken by Nitrogen in water. In aerobic conditions, nitrate can be transformed into organic nitrogen, and to ammonia. Nitrogen is a food component for aquatic creatures including Cyanobacteria. The presence of nitrogen in water therefore is acknowledged as an essential substance for Cyanobacteria to grow. However, a high nitrate concentration in water can be a toxic inorganic substance for drinking water (Davis & Cornwell 1998).

The simulated range of nitrate concentrations in Cooby storage during the warm period is from 0.35 to 1.50 mg $L^{-1}$ with a median of 0.90 mg $L^{-1}$. This range is mostly acceptable for a freshwater reservoir (EPA Queensland 2005). Artificial mixers reduce the median nitrate concentrations to 0.65 mg $L^{-1}$ with a range 0.10 – 1.30 mg $L^{-1}$. The average nitrate concentrations are lower during the cold period than the warm period. The mixers slightly reduce the concentrations in the storage as shown in Figure 6.15.

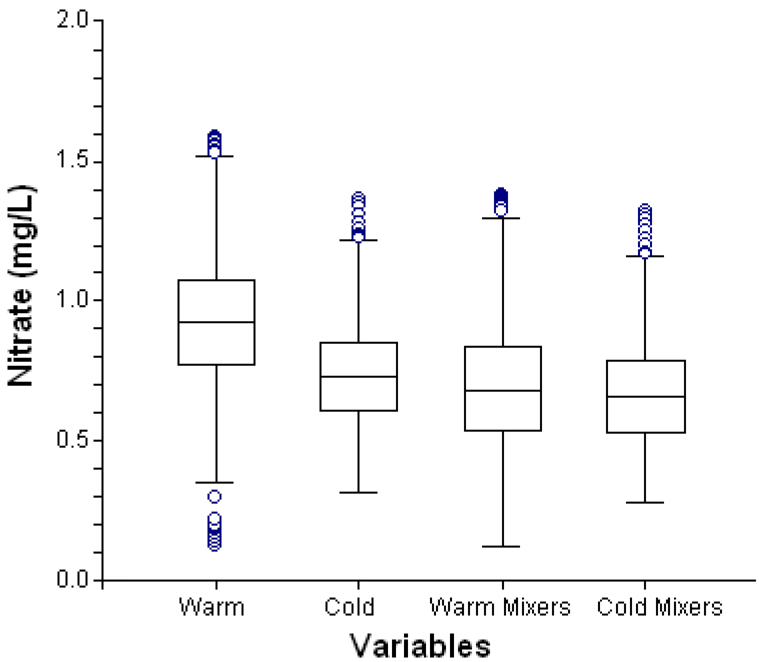



Figure 6.15 Box plots of the average nitrate concentrations of Cooby reservoir.

The average concentrations of nitrate in Cressbrook reservoir are relatively higher than those in Cooby. Figure 6.16 shows that the normal concentrations range from 1.0 to 2.6 mg $L^{-1}$ and from 0.8 to 2.3 mg $L^{-1}$ during the warm and the cold period, respectively. When six SMDI-5 mixers are simulated, the median of the average concentrations decreases by 0.15 mg $L^{-1}$ during the warm period and 0.05 mg $L^{-1}$ during the cold period.

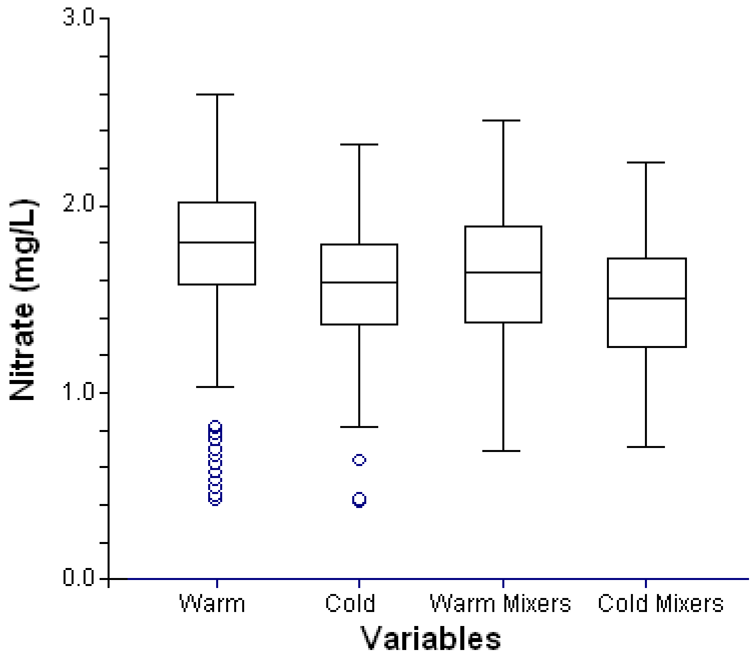



Figure 6.16 Box plots of the average nitrate concentrations of Cressbrook reservoir.

### *6.2.5 Total phosphorus*

Phosphorus is another nutrient which can be controlled to limit the growth of Cyanobacteria in a reservoir (Donelly et al. 1998). Total phosphorus in a reservoir mostly comes from clay sediment in inflows. The phosphorus concentration in the water can be reduced by controlling the input, by flushing from the reservoir, or by allowing a sedimentation process in the reservoir. The use of artificial mixers with a draft tube, however, may obstruct the natural sedimentation in the water column by intensifying the vertical circulation in the storage. Vertical profiles of total phosphorus in Cooby and Cressbrook storages are discussed in Chapter 7, while this section discusses the overall loading and impact of mixers.

In Cooby, the operation of the surface mixers during the warm period increases the median value of the average phosphorus concentrations from 0.06 to 0.07 mg $L^{-1}$. Conversely, the mixers decrease the average total phosphorus concentrations by 0.01 mg $L^{-1}$ during the cold period. Detailed box plots of average total phosphorus concentration in Cooby storage are presented in Figure 6.17.

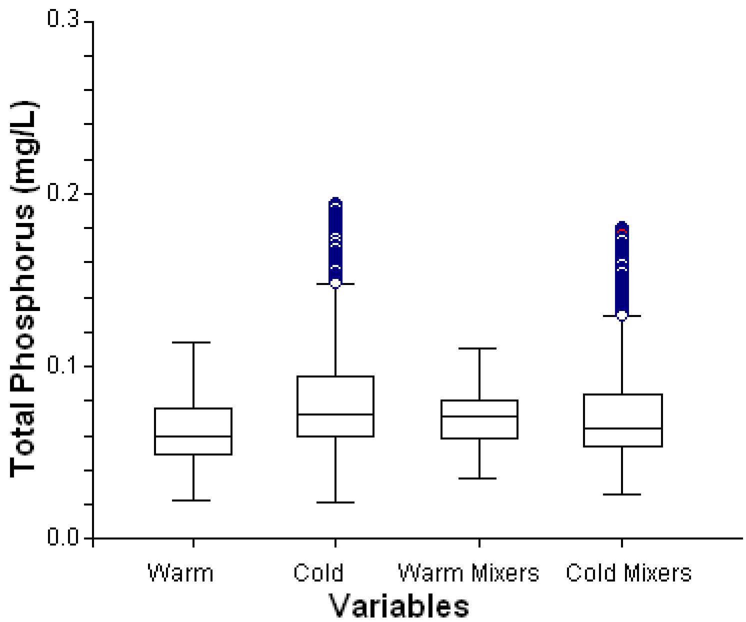



Figure 6.17 Box plots of the average total phosphorus concentrations of Cooby reservoir.

Cressbrook Dam has higher average total phosphorus concentrations than does Cooby. The average concentration during the warm period ranges from 0.06 to 0.26 mg $L^{-1}$ with a median 0.14 mg $L^{-1}$. The mixers are able to decrease the median by 0.02 mg $L^{-1}$ and widen the range to 0.05 – 0.27 mg $L^{-1}$.

The average total phosphorus concentration during the cold period is relatively higher than that during the warm period. Figure 6.18 shows that the range of the average concentration values is wider (0.04 – 0.37 mg $L^{-1}$) and the median higher by about 0.02 mg $L^{-1}$ when compared to the period October – April. The use of the destratifiers in the storage decreases the median, the first and the third quartiles of the average concentration by 0.02, 0.01 and 0.03 mg $L^{-1}$, respectively.

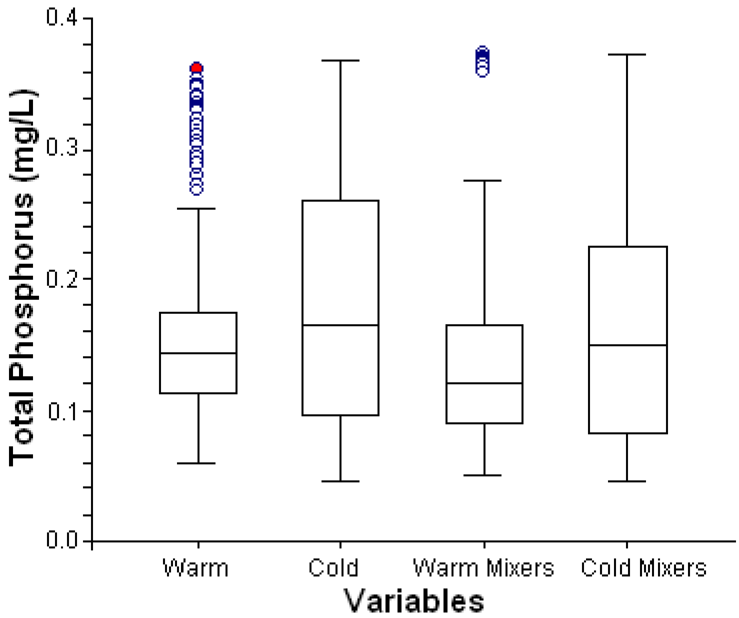



Figure 6.18 Box plots of the average total phosphorus concentrations of Cressbrook reservoir.

### *6.2.6 pH*

The pH level in a reservoir can be a limiting factor for the survival of aquatic species. Some fish species grow optimally within a pH range of 6.5 to 9.0. For water supply purposes, the recommended pH values are 6.5 to 8.0 (EPA Queensland 2005). For these reasons, it is important to monitor pH levels in multi purpose reservoirs such as Cooby and Cressbrook. The distribution of this parameter was established from the 50 year sequence of simulated values.

The average pH levels in Cooby reservoir range from 6.7 to 10.0 (excluding outliers) with a median value of 8.2 during the warm and cold periods. The mixers' operation results in insignificant changes to the average pH levels in the storage. The lower data range slightly decreases by 0.1 and the upper data range decreases by 0.2, as shown in Figure 6.19.

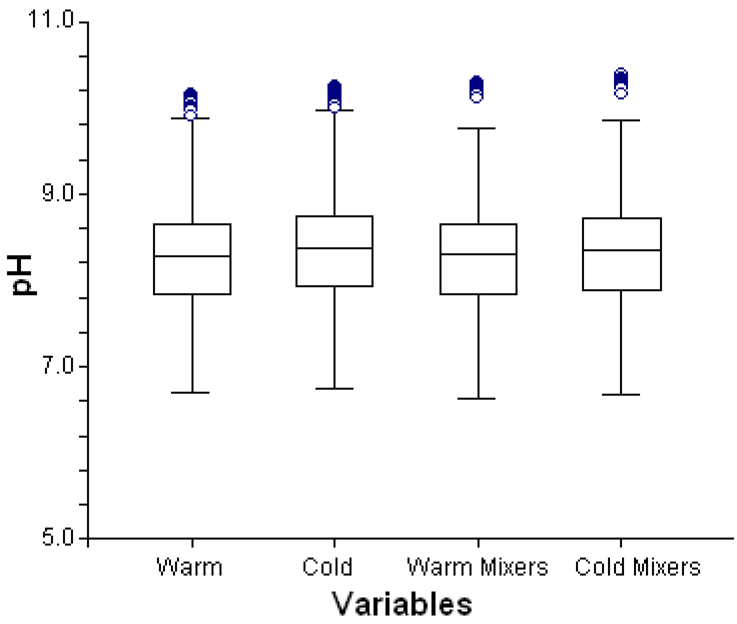



Figure 6.19 Box plots of the average pH levels in Cooby reservoir.

The average pH values in Cressbrook reservoir range from about 7.8 to 10.6, higher than levels in Cooby. The median of these average pH levels is about 9.4. There is no significant difference in the percentile data during the warm and the cold period, nor is there any effect from the artificial mixers in the storage.

There are two implications of these facts. Firstly, the variation of the pH value between seasons is very small and any fluctuation of the pH values is related to the inflows to the reservoirs (indicated by a negative correlation between the water surface levels and the pH levels). Secondly, the variation in the pH of the water column is very small during the stratified period. Therefore, the operation of the mechanical mixers is irrelevant to pH values in the storage. Detailed box plots of the average pH values for all categories in the storage are presented in Figure 6.20.

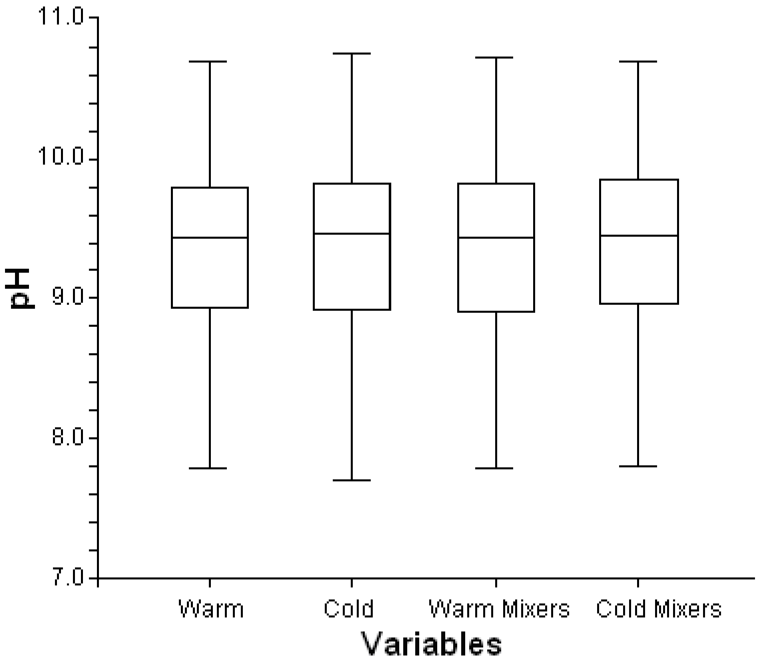



Figure 6.20 Box plots of the average pH levels in Cressbrook reservoir.

### *6.2.7 Salinity*

A salinity concentration below 5 psu (electro-conductivity in µS/mm) represents an acceptable level for optimal growth of most freshwater species (EPA Queensland 2005). The historic and simulated future salinity concentrations in Cooby and Cressbrook reservoir show an even lower salinity level (less than 1 psu). The data range indicates that no quality problem exists in relation to the salinity concentration in the storages.

The salinity concentration in Cooby Dam varies from 0.48 to 0.72 psu with a median of 0.58 psu during the warm period. Figure 6.21 indicates that salinity remains constant throughout the stratification and mixing processes. The average salinity concentration range is also independent of weather changes. Statistically, there is no significant difference between the average salinity concentrations with and without mechanical mixers in operation in the storage.

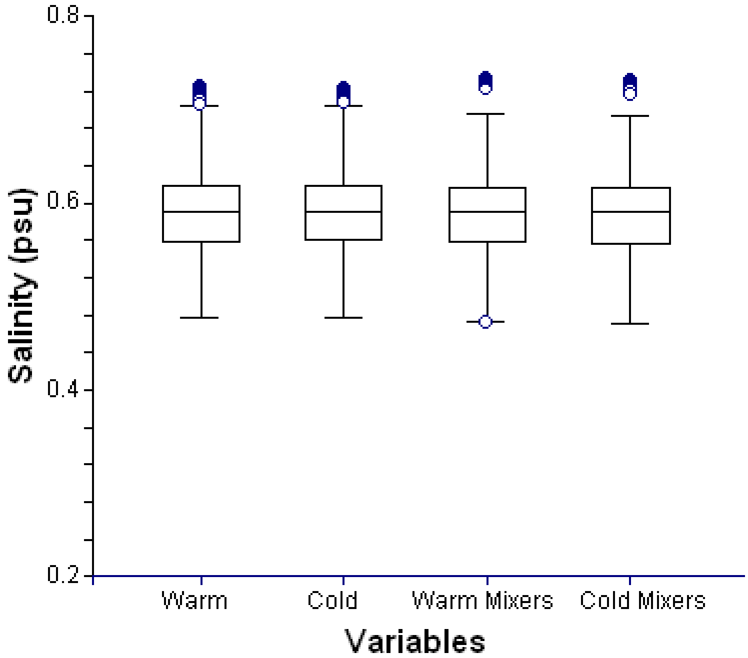



Figure 6.21 Box plots of the average salinity concentrations of Cooby reservoir.

In Cressbrook Dam, the average salinity concentration lies between 0.46 psu and 0.78 psu with a median value of 0.66 psu during the warm period. Figure 6.22 indicates that there is slightly less variation in salinity the warm period. The mixer is able to reduce the lower and upper bounds of average salinity concentration by 0.02 psu (from 0.46 to 0.44 psu) and 0.01 psu (from 0.78 to 0.77 psu), respectively during the warm period. The median, first and third percentiles of the parameter remain same.

The average salinity concentration in the storage during the cold period lies between 0.44 psu and 0.78 psu with a median of 0.66 psu. A vertical circulation in the water column has no effect on the average salinity concentration descriptors during the unstratified period.

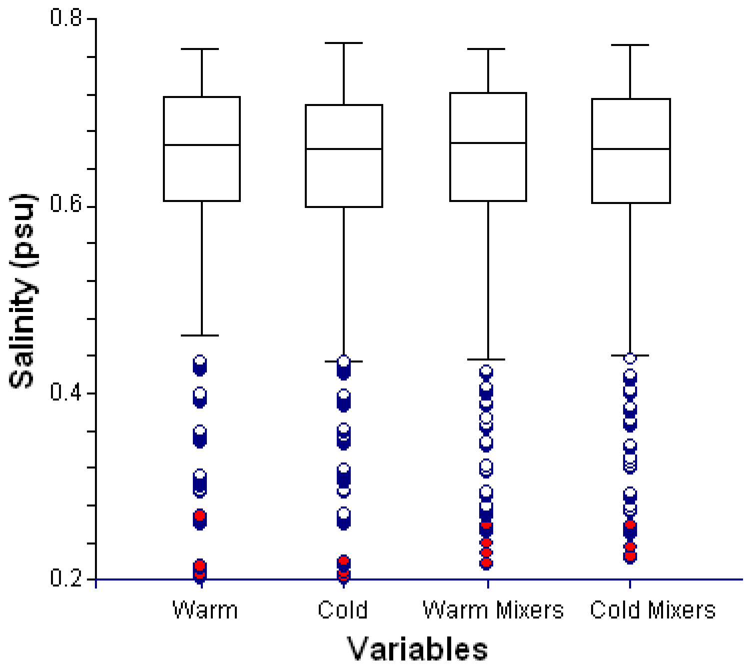


Figure 6.22 Box plots of the average salinity concentrations of Cressbrook reservoir.

The outliers in the box plots are mainly a result of selected initial model conditions. It requires 10 years of simulation for the concentration to reach operating conditions when the initial salinity is set at an arbitrary value of 0.2 psu.

### *6.2.8 Total iron*

Aquatic life can be very sensitive to total iron, and a high level of this parameter can be a dangerous pollutant. Few species can adapt to a water environment which contains more than 0.1 mg $L^{-1}$ total iron (EPA Queensland 2005; Popov & Bezzaponnaya 2004). Popov & Bezzaponnaya (2004) found a high correlation between the iron concentration and suspended sediment and dissolved oxygen concentrations in the water column.

The average total iron concentration in Cooby storage during the warm period is 0 – 0.16 mg $L^{-1}$ with a median value of 0.04 mg $L^{-1}$. Mechanical mixers act to reduce the median value of average total iron concentrations to below 0.02 mg $L^{-1}$. The mixers also increase the spread in percentile data of total iron to 0 – 0.4 mg $L^{-1}$.

The average concentration of total iron during the cold period is considerably lower than it is in the warm period. The use of the destratifiers also reduces the average concentration of total iron. Detailed box plots for both periods with and without the use of the mechanical destratifiers in the reservoir are presented in Figure 6.23.

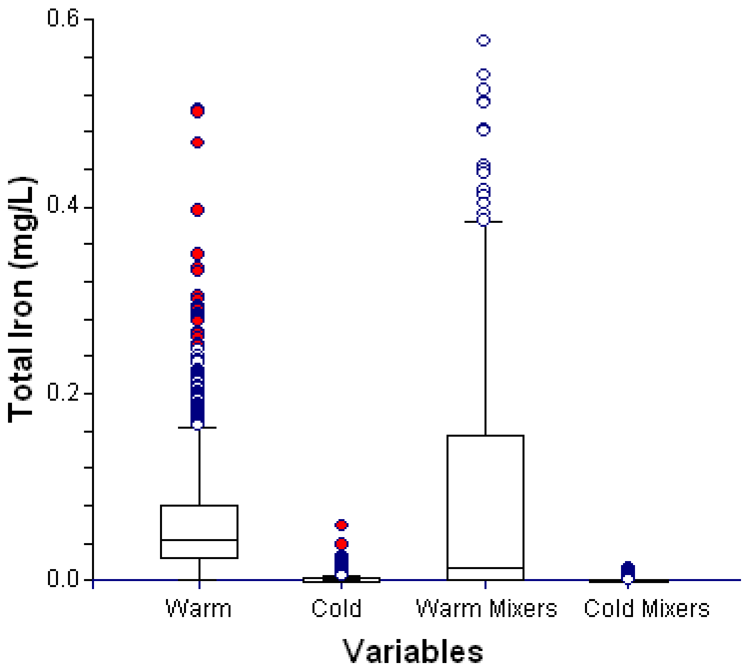



Figure 6.23 Box plots of the average total iron concentrations of Cooby reservoir.

In Cressbrook reservoir, the average concentration of iron is lower (less than 0.01 mg $L^{-1}$) than the EPA Queensland (2005) recommendation for aquatic environment and for raw water for the water supply. A number of severe outliers (less than 1 per cent of total data) for all categories (warm and cold periods and with and without surface mixers) are present between 0.02 mg $L^{-1}$ and 0.15 mg $L^{-1}$. Detailed box plots of the average total iron concentrations in Cressbrook storage are presented in Figure 6.24.

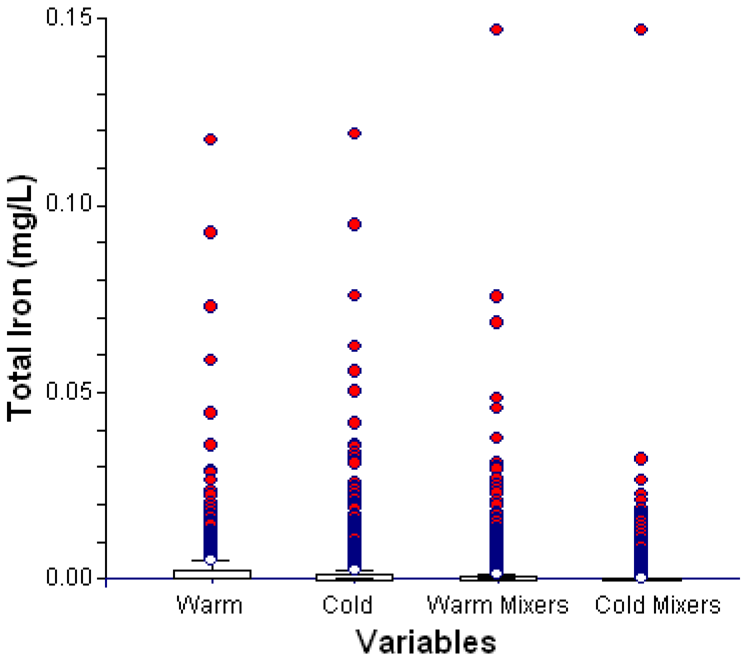



Figure 6.24 Box plots of the average total iron concentrations of Cressbrook reservoir.

### *6.2.9 Total manganese*

Total manganese in a water body is understood to indicate siltation in the reservoir and an increase in the concentration of other chemical substances (Kosov et al. 2004). The occurrence of manganese in excessive amounts creates odours in the water column. The Toowoomba water authority monitors this parameter as well as total iron concentration (Toowoomba City Council 2003).

The average concentration of total manganese in Cooby storage during the warm period is lower than 0.15 mg $L^{-1}$ with median, first and third quartile values of 0.04, 0.02 and 0.07 mg $L^{-1}$, respectively. The mixers dramatically reduce total manganese from 0 – 0.15 mg $L^{-1}$ to a range of 0 – 0.08 mg $L^{-1}$ with a median value less than 0.01 mg $L^{-1}$. Detailed box plots of average total manganese concentrations are presented in Figure 6.25.

As can be seen from Figure 6.25, the average concentration of manganese during the cold period is less than 0.01 mg $L^{-1}$ but mild and severe outliers occur from

0.01 to 0.04 mg $L^{-1}$. These values are much lower than the recommended acceptable value for freshwater.

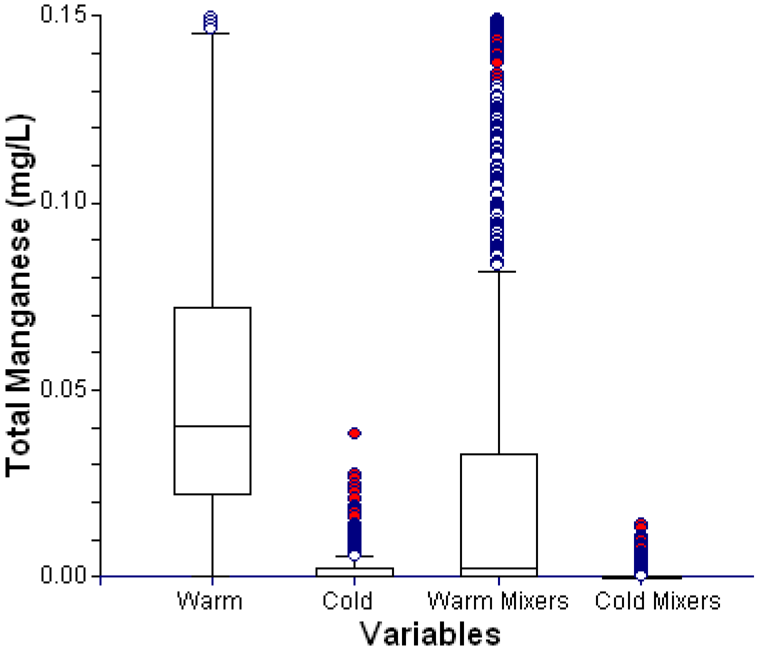



Figure 6.25 Box plots of the average total manganese concentrations of Cooby reservoir.

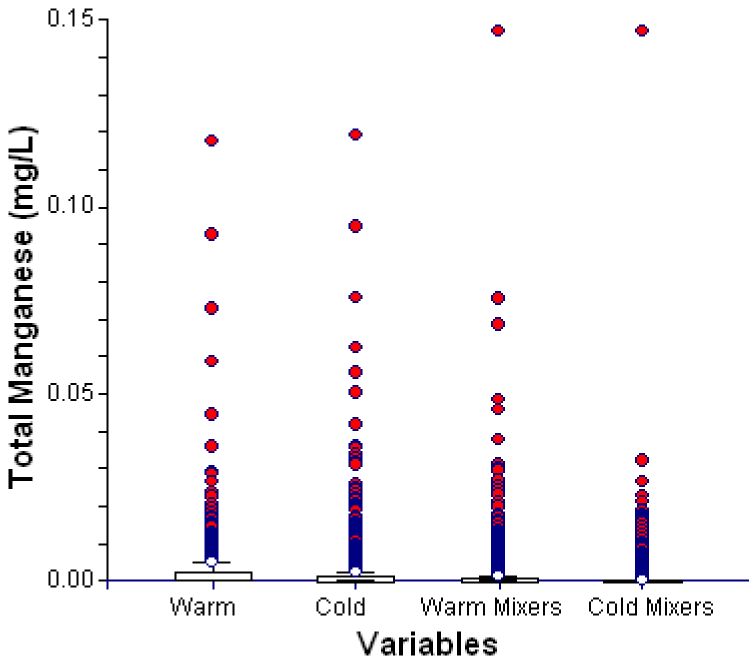



Figure 6.26 Box plots of the average total manganese concentrations of Cressbrook reservoir.

The average total manganese concentration in Cressbrook Dam is low as shown in Figure 6.26. This figure present box plots of average total manganese concentration values during the warm and cold periods with and without the use of six mechanical mixers in Cressbrook storage. The data lies in the range from 0 to 0.005 mg $L^{-1}$, with only outliers occurring between 0.005 and 0.15 mg $L^{-1}$.

## 6.3 Sustainability of Reservoirs

The sustainability of reservoirs can be determined based on the availability of water (quantity) and the quality of water in the storages. The quantity and quality of water in a reservoir can be used to calculate a single sustainability index (Beck & Straten 1983; Cude 2001; Kundzewicz 1995).

However, the sustainability of reservoirs in this study was assessed only from quality considerations. Five levels of water restriction policy (Level 1, 2, 3, 4, and 5) based on the water surface level underpin the management of in Toowoomba's dams. Level 1 is applied when the total volume in the storages lies in between 75 and 85 per cent; Level 2 is applied if the volume of the storage falls to between 65 and 75 per cent; Levels 3, 4 and 5 are applied when the volume of the storages is in between 55 and 65 per cent, 45 and 55 per cent and 35 and 45 per cent, respectively (Toowoomba City Council 2001). An assessment of the water restriction policy was not included in this study.

### *6.3.1 Water quality rating*

Nine selected indicators were used to determine quality aspect of sustainability in the reservoirs. The indicators were rated using some references including the Queensland water quality guidelines (Cude 2001; EPA Queensland 2005).

A function was developed to transform the nine water quality parameters into a rating value based on the acceptability of each indicator. Acceptable values were rated to be equal or higher than 60, while unacceptable values were lower than this value. The rating values were interpreted at five qualitative levels, as described in Table 6.1

Table 6.1 Description of the range of rating values.

| Rating | Descriptions |
|---|---|
| $80 \leq R < 100$ | Excellent: eminently usable for all purposes |
| $60 \leq R < 80$ | Good: suitable for all uses |
| $40 \leq R < 60$ | Intermediate: main uses and/or some uses are risk |
| $20 \leq R < 40$ | Bad: unsuitable for main and/or several uses |
| $0 \leq R < 20$ | Very bad: totally unsuitable for main and/or many uses |

Source: Hambright, Parparov & Berman 2000.

Water quality rankings for Cyanobacteria were based on a combination of ratings from Lake Kinneret and the Queensland water quality guidelines (EPA Queensland 2005; Hambright, Parparov & Berman 2000). Cyanobacterial concentrations less than 1.0 mg $m^{-3}$ were given a quality rating of 90 – 100; while concentrations between 1.0 and 3.5 mg $m^{-3}$ were rated as 60 – 90; concentrations between 3.5 and 10.0 mg $m^{-3}$ were rated as 20 – 60; and concentrations above 10 mg $m^{-3}$ were rated as 0– 20.

Dissolved oxygen concentrations were ascribed ratings with 4 mg $L^{-1}$ as a critical threshold. DO values higher than 8 mg $L^{-1}$ were rated as 90 to 100, while concentrations below 2 mg $L^{-1}$ were rated as less than 20. These critical values were adopted from EPA Queensland (2005).

Acceptability ratings for pH were based on the Queensland Water Quality Guidelines. Values between 6.5 and 8.0 were accepted as the optimum range with rating of 100. Critical values for pH are 5.0 and 9.5 and these vales were assigned a rating of 60. pH values which are lower or higher than these critical values were rated below 60 (EPA Queensland 2005).

Salinity concentrations were converted to an acceptability rating with a critical point at 5 psu. The concentrations below 5 psu were rated higher than 60 (EPA Queensland 2005).

Water temperatures between 21$^{o}$C and 32$^{o}$C assigned an aceeptability rating of 100. The rating for temperatures above 32 $^{o}$C decreased sharply to a minimum value of 20 while values of 0 $^{o}$C and 8 $^{o}$C were rated as 20 and 50, respectively (EPA Queensland 2005).

Nitrate and total phosphorus concentrations have a similar acceptability rating pattern (at different scales). The concentration of nitrate below 0.25 mg $L^{-1}$ was valued between 100 and 40. Values between 0.25 mg $L^{-1}$ and 1.50 mg $L^{-1}$ were given acceptability rating from 60 to 100 with the optimum occurring at 0.25 mg $L^{-1}$. Total phosphorus concentrations below 0.010 mg $L^{-1}$ represents oligotrophic water, and were ascribed ratings from 100 to 40. A concentration between 0.010 mg $L^{-1}$ and 0.100 mg $L^{-1}$ represents an acceptable level of concentration, and so was rated from 60 to 100 with a peak value at 0.025 mg $L^{-1}$. A concentration above 0.100 mg $L^{-1}$ indicates a eutrophic aquatic condition and is rated below 60 (Pavoni & Perrich 1977).

Total iron and total manganese concentrations were ascribed the same rating value. These chemical substances pose a high risk to human health although some fish species such as Barramundi and Redclaw can survive in freshwater with iron and manganese concentrations up to 0.1 mg $L^{-1}$ (EPA Queensland 2005). The critical point for these substances is 0.05 mg $L^{-1}$. The ratings were assigned as an exponential function from 100 to 10 points to reflect the potential health risk of the iron and manganese concentration.

All these water quality acceptability ratings are presented in Figure 6.27.

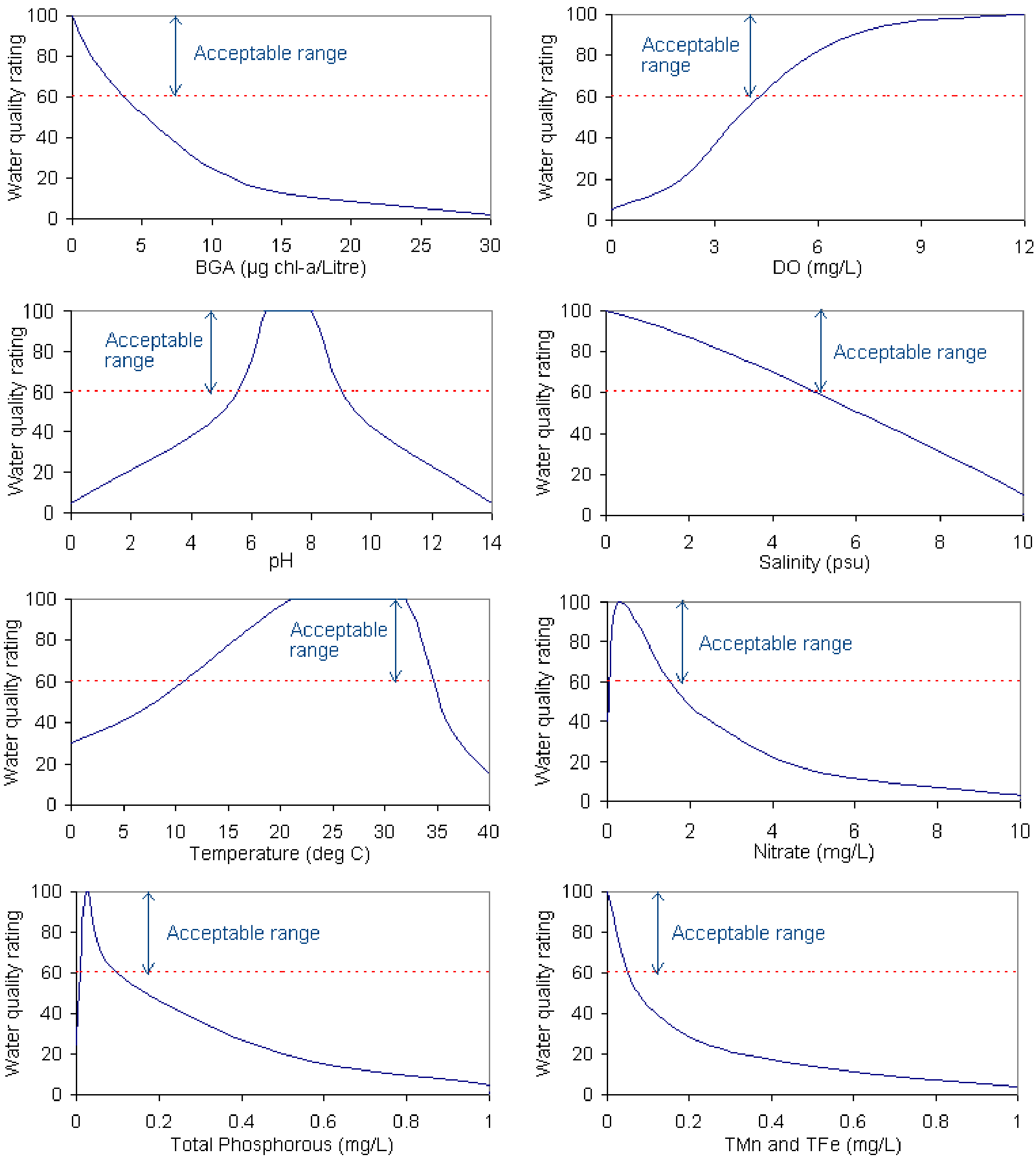



Figure 6.27 Water-quality rating of selected parameter indicators based on local considerations in Toowoomba.

### *6.3.2 Water quality index*

With nine different rating values, a quick assessment of overall quality is not as easy as it would be with a single index. A water quality index is required to describe the overall situation in the reservoirs (Straškraba & Tundisi 1999). To create a useable single water quality index, all the analysed parameters need to be combined with relevant weightings to reflect individual significance. This is the first time an index has been sought for Toowoomba's reservoirs; so the weightings of parameters were adopted from other sources. Major considerations in setting weightings in this particular case were:

(a) Chlorophyll-*a* concentration of Cyanobacteria is a major biological indicator for Toowoomba's reservoirs (Clark, *pers. comm.*, 28 August 2002; Kleinscmidt, *pers. comm.*, 29 May 2003),

(b) Salinity is not an issue in Toowoomba's dams as the values are mostly lower than 1 psu (Kleinscmidt, *pers. comm.*, 29 May 2003), and

(c) Manganese and iron concentrations represent a significant problem which is related to the siltation processes (Clark, *pers. comm.*, 28 August 2002).

A single water quality index was made by modifying the *Mitchell and Stapp Index* which was developed for Sinking Creek, the Missouri River and other river systems in the USA (McClelland 1974). Modifications to the weighted parameter indicators were made by replacing faecal coliform with Cyanobacteria and suspended solids with salinity. The adopted weighted indicators are presented in Table 6.2.

Table 6.2 The weighted values of parameter indicators for Toowoomba's reservoirs.

| **Parameter Indicators** | **Unit** | **Weighting** |
|---|---|---|
| Cyanobacteria | mg chl-*a* $m^{-3}$ | 0.17 |
| Dissolved oxygen | mg $L^{-1}$ | 0.16 |
| pH | Non dimensional | 0.11 |
| Temperature | $^{o}C$ | 0.10 |
| Total Phosphorus | mg $L^{-1}$ | 0.10 |
| Nitrate | mg $L^{-1}$ | 0.10 |
| Salinity | psu | 0.07 |
| Total Manganese | mg $L^{-1}$ | 0.10 |
| Total Iron | mg $L^{-1}$ | 0.10 |

Source: Modified from McClelland 1974.

Using the rating and weighting system described above, a water quality index was determined using the following equation.

$$WQI = \sum_{i=1}^{n} w_i R_i \tag{6.3}$$

where $WQI$ is a water quality index; $w_i$ is weighting factor for parameter $i$; $R_i$ is individual rating for parameter $i$; and $i$ is the index of parameter ( $i$ = 1 to $n$) and $n$ is the number of calculated parameters (in this study $n$ = 9).

### *6.3.3 Water quality index of Cooby Dam*

Two individual layers (the surface and pumping layers) and the average of all layers were selected to represent the water quality conditions in the reservoir over time with and without using artificial mixers. This index was produced for warm and cold periods on a weekly time step.

Generally, the indices show large fluctuations in a year. They also show sinusoidal cycloids periods during the simulated 50-year period. Two cycles were simulated over approximately 17 years from 2004 and about 18 years from 2021 to 2039.

#### 6.3.3.1 Surface layer quality and sustainability

The water quality in Cooby reservoir during the warm period is good to excellent. Figure 6.28 presents the water quality index (WQI) for the surface layer of Cooby Dam with and without the use of artificial mixers during the warm period for the simulated period 2004 – 2053. Without artificial mixers, the WQI of the layer trends downwards from about 85 to about 77 over the 50-year period. The use of two SMDI-5s (mechanical mixers) in the reservoir improves the average water quality condition by about 10 per cent throughout the 50-year period, but does not alter the trend line.

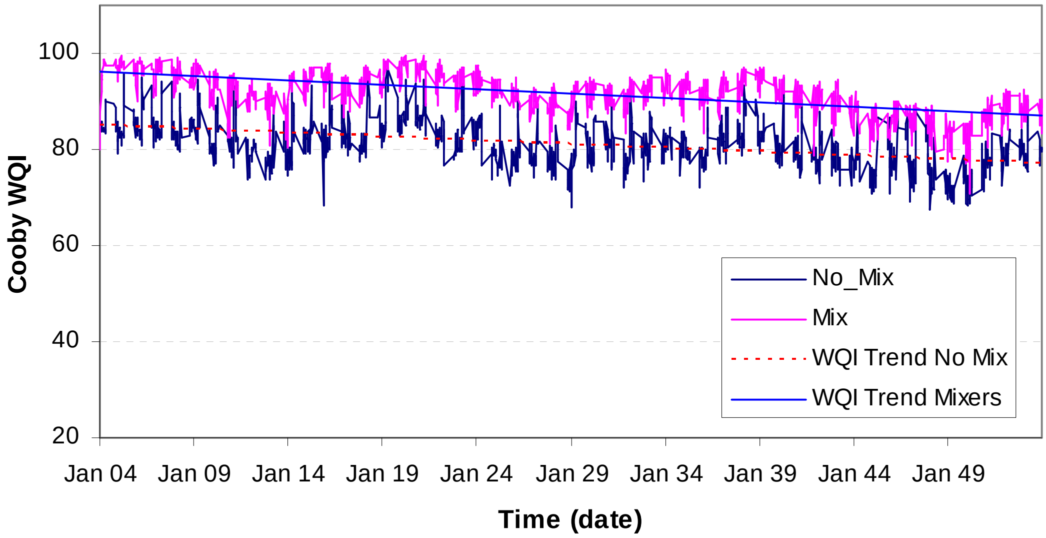



Figure 6.28 Time series of WQI at the surface layer in Cooby storage during the warm period of the years 2004 - 2053.

For the cold periods, the seasonal variation in the WQI is less in the surface water. The individual acceptability indices are relatively higher than the warm period and this is reflected in the overall value. The quality of water also drops more gradually over the simulated period from 87 to 82. The use of mechanical surface mixers increases the WQI of Cooby by about 5 per cent, with a similar trend in WQI to that occurring without the mixers. The WQI is predicted to decline from grade 95 to 88 over the 50-year period.

A basic frequency analysis quantified the probability of getting an excellent quality (WQI > 80) at about 60 per cent in the surface layer during the warm period. A good level of quality (WQI > 60) has an occurrence probability of 100 per cent during this period without the artificial mixers. The mixers are predicted to improve water quality with the probability of excellent quality water rising to almost 100 per cent.

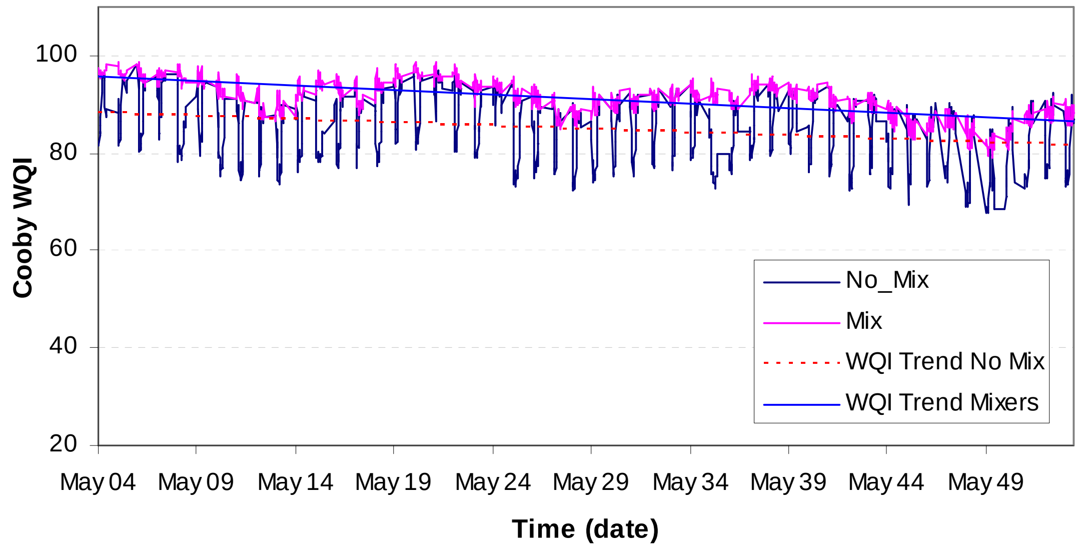



Figure 6.29 Time series of WQI at the surface layer of Cooby storage during the cold period.

6.3.3.2 Pumping layer quality and sustainability

The WQI of the pumping layer was selected to represent the quality of raw water to the Toowoomba Water Treatment Plant. Without artificial mixers, the WQI of the pumping layer in Cooby during the warm period declines from 80 to 73 over the simulation period. The trend is not severe thought and good quality water (WQI > 60) is maintained during the stratified period for the entire simulation. The probability of getting excellent water quality at this depth is assessed at only about 30 per cent.

The artificial mixers in the storage increase the probability of occurrence of excellent water quality to nearly 100 per cent. The WQI during the warm period is then predicted to decrease from grade 98 to 90 over the-50 year period as presented in Figure 6.30.

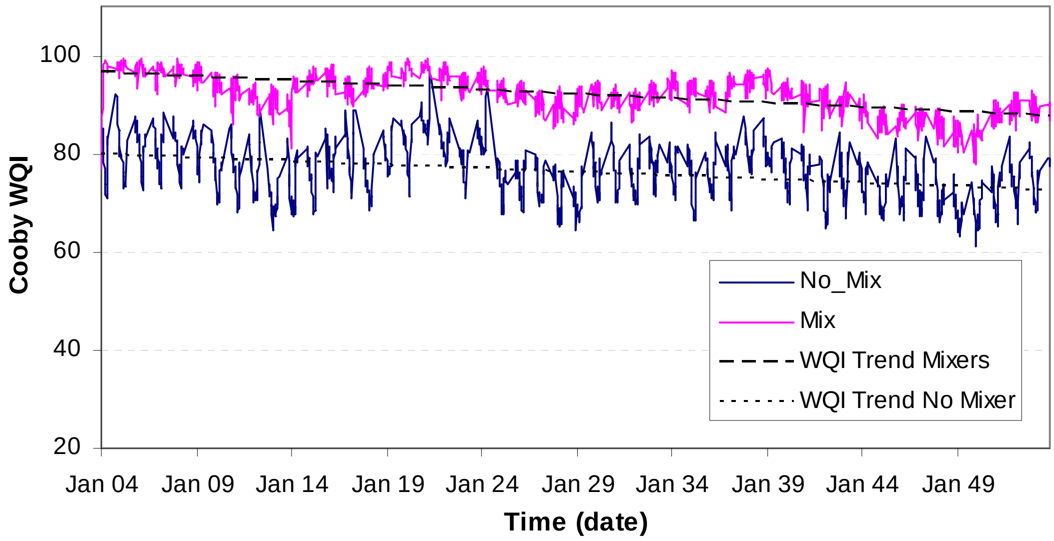



Figure 6.30 Time series of WQI at the pumping layer of Cooby storage during the warm period.

During the cold period and without the operation of the mixers, the probability of having excellent and good water quality levels at the pumping elevation is about 55 per cent and almost 100 per cent, respectively. The WQI slightly decreases by only two grade points (from grade 85 to 83).

Figure 6.31 shows the impact of the mixers in the storage on the water quality in the dam during the cold period. It indicates an increase in probability of occurrence of excellent quality water (WQI > 80) to almost 100 per cent. The WQI trend decreases from grade 98 to 93 over 50 years. This means that the use of the mechanical mixers would assure a high probability of excellent water quality at the pumping elevation for the next 50 year even though the quality decreases over this period.

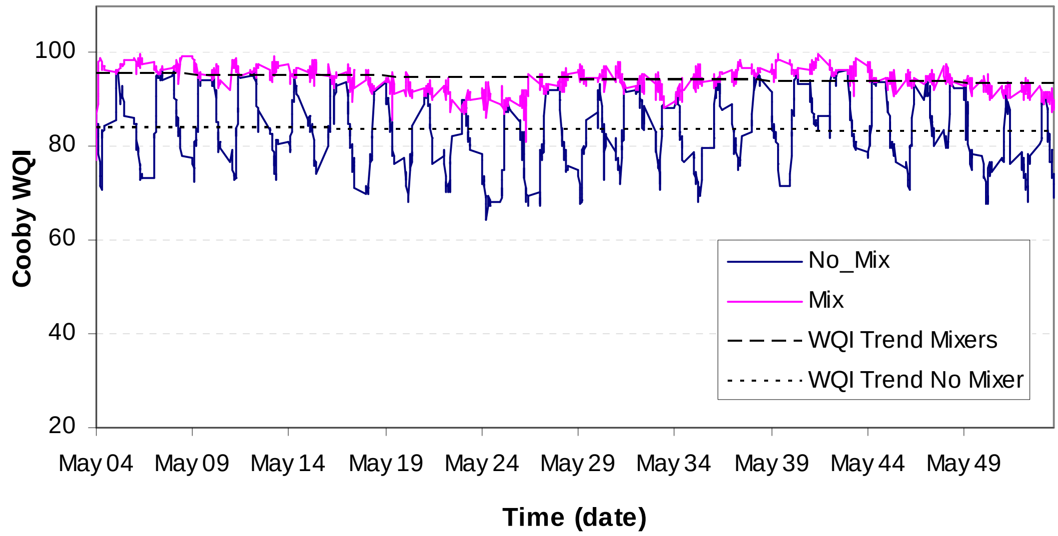



Figure 6.31 Time series of WQI at the pumping layer of Cooby storage during the cold period.

6.3.3.3 The water column quality and sustainability

The water quality of the entire water column is estimated by using the average value of all layers to represent the whole water body in the storage.

In the warm period and without mixing, the probability of occurrence excellent quality in the entire water column is about 42 per cent. The probability of having good water (WQI > 60) is however almost 100 per cent. The WQI has a decreasing trend with a drop of nine grade points from 82 to about grade 73 over the simulation period.

Figure 6.32 shows that artificial mixers in the storage during this period would create even better water quality level in the storage. The average of WQIs is increased by 15 grade points, creating excellent water quality throughout the simulation period. The predicted trend is then decrease from grade 95 to 86.

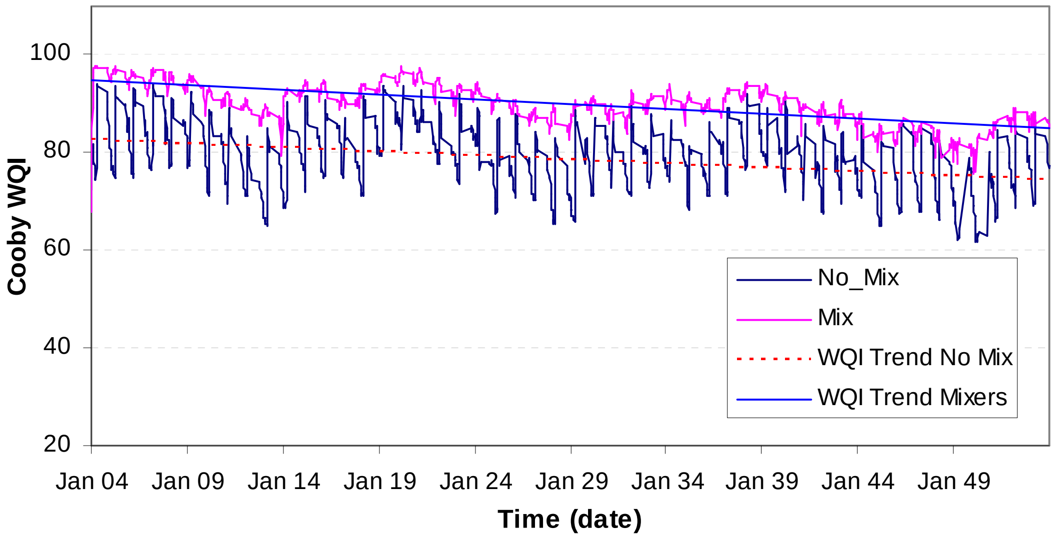



Figure 6.32 Time series of WQI in the water column (average layers) of Cooby storage during the warm period.

The WQI values for the storage during the cold period vary from 66 to 97 due to seasonal fluctuations. Excellent and good water qualities in the water column have occurrence probabilities of about 55 per cent and nearly 100 per cent, respectively. The trend in WQI values is to decrease from 88 to 80 (eight grade points) over the 50-year period. A detailed representation of estimated whole column WQI values during the cold period is presented in Figure 6.33.

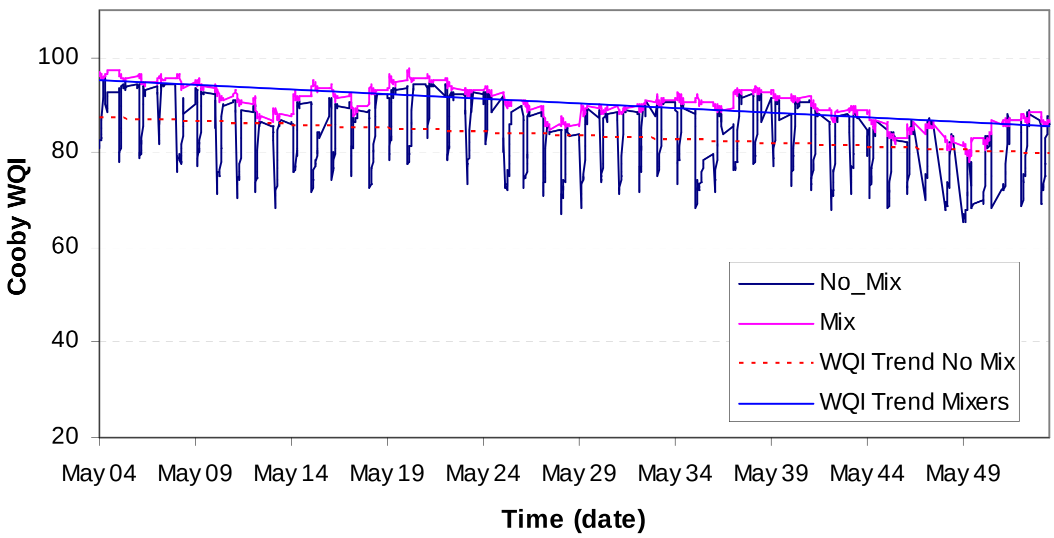



Figure 6.33 Time series of WQI in the water column (average layers) of Cooby storage during the cold period.

Figure 6.33 also shows that the use of surface mixers in the storage during the cold period would upgrade the water quality level in the dam. This is indicated by an increase in the probability of occurrence of the excellent rating (WQI > 80) to about 45 per cent. The trend in WQI is to decrease from 97 to 86.

The trends of WQI during the warm and the cold periods may provide a useful basis for further analysis into the cause of water quality degradation in the storage. There appears to be a rough correlation between the surface water level and the WQI in the dam.

### *6.3.4 Water quality index of Cressbrook Dam*

The water quality in Cressbrook is summarised in a similar way to that in Cooby. Two separated layers (the surface and pumping layers) were selected with the averaged water column values to generate a time series of Water Quality Index (WQI) data in Cressbrook reservoir with and without artificial mixers. The weekly water quality index data were examined in two parts associated with the warm and cold periods.

#### 6.3.4.1 Surface layer quality and sustainability

Water in the surface layer of the storage has a WQI quality grade from 62 to 98 during the warm period. The WQI oscillated during the 50 year simulation period in cycles of about 10 years. Figure 6.34 shows two distinct periods; from 2034 to 2043 (the WQI drops from 95 to 78) and from 2044 to 2053 (the WQI drops from 95 to 76). However, there is a slight improvement in water quality over the simulated period, with the trend line showing an increase in WQI from 78 to 85. The probability of occurrence of an excellent water quality level in the surface layer is about 60 per cent.

The operation of the six SMDI-5s (surface mixers) would decrease this probability to 56 per cent.

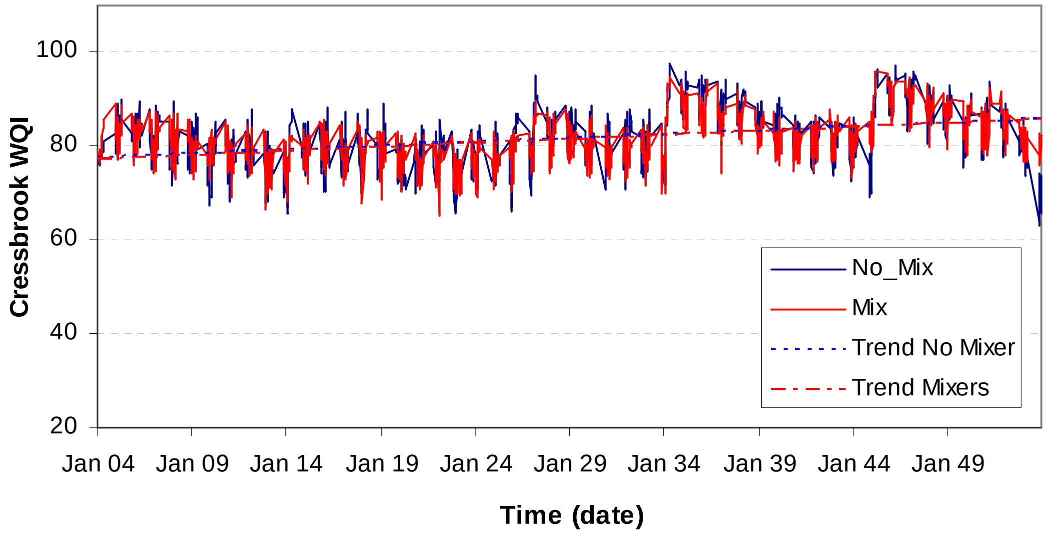



Figure 6.34 Time series of WQI at the surface layer of Cressbrook storage during the warm period.

The WQI values obtained for the surface layer in Cressbrook reservoir during the cold period ranged between 66 and 96. The WQI values follow a rising trend line from 80 in 2004 to 87 in 2053. The probability of occurrence of excellent and good quality water is about 64 per cent and 100 per cent, respectively.

The operation of six SMDI-5s (surface mixers) in the storage slightly improves the quality level of the storage. The probability of having excellent quality water (WQI > 80) increases from 64 to 72 per cent, but the improvement is statistically insignificant. The WQI values in Cressbrook storage for the cold period, with and without the use of mechanical mixers is presented in Figure 6.35 for a 50 year period.

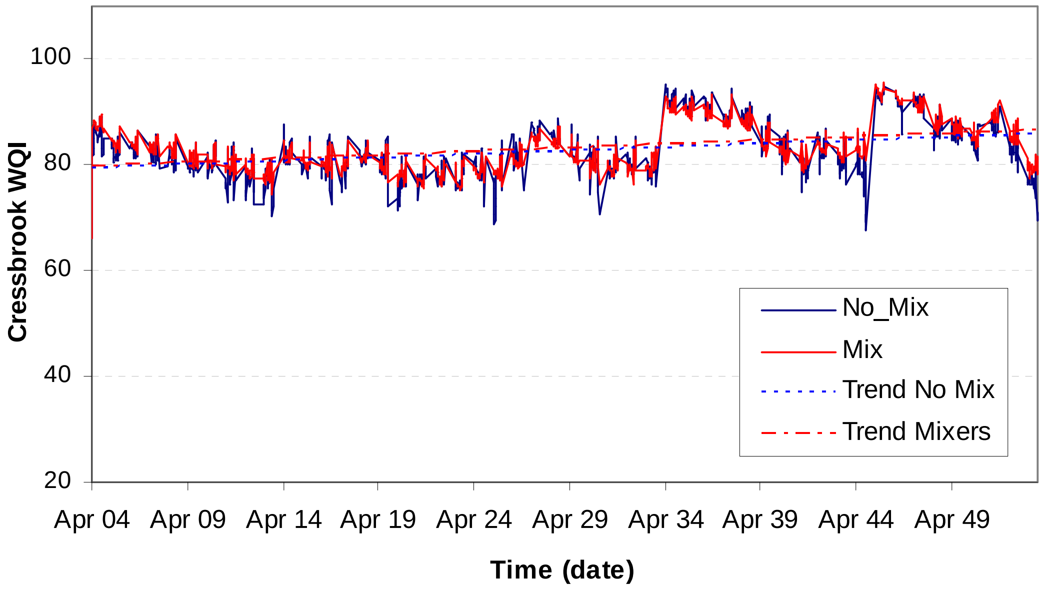



Figure 6.35 Time series of WQI at the surface layer of Cressbrook storage during the cold period.

6.3.4.2 Pumping layer quality and sustainability

The pumping elevation in the storage is the key layer for water supply purposes. Water from this layer provides the raw material for the Mt. Kynoch water treatment plant.

The simulated WQI values during the warm period range between 60 and 96, with a big variation occurring within each yearly period. The probability of occurrence of excellent quality water is about 32 per cent based on these simulations. The predicted WQI increases from 70 in 2004 to 85 in 2053, as shown in Figure 6.36.

Figure 6.36 also shows the positive impact of mechanical mixers in this storage. The action of the mechanical mixers increases the average WQI to about 83 with fluctuations occurring between 70 and 97 and a probability of excellent water quality at about 82 per cent. The WQI values increase by 5 grade points over the 50-year period.

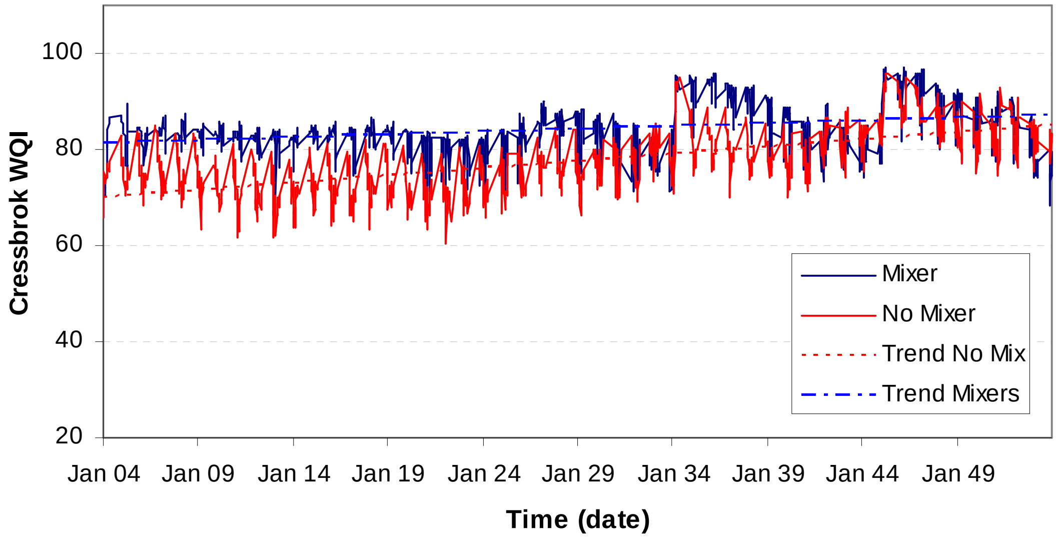



Figure 6.36 Time series of WQI at the pumping layer of Cressbrook storage during the warm period.

During the cold period, the WQIs in the storage lie between 70 and 95 with big variations occurring. The probability of having excellent water quality at the pumping elevation is about 75 per cent. The WQI is predicted to increase from 79 in 2004 to 86 at the end of the simulation period, as shown in Figure 6.37.

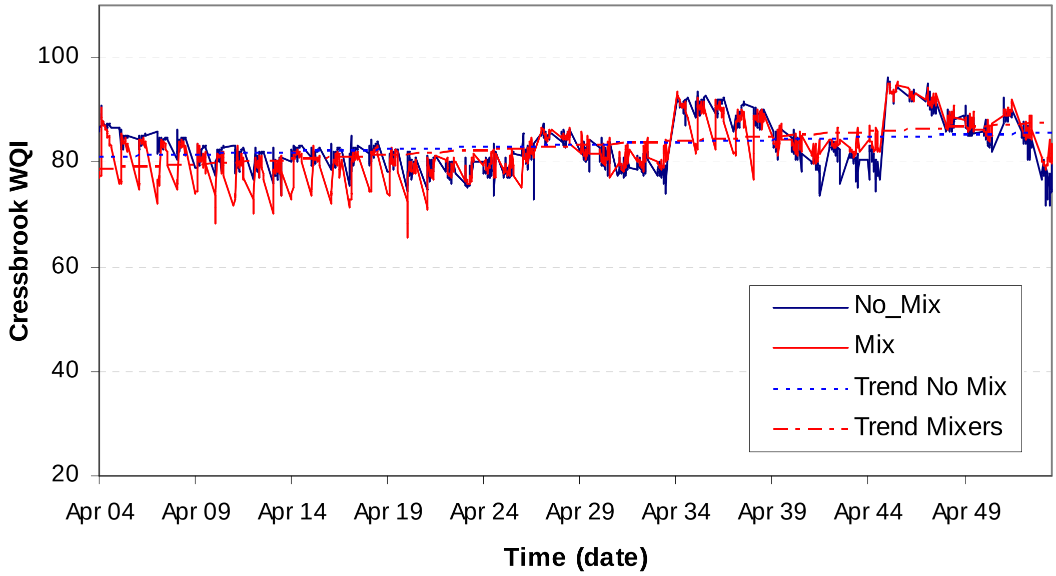



Figure 6.37 Time series of WQI at the pumping layer of Cressbrook storage during the cold period.

The time series data shows a small positive impact from the mechanical mixers at the pumping layer with mechanical mixers in use, the WQI values fluctuate between 67 and 96 with a probability of having excellent quality water at about 75 per cent. The WQI increases from 81 to 84 over the simulated period.

6.3.4.3 The water column quality and sustainability

WQI values for the entire water column are calculated from the averaged values of the selected parameters. This analysis may assist in assessing the ecological impact of the mixers in the storage.

During the warm period, without the artificial mixers, the probability of having excellent water quality for the whole column is only about 20 per cent. However, the probability of having good water quality is 100 per cent. The WQI rises by nine grade points (from 72 in 2004 to about 81 in 2053) during the simulation period.

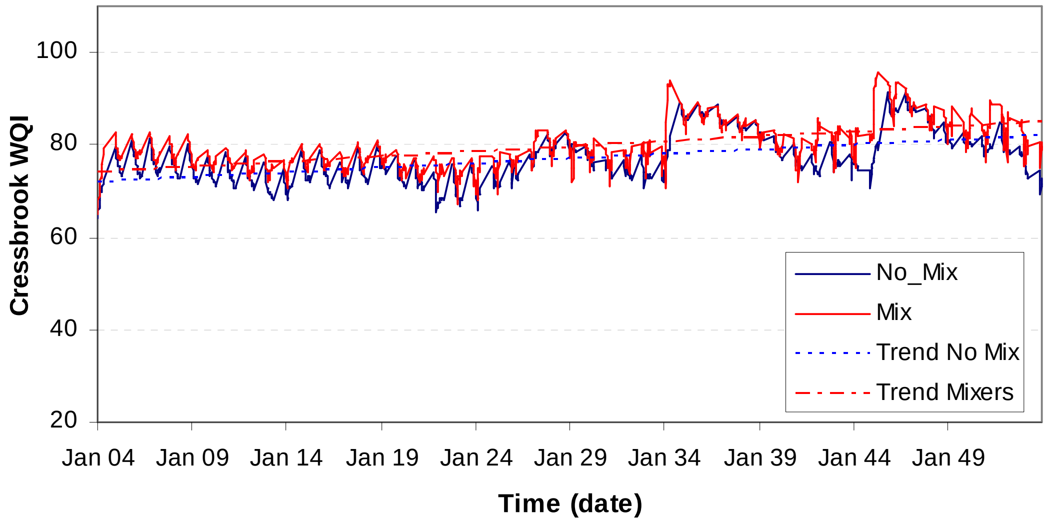



Figure 6.38 Time series of WQI in the water column (average layers) of Cressbrook storage during the warm period.

Figure 6.38 indicates that the artificial mixers in the storage are able to create a small improvement in water quality levels in the storage. The average WQI can be increased by 3 grade points. The mixers increase the probability of having excellent water quality to 40 per cent. The trend line on the WQI values increases from 79 to 88.

The column WQI values during the cold period fluctuate between 64 and 95. The probability of occurrence of excellent and good quality water in the water column is about 46 per cent and 100 per cent, respectively. The WQI increases from 77 to 83 (six grade points) over a half century of simulation. The time series of column WQI data during the cold period is presented in Figure 6.39.

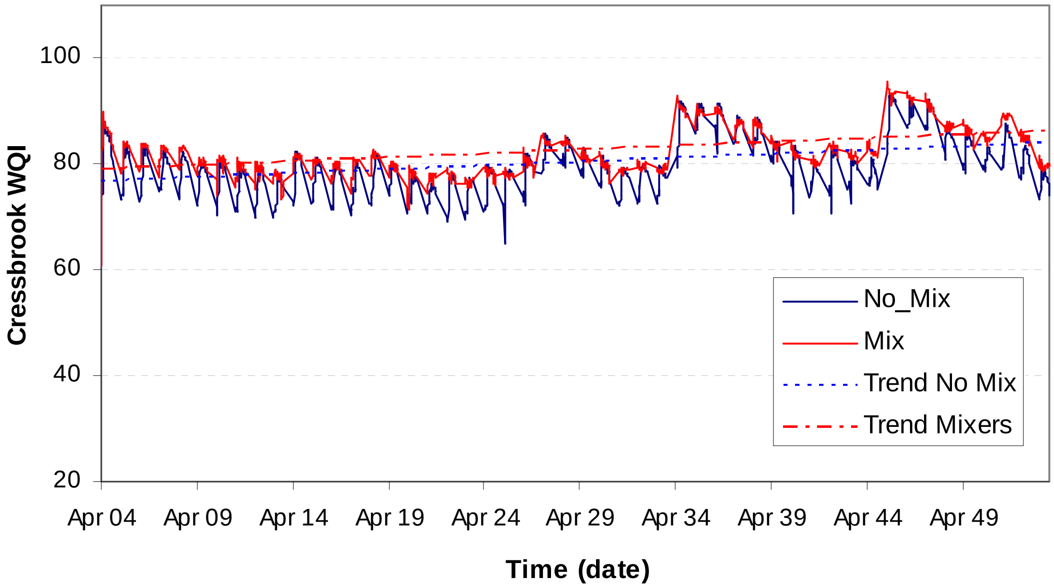



Figure 6.39 Time series of WQI in the water column (average layers) of Cressbrook storage during the cold period.

Figure 6.39 shows that surface mixers in the storage during the cold period would slightly upgrade the water quality level (WQI) in the dam. This is indicated by an increase in the probability of occurrence of excellent quality (WQI > 80) to 64 per cent. The WQI trends from 79 to 86 over the simulation period.

# Chapter 7

# RISK ASSESSMENT OF THE RESERVOIRS

## 7.1 Introduction

The probability of occurrence of different water quality levels in the reservoirs at different seasons can be used to establish a risk management approach to the use of mixers. The information provided in this project could enable managers to make decisions appropriate to the level of risk of problems in the storages. Appropriate management can reduce or eliminate the occurrence of undesirable water quality conditions. This chapter further analyses the probability of occurrence of water quality levels in the two reservoirs (Cooby and Cressbrook reservoirs). Nine selected water quality indicators on a weekly basis form the basis of this appraisal.

The environmental risk in the dams is evaluated from as the probability of occurrence of nine water quality indicators: one biological and eight physicochemical.

## 7.2 Water Quality Indicators

Water quality assessment of freshwater lakes and reservoirs in Australia routinely employs biological and physicochemical indicators (EPA Queensland 2005; USEPA 1998). Water quality indicators were adopted for Cooby and Cressbrook reservoirs from parameters monitored by the Toowoomba managers. The assessment uses cyanobacterial concentration as the key biological indicator with dissolved oxygen concentration, water temperature level, nitrate, total phosphorous, total iron, total manganese concentration, salinity, and pH levels adopted as physicochemical indicators which determine the environment for algal growth. Many other biological and ecological aspects of the reservoirs (such as zooplankton and fish) were not adopted in this project because of a limitation in measured field data and/or a low connection to Cyanobacteria.

The assessment of an ecosystem is best done with biological rather than physicochemical indicators because of their integrating effect (USEPA 1998). However, ecosystem modifiers are important as causes of change to the biological indicators (EPA Queensland 2005; Ganf 1980). Physicochemical indicators complement the analysis to establish the causes of cyanobacterial blooms.

All indicators are represented here by the probability of occurrence of different levels of water quality. The probability is calculated for a vertical column in the water body and was established from simulated weekly data. The data were again subdivided into a warm period from October to March and a cold period from April to September. Simulations of water quality were completed to establish the effects of artificial mixers. The results are divided into four categories in this chapter: which are (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers. Profiles of the average values for selected water quality parameters are also presented to support the conclusions made as to mixer operation.

### *7.2.1 Cyanobacteria*

The cyanobacterial level in the dam is classified into four quality states. These states are based on guidelines for blue-green algae levels for primary contact recreation in Queensland (EPA Queensland 2005). They combine the quality limits from two states. A cyanobacterial concentration less than 1 μg $L^{-1}$ is classified as safe, while concentrations between 1 and 5 μg $L^{-1}$ are classified as low quality risk, 5 – 10 μg $L^{-1}$ is classified as moderate, and concentration above 10 μg $L^{-1}$ is classified as a state of high risk to users.

The probability of occurrence of different cyanobacterial states in Cooby reservoir are presented in Figure 7.1 for both periods (warm and cold) with and without mixers. Generally, cyanobacterial concentration during the warm period is significantly higher than that in the cold period from the surface down to 9.5 m depth. The concentration of Cyanobacteria below 9.5 m is however considerably higher in the cold period.

Figures 7.1(a) and (c) show the probability of occurrence of cyanobacterial states in the water column during the warm and cold period without mixers. The probability of occurrence of a high cyanobacterial state during the warm period can reach about 35 % at 3.5 m below the water surface. It is only about 1 % during the cold period. The maximum probability of occurrence for moderate state of cyanobacterial concentration in the warm period is found at 4.5 m depth, and is about 54 %. This is three times probability occurring during the cold period at 4.5 m depth. The cyanobacterial concentration during the cold period is likely to be lower than 5 μg $L^{-1}$ throughout the water column, except for one area around 4.5 m depth.

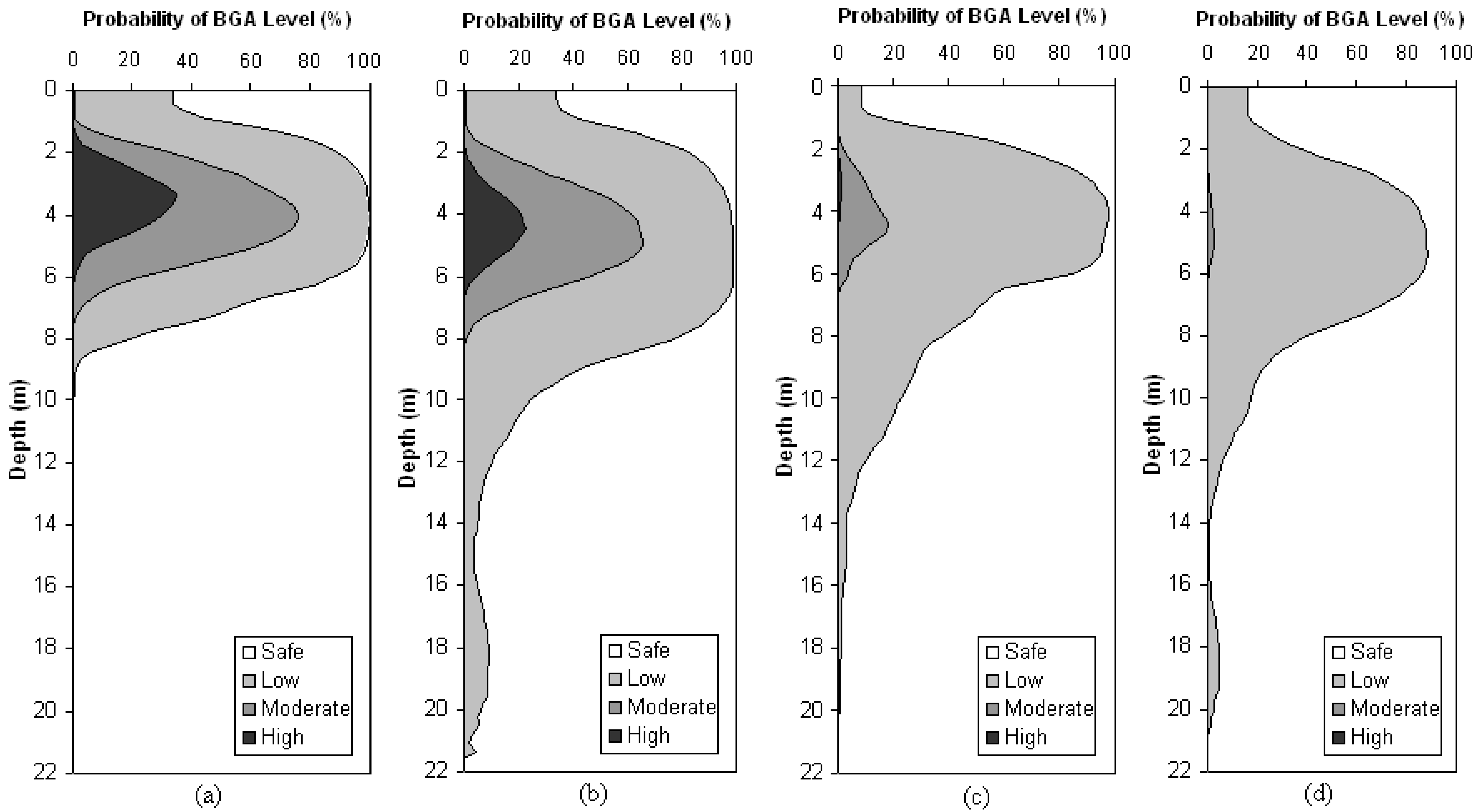



Figure 7.1 Probability occurrences of Cyanobacterial levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

Surface mechanical mixers increase the potential growth of Cyanobacteria deeper in the storage because the mixers push the thermocline lower in the profile. An increase of dissolved oxygen in the water column (see Figure 7.5) also contributes to an increased algal growth rate as extra oxygen becomes available for the photosynthetic processes.

Critical depth for cyanobacterial concentration is about 3.5 m depth with the high risk level about 36 % during the warm period. The critical depth for algae is about one metre lower than in the case without mixers with the high risk level approximately 20 %.

The changing probability of occurrence of cyanobacterial concentration through the water column as a result of the mixers in Cooby reservoir is shown by Figures 7.1(b) and (d). The mixers result in a reduction of algal risk in the epilimnion during the whole simulation period. The hypolimnion layer on the other hand suffers increasing cyanobacterial risk levels.

Figure 7.2(a) shows that the artificial mixers improve overall water quality by reducing average cyanobacterial concentrations by 3.3 $\mu g\ L^{-1}$ in the epilimnion layer (surface to 4.7 metres depth) during the warm period. However, the quality of water is getting worse below 4.7 m depth. The average cyanobacterial concentration is increased by up to 1.8 $\mu g\ L^{-1}$ in these layers.

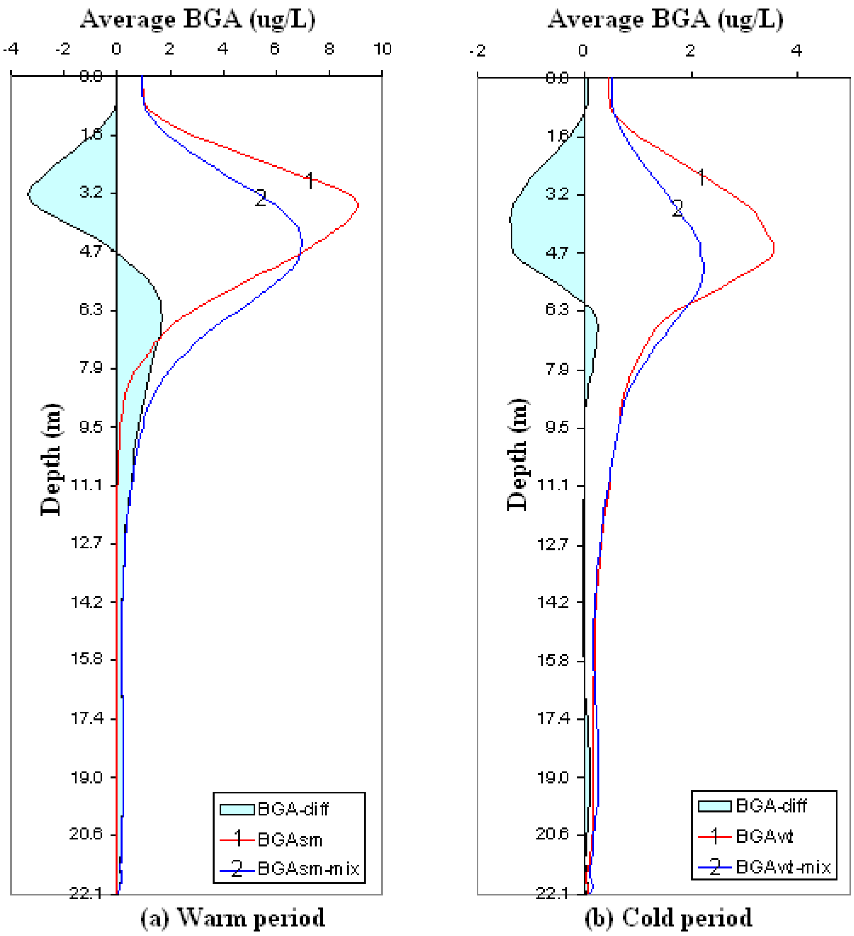



Figure 7.2 Profiles of average value of Cyanobacteria through water column with and without mixers in Cooby reservoir during warm and cold periods.

During the cold period, the surface mixers achieve a better result with controlling cyanobacterial concentrations. The mixers reduce the average cyanobacterial concentration from about one metre below the surface to a depth of 6.0 m. The mixers are able to reduce the algal concentrations by a maximum of 1.3 μg $L^{-1}$ in the epilimnion (Figure 7.2b).

Cressbrook reservoir displays a similar pattern in the probability of occurrence profile of cyanobacterial levels in Cooby reservoir. The highest concentration of algae can be found at the epilimnion area. High and moderate levels of algae in the epilimnion layer are much more common during the warm period than during the cold period while the concentration in the hypolimnion is considerably lower than the concentration in the epilimnion layer.

Figure 7.3 displays the simulated cyanobacterial profiles through the water column. Four profiles are given to represent warm and cold periods with and without mixers in Cressbrook Reservoir. Cyanobacterial levels are again classified into four categories; safe, low, moderate and high levels.

During the warm period, a high algal level (equivalent to alert level 3) can be found in the epilimnion layer to about 10 m below the water surface. The maximum probability of occurrence of this algal state is about 58 per cent at 6 m depth as shown in Figure 7.3(a).

Moderate and low cyanobacterial states can occur at greater depths. The occurrence of the high cyanobacterial state in the epilimnion layer is a consequence of a suitable growth environment and particularly the availability of solar radiation. Solar radiation can penetrate to a depth of 10 m. Reduced radiation levels at 10 – 15 m below the water surface decreases the cyanobacterial concentration at these depths.

The cyanobacterial cells during the cold period are also concentrated in the surface 5 metres of water although there is reduced frequencies of moderate and high algal states. A low level of Cyanobacteria is found throughout the water column as presented in Figure 7.3(c). The surface mixers appear not to reduce the high cyanobacterial states in the epilimnion layer and they may even create more opportunity for Cyanobacteria to grow in the deeper layers. Figure 7.3(b) shows the presence of low levels of Cyanobacteria to a depth of 39 m below the surface, which does not occur in the absence of mixers.

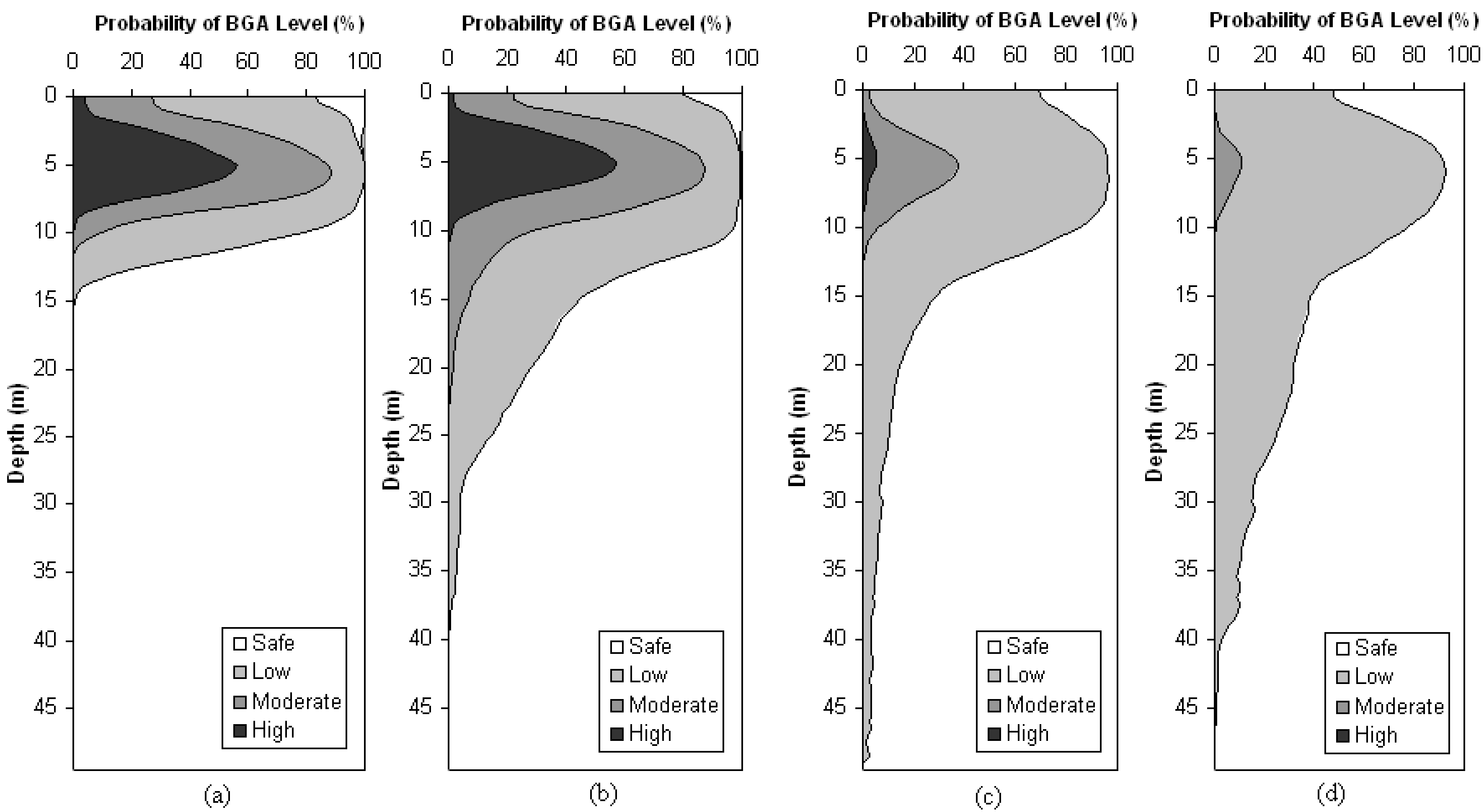



Figure 7.3 Probability occurrences of Cyanobacterial levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

The artificial mixers do upgrade overall water quality in the epilimnion layer by reducing the average cyanobacterial concentrations by up to 1.5 μg $L^{-1}$ (from surface to 7 m depth) during the warm period. However, the quality of water declines in the layer below 7 m depth. This is indicated by an increase in the average cyanobacterial concentration of up to 2.3 μg $L^{-1}$ as shown in Figure 7.4(a).

During the cold period, the surface mixer reduces the average Cyanobacteria concentration to a depth of 13.5 metres by up to 2 μg $L^{-1}$.

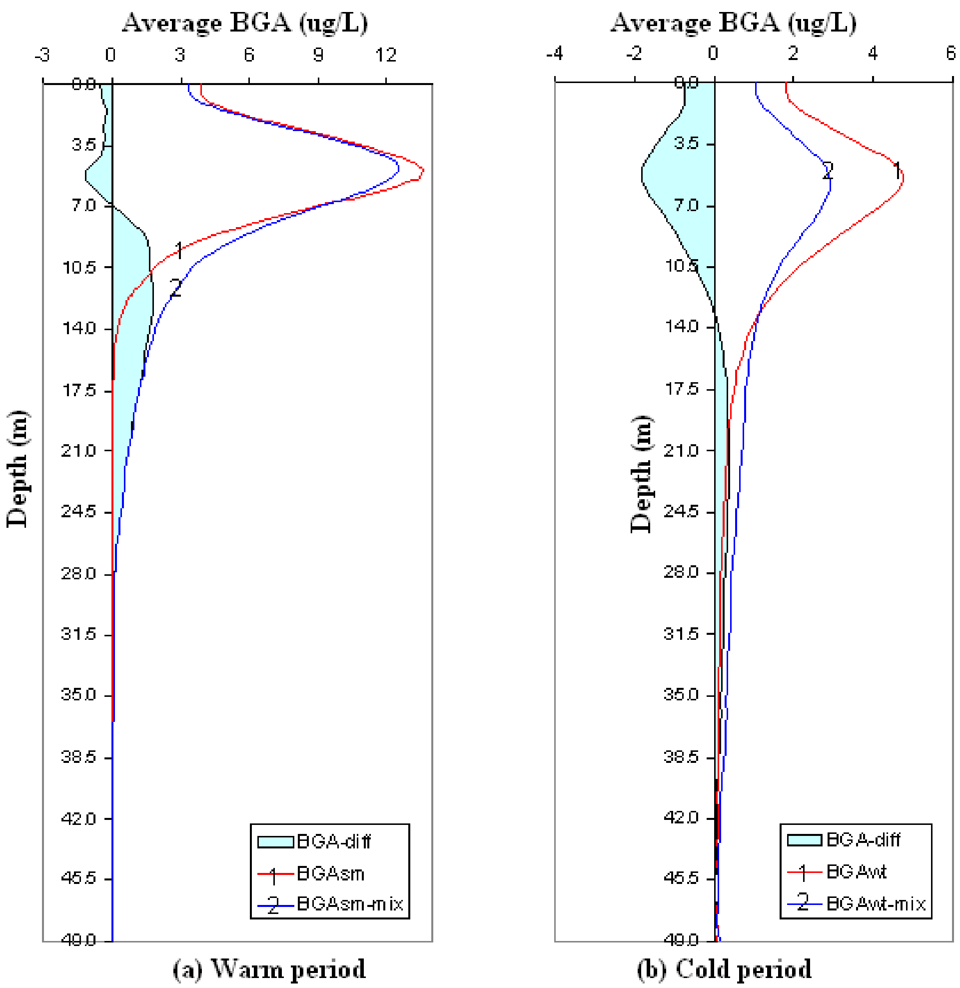



Figure 7.4 Profile of average value of Cyanobacteria through water column with and without mixers in Cressbrook reservoir during warm and cold periods.

### *7.2.2 Dissolved oxygen*

Desirable dissolved oxygen (DO) levels are based on the requirements of aquatic life. Most aquatic organisms will survive with a level of oxygen concentration from 4 to 8 mg $L^{-1}$. This range is categorized as “fair”. An oxygen concentration below 4 mg $L^{-1}$ represents a “poor” condition, which can include water that has become anoxic through oxygen depletion. Dissolved oxygen concentrations between 8 and 9.5 mg $L^{-1}$ and over 9.5 mg $L^{-1}$ are classified as “good” and “very good” states, respectively.

Comparison of Figure 7.5(a) and (c) indicates that the dissolved oxygen concentration in Cooby storage is lower during the warmer period of the year. The quality is very good for the majority of time during the cold period. In the warmer period it tends to be good near the surface but fair or poor at depth At 17 m depth, there is 40 per cent probability of poor quality water during the warm period but less than during the cold period. The epilimnion layer always has good or fair quality water (with respect to DO) when the reservoir is stratified. The thermocline at a depth of 4.7 m prevents oxygen circulation into the hypolimnion layer (Achmad & Porter 2004). This causes oxygen depletion in the lower layer as shown in Figure 7.5(a). The water circulation during turnover improves the DO state throughout, and particularly in the hypolimnion. Figure 7.5(c) shows that good and very good states of DO are always achieved from the surface to a depth of 9.5 m, and present for about 90 per cent of the time in the layer below the depth of 9.5 m.

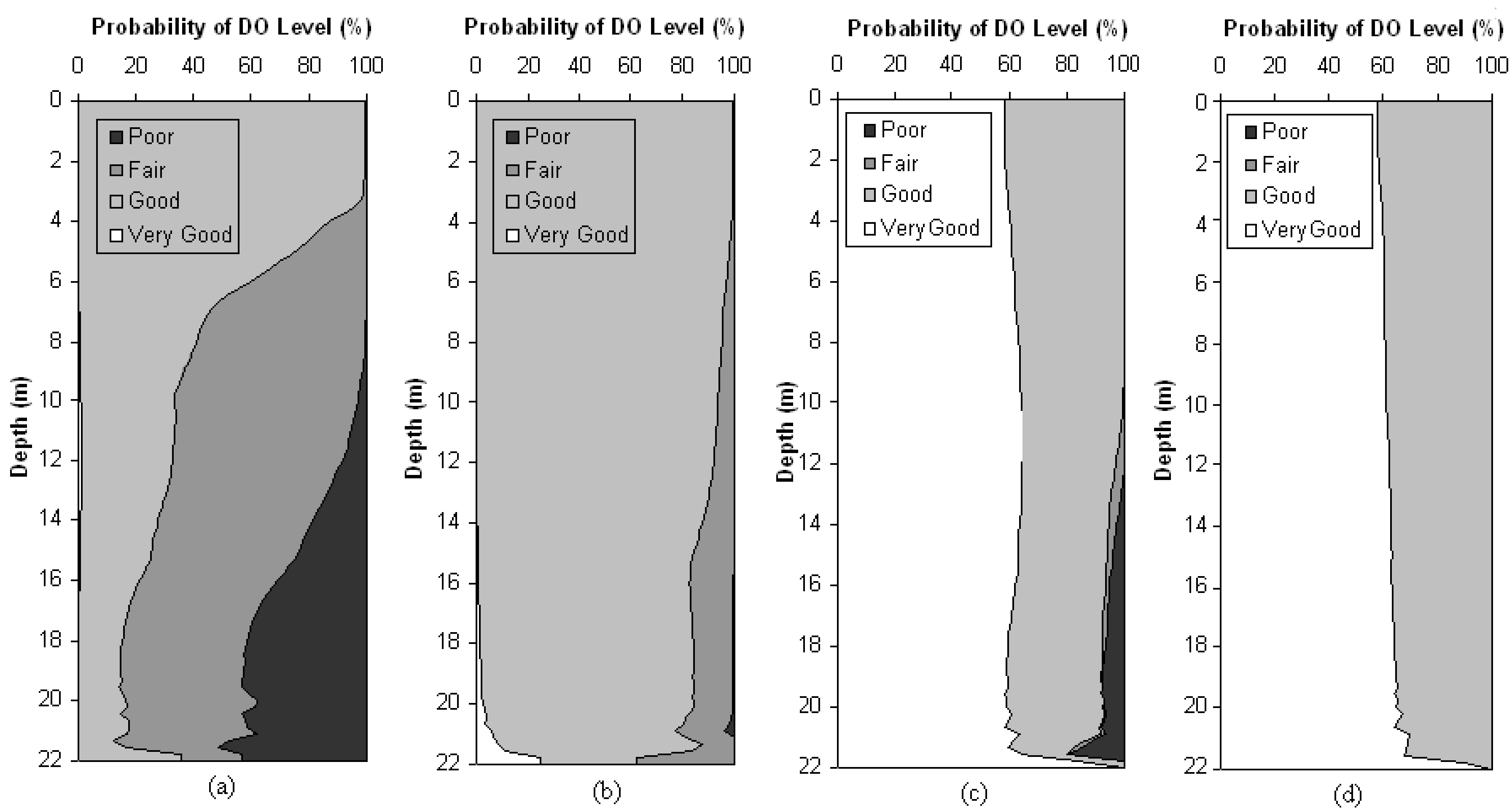



Figure 7.5 Probability occurrences of dissolved oxygen levels in Cooby reservoir (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

Figure 7.5 shows that a couple of artificial mixers improved the dissolved oxygen states at all times of the year. During the warm period there is a less than 5 per cent chance of experiencing poor quality water. There is more than an 80 per cent chance of getting good quality DO in all layers of the reservoir. The results shows that the mixers circulate oxygen through the thermocline down to the bottom of the reservoir. In the absence of the thermocline during the cold period, the mixers successfully raise DO levels to at least a good state and remove the possibility of poor levels of DO through profile. Probability of occurrence of a very good DO state is on average 60 per cent with the remaining time experiencing a good DO state.

Profiles of average DO values in Cooby dam during warm and cold periods are presented in Figure 7.6 to supplement the probability information in Figure 7.5.

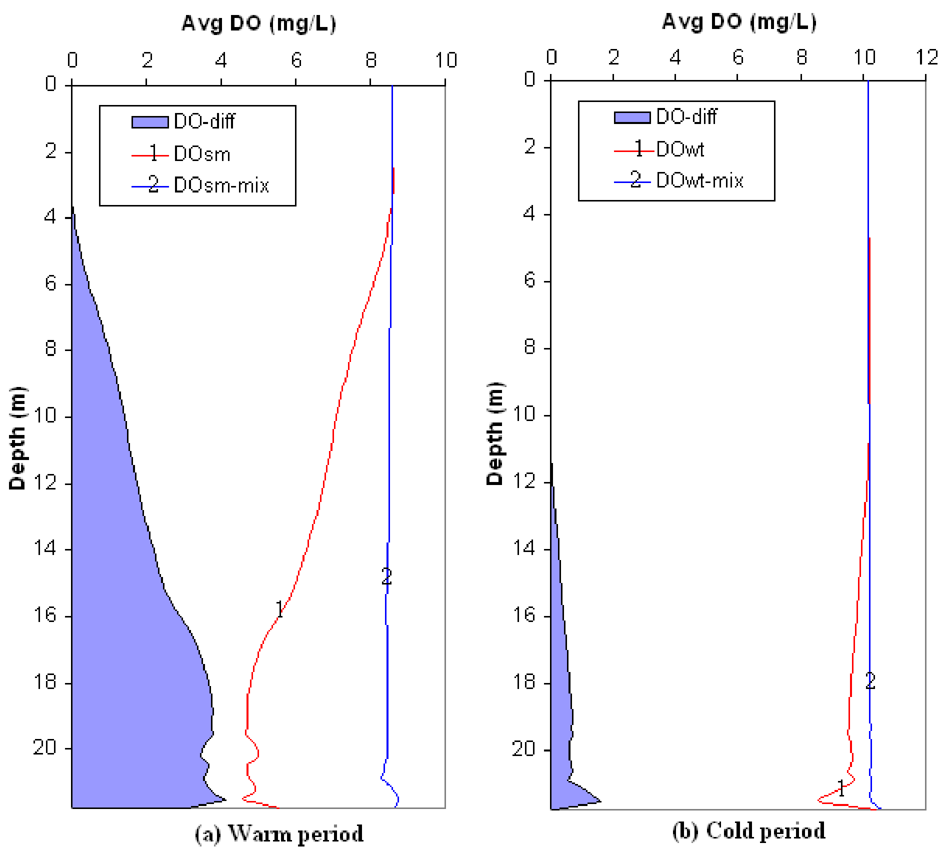



Figure 7.6 Profiles of average value of dissolved oxygen through the water column with and without mixers in Cooby reservoir during warm and cold periods.

Figure 7.6(a) illustrates the improvement in average DO concentrations through the water column as a result of mixing during the warm period. It proves the capability of the mechanical destratifiers to create a better DO environment when the reservoir is stratified (the warm period). The mixers improve the oxygen status from about 4 m depth to the bottom of the reservoir. A large improvement of up to 4 mg $L^{-1}$ can be found in the hypolimnion layer. As a result, the average DO concentrations rise above 8 mg $L^{-1}$.

As the reservoir cools (the cold period), the process of mixing in the reservoir occurs due to the natural energy of wind. The result is better aeration throughout the water column. Figure 7.6(b) shows that the artificial mixers improve DO concentrations by less than 1 mg $L^{-1}$ under these conditions. The mixers do not then make a significant improvement to the DO in the reservoir.

Cressbrook dam behaves differently to Cooby, because it is much deeper. Bowie et al. (1985) compare reaeration coefficients at various depths in water bodies. They found that the coefficient has a negative correlation with the depth. For deep-storage reservoirs, the natural process of aeration is unable to circulate oxygen from the surface to the bottom of the water body (Weitzel 1997; Wetzel 2001). In most cases, DO levels at the bottom of deep reservoirs are very low where the aeration and circulation is poor (Wetzel 2001). Cressbrook reservoir exhibits this problem with DO levels in the hypolimnion layer dropping below 4 mg $L^{-1}$.

The presence of a thermocline at 11 m below the surface in Cressbrook storage prevents oxygen circulation in the storage during the warm period. Good levels of DO are only likely to occur in the epilimnion layer at that time. The probability of occurrence of good DO states decreases dramatically in the metalimnion and the hypolimnion layer.

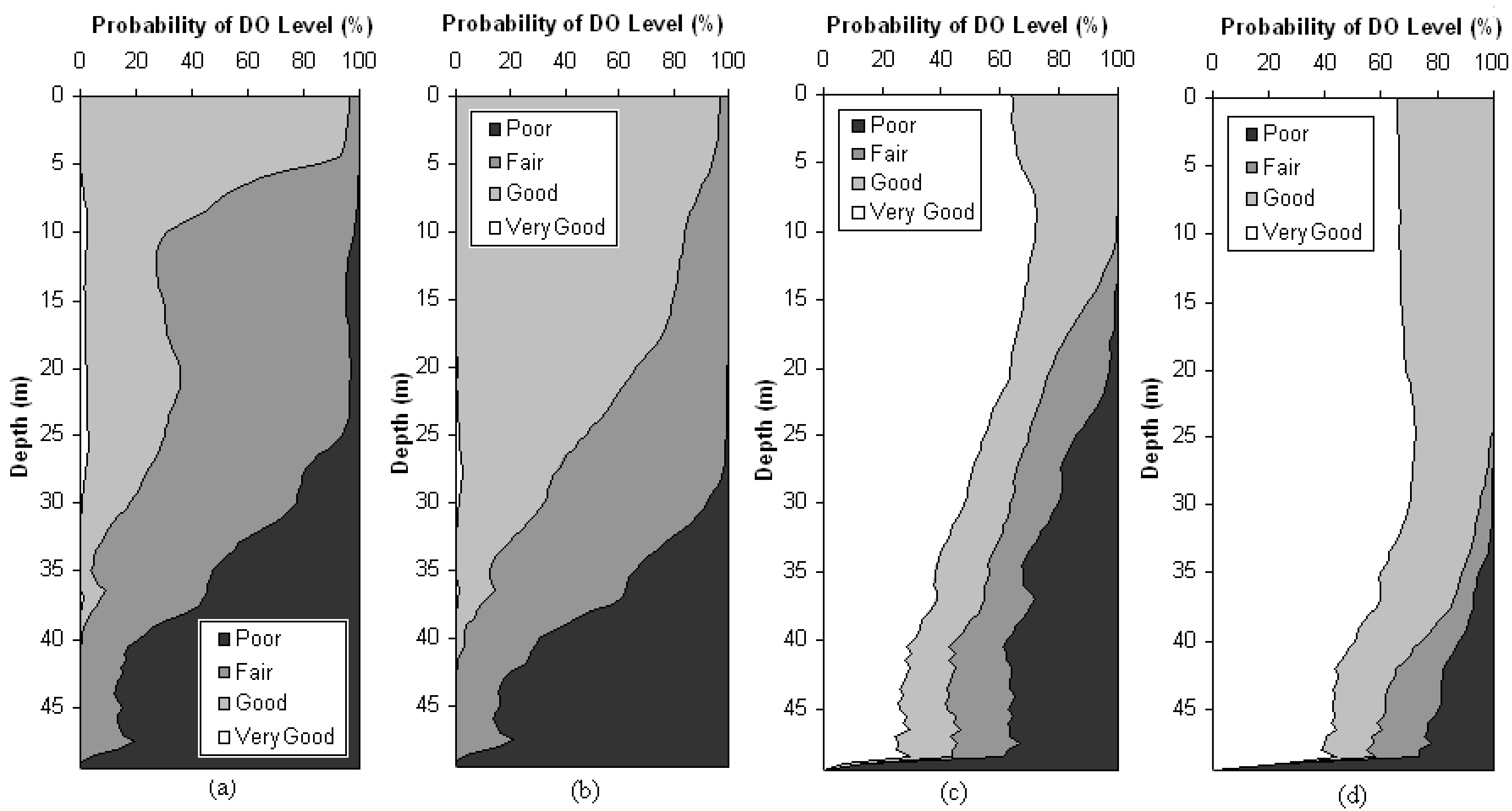



Figure 7.7 Probability occurrences of dissolved oxygen levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

At a depth of 40 m, for example, there is an 83 per cent probability that the DO will be below 4 mg $L^{-1}$ at any one time. Artificial mixers would change the DO profile in the water column by pushing the thermocline down to about 17 m. This promotes a greater transport of atmospheric oxygen into the storage. A comparison of DO probability profiles with and without artificial mixers during the warm period is given in Figures 7.7(a) and (b).

During the naturally mixed period, the probability of occurrence of poor DO states is less than 40 per cent except at the bottom of the reservoir. This probability gradually increases from 14 m depth to the bottom of the reservoir. Artificial mixers would again improve the level of DO in the storage. With their assistance there is less than 30 per cent probability of poor DO levels at depths of 30 – 48 m.

The average DO concentrations in the storage (see Figure 7.8) quantify the improvement that artificial mixers make to water quality in the water column, from a depth of about 5 m during the warm period. During this period, the mixers transport oxygen enriched water to depths below 5 m. This increases the concentration in the water column by up to 1.8 mg $L^{-1}$. Similarly, an improvement in oxygen status starts at 10.5 m below the water surface during the cold period. The oxygen concentrations increase by up to 2.7 mg $L^{-1}$ during this period.

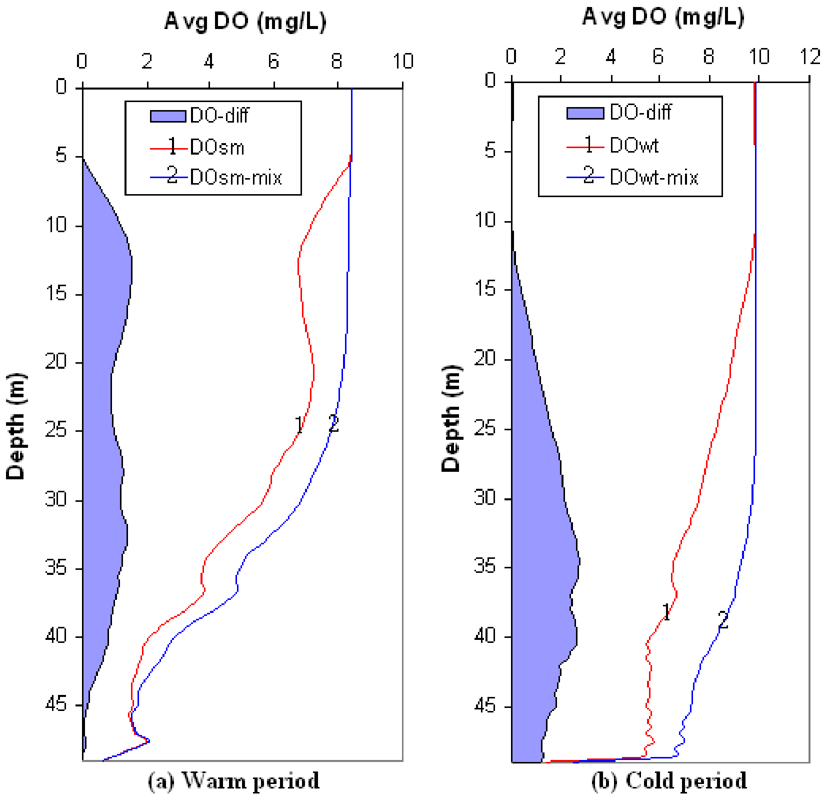



Figure 7.8 Profiles of average value of dissolved oxygen through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

### *7.2.3 Water temperature*

Temperature is monitored in most water supplies because it affects many internal processes in an aquatic environment. The chemical reaction rates used in water quality modelling depend on the temperature of the environment (Bowie et al. 1985; Romero et al. 2003). Water temperature profiles can also be used as a visual indicator of the occurrence of stratification in lakes and reservoirs (Martin & McCutcheon 1998).

Figure 7.9 shows probability of occurrence profiles for four thermal ranges in Cooby reservoir. The figure clearly shows thermal stratification during the warm period. Figure 7.9(a) shows that a water temperature higher than 19$^{o}$C will occur in the top layer of the reservoir 90 per cent of the time. The hypolimnion layer has a contrasting high probability (about 85 per cent) for water temperature below 14$^{o}$C.

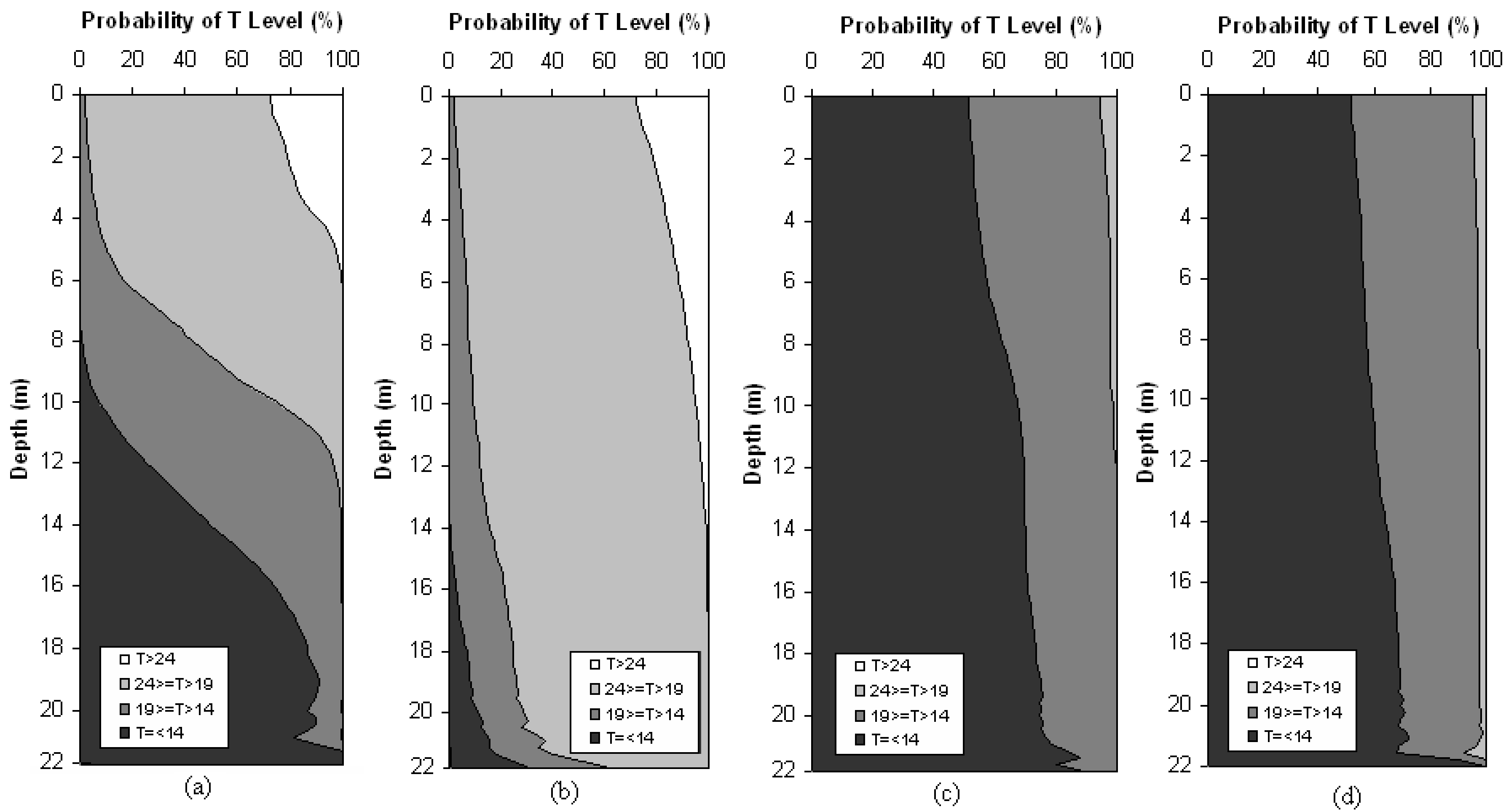



Figure 7.9 Probability occurrences of water temperature levels in Cooby reservoir (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

Artificial destratifiers break the thermocline down and transport warmer water into the hypolimnion during the warm period (Achmad and Porter 2004). The mixers change the temperature profile of the storage to create a high probability (more than 90 per cent) of water temperature above 19$^o$C. However, there is no significant difference in the temperature profile during the cold period in the reservoir. This is because the reservoir is in the natural turnover period where the stratification is weak. The probability of occurrence of a water temperature below 14$^o$C is more than 50 per cent for the entire water column while a water temperature between 10 to 24$^o$C has a probability less than 5 per cent of occurring during the cold period.

Average values of water temperature in the water column for the 50-year simulation period show the effect of mixers in both warm and cold periods (Figure 7.10). The temperature of the water from 3 m below the water surface to the bottom of the reservoir can be increased by 8$^o$C during the warm period as shown in Figure 7.10(a). Figure 7.10(b) shows no significant difference in average water column temperatures during the cold period with and without the use of artificial mixers. The mixers are able to increase the average water temperature through the water column by only about 1$^o$C.

Cressbrook reservoir is always stratified during the warm period. Warm water is dominant in the epilimnion layer while the hypolimnion (15 m below water surface) is dominated by water temperatures below 14$^o$C as shown in Figure 7.11(a). The thermocline (metalimnion) layer lies between 7 m and 17 m below the water surface. The mixers reduce the probability of stratification to just about 85 per cent (see Figure 7.11(b)). The thermocline still exists but tends to be further below the surface (18 – 32 m) than it is without mixers.

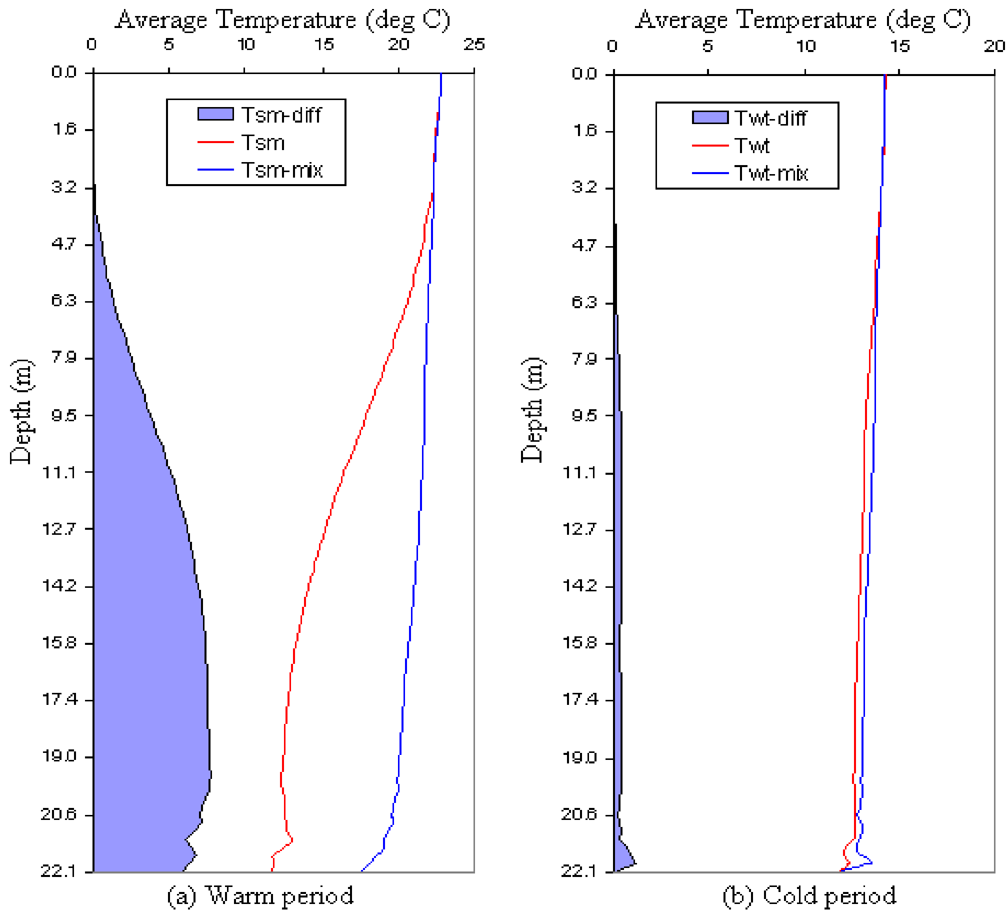



Figure 7.10 Profiles of average value of water temperature through the water column with and without mixers in Cooby reservoir during warm and cold periods.

Figure 7.11(c) shows that the probability of occurrence of water temperatures below 14°C during the cold period is about 40 per cent in the epilimnion and 100 per cent in hypolimnion layers. The artificial mixers are able to reduce the probability of occurrence of low temperatures in the hypolimnion layer. The mixers have no effect on the probabilities in the epilimnion layer (from surface to the layer 7 m depth).

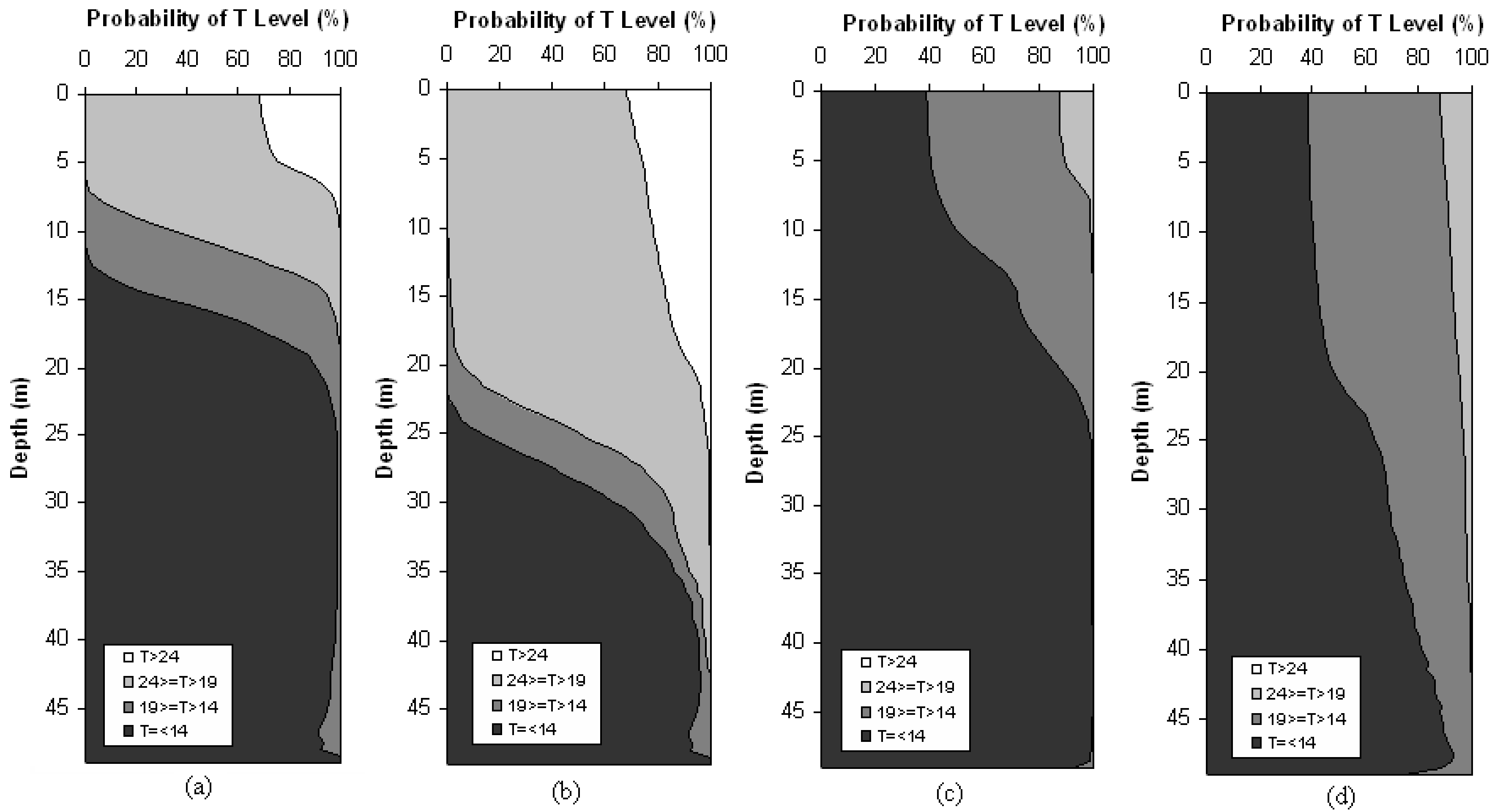
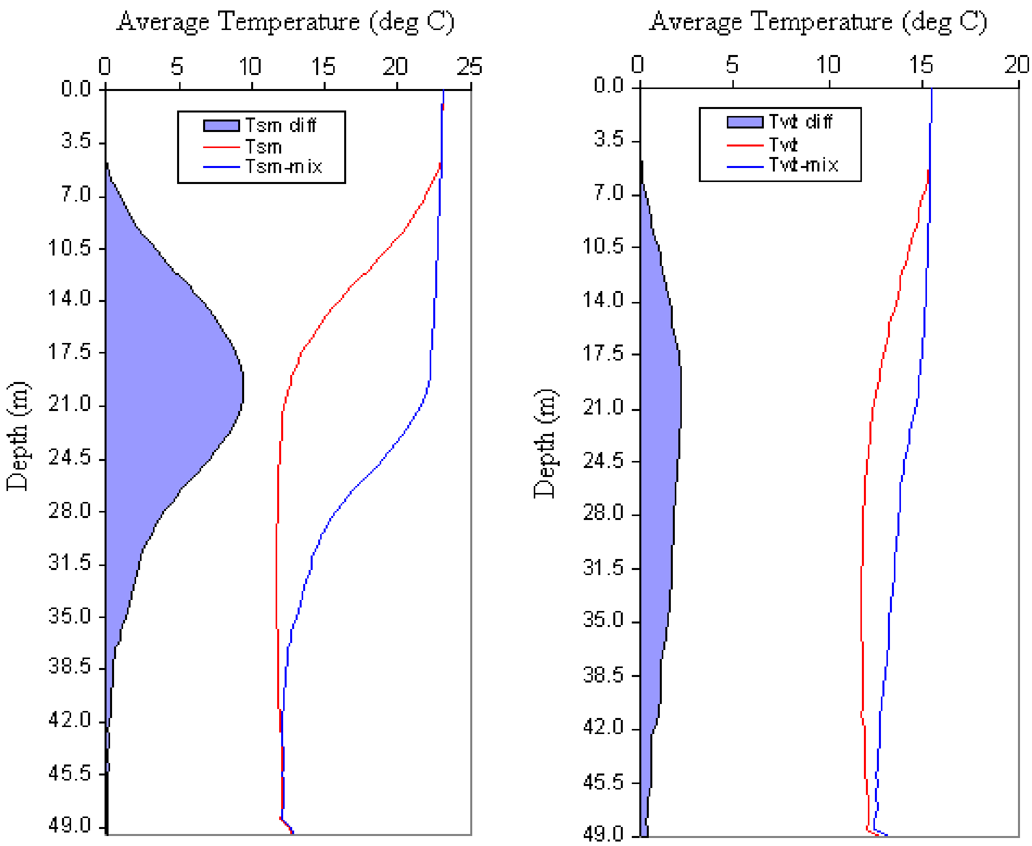



Figure 7.11 Probability occurrences of water temperature levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

The effect of artificial mixers during the warm and cold periods has also been assessed by comparing the average water temperature in the water column with and without artificial mixers as shown in Figure 7.12. The mixers introduce warm water to the middle layer of the water column. During the warm period, the mixers introduce warm water between 5 m and 43 m depth. The temperature at 20 m depth shows the highest impact of the mixers, with a temperature increment of 10°C.




(a) Warm period (b) Cold period

Figure 7.12 Profiles of average value of water temperature through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

During the cold period, the average water temperature profile in Cressbrook storage ranges from about 11°C to 16°C. The destratifiers increase the average water temperature by 2.5°C, from 5 m depth to the bottom of the reservoir.

### *7.2.4 Nitrate ($NO_3$)*

Nitrate in a reservoir influences the growth of most aquatic creatures. This nutrient affects the competitive capability of Cyanobacteria. Vollenweider (1968) determined that the ratio between nitrogen concentration and other chemical substances such as phosphorus and carbon plays a significant role in cyanobacterial growth in water bodies.

Four states of nitrate concentration were established in this study as follows:

- $NO_3 \leq 0.5$ mg $L^{-1}$,
- 0.5 mg $L^{-1}$ < $NO_3 \leq 1.0$ mg $L^{-1}$,
- 1.0 mg $L^{-1}$ < $NO_3 \leq 2.0$ mg $L^{-1}$, and
- $NO_3 > 2.0$ mg $L^{-1}$.

These states were developed from the significance of nitrate concentrations in multi-purpose reservoirs. The EPA Queensland (2005) recommended a nitrate concentration below 100 mg $L^{-1}$ for optimal growth of particular species (aquaculture) in freshwater. The recommended concentration is much higher compared to recommendation for drinking water.

The greatest probability of occurrence of the highest range of nitrate (> 2 mg$L^{-1}$) in Cooby reservoir (Fig 7.13) in the warm period occurs in the hypolimnion with a value less than 2 per cent. Nitrate concentrations from 1 mg $L^{-1}$ to 2 mg $L^{-1}$ have a high probability of occurring (about 75 per cent). In the epilimnion layers, nitrate concentrations between 0.5 mg $L^{-1}$ and 1 mg $L^{-1}$ occur about 50 per cent of the time. Mixers operating in the warm period will reduce the probability of occurrence of high nitrate concentrations throughout the water column as shown in Figure 7.13(b). The low nitrate state of 0.5 mg $L^{-1}$ < $NO_3 \leq 1.0$ mg $L^{-1}$ is most common with 70 per cent probability throughout the column.

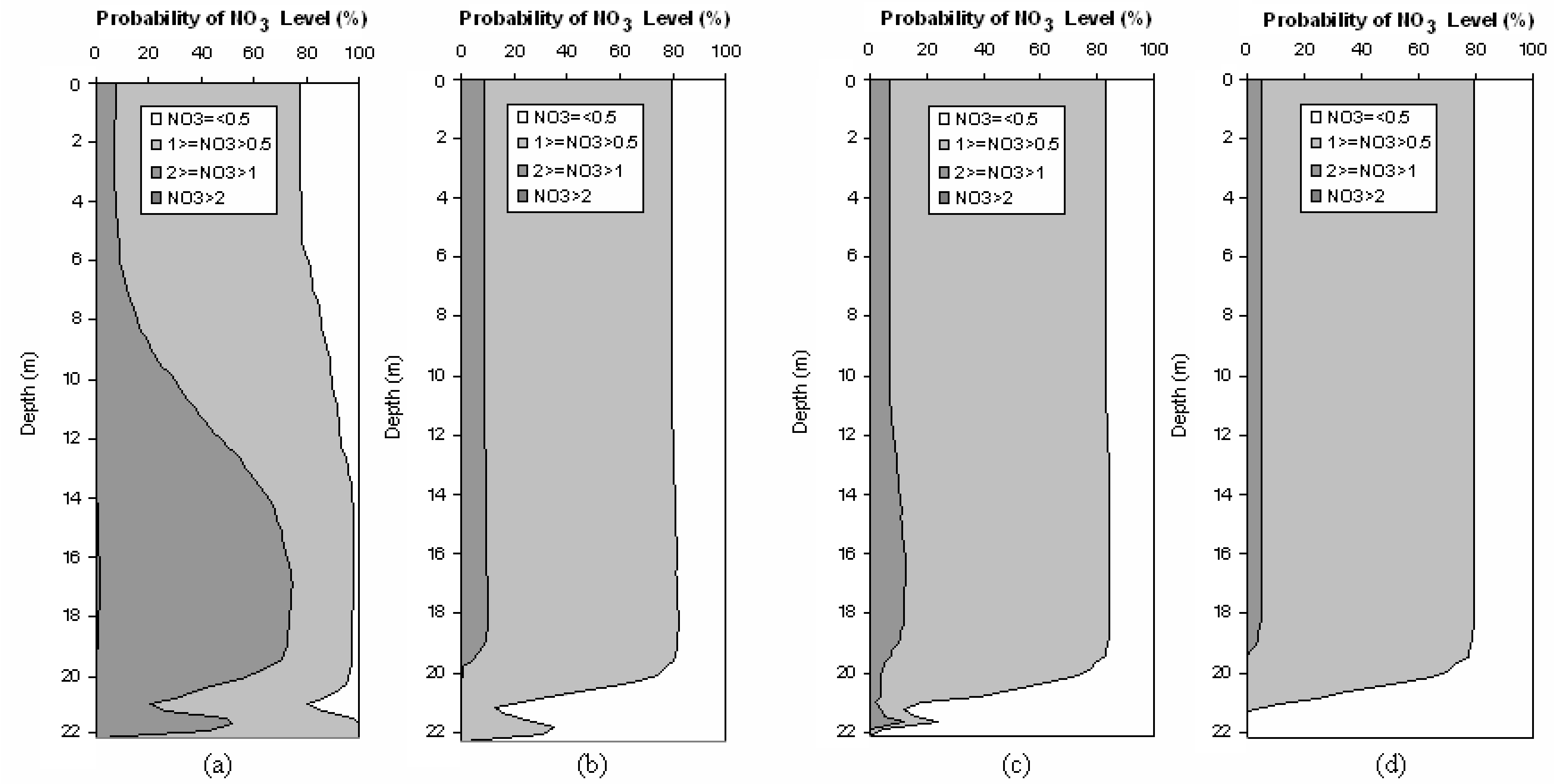



Figure 7.13 Probability occurrences of nitrate ($NO_3$) levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

Figure 7.13 also summarises the nitrate states during the cold period. The high state of 1 mg $L^{-1}$ to 2 mg $L^{-1}$ occurs about 70 per cent of the time. The mixers cause insignificant changes to the probability of nitrate levels occurring in the cold season shown in Figure 7.13(c) and (d).

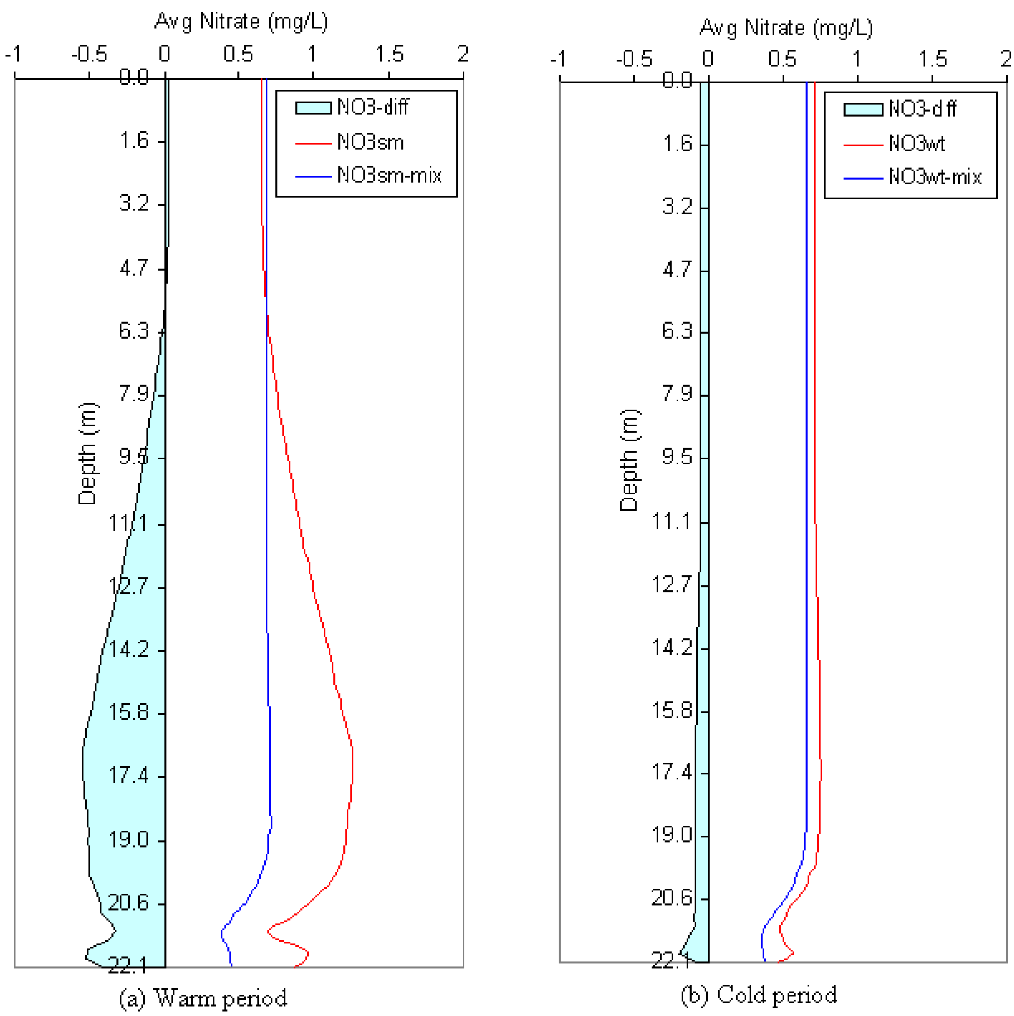



Figure 7.14 Profiles of average value of Nitrate ($NO_3$) through the water column with and without mixers in Cooby reservoir during warm and cold periods.

The average concentration profiles in the water column are plotted in Figure 7.14 to demonstrate the significance of artificial mixers during the warm and cold period. Figure 7.14 shows that the mixers can reduce nitrate concentrations in the hypolimnion layer by 0.7 mg $L^{-1}$ during the warm season. The average value of nitrate concentration during the cold period is about 0.7 mg $L^{-1}$, and there is no significant effect of mixers at this time with the reduction shown at less than 0.05 mg $L^{-1}$.

In Cressbrook Dam, the probability of very high nitrate concentrations (> 2 mg $L^{-1}$) is higher to that in Cooby Dam. During the warm period, the probability is 5 per cent and 65 per cent in the epilimnion and the hypolimnion layers, respectively. Continuous operation of artificial destratifiers during this period will reduce this probability at 9 – 23 m below the water surface to about 8 per cent. A detailed comparison of the probability occurrence of nitrate levels in Cressbrook Dam with and without artificial mixers during the warm period is presented in Figure 7.15(a) and (b).

During the cold period, the probability of high nitrate level occurring is much lower than it is during the warm period. A high nitrate state of 1 – 2 mg $L^{-1}$ has about 70 per cent chance of occurring. Concentrations above 2 mg $L^{-1}$ are possible with probabilities of 40 per cent and 15 per cent respectively with and without artificial mixers. Generally, artificial mixers reduce the probability of high levels of nitrate concentration in the reservoir.

The effect of mixers on average nitrate concentrations is shown in Figure 7.16. During the warm period the mixers slightly increase the concentration in the epilimnion layer and at the bottom of the reservoir. The average concentration decreases by 0.5 mg $L^{-1}$ in the upper part of the hypolimnion layer (9 m – 32 m depth). The distribution of average nitrate concentrations in the water column during the cold period is also changed by the mixers' operation as shown in Figure 7.16.

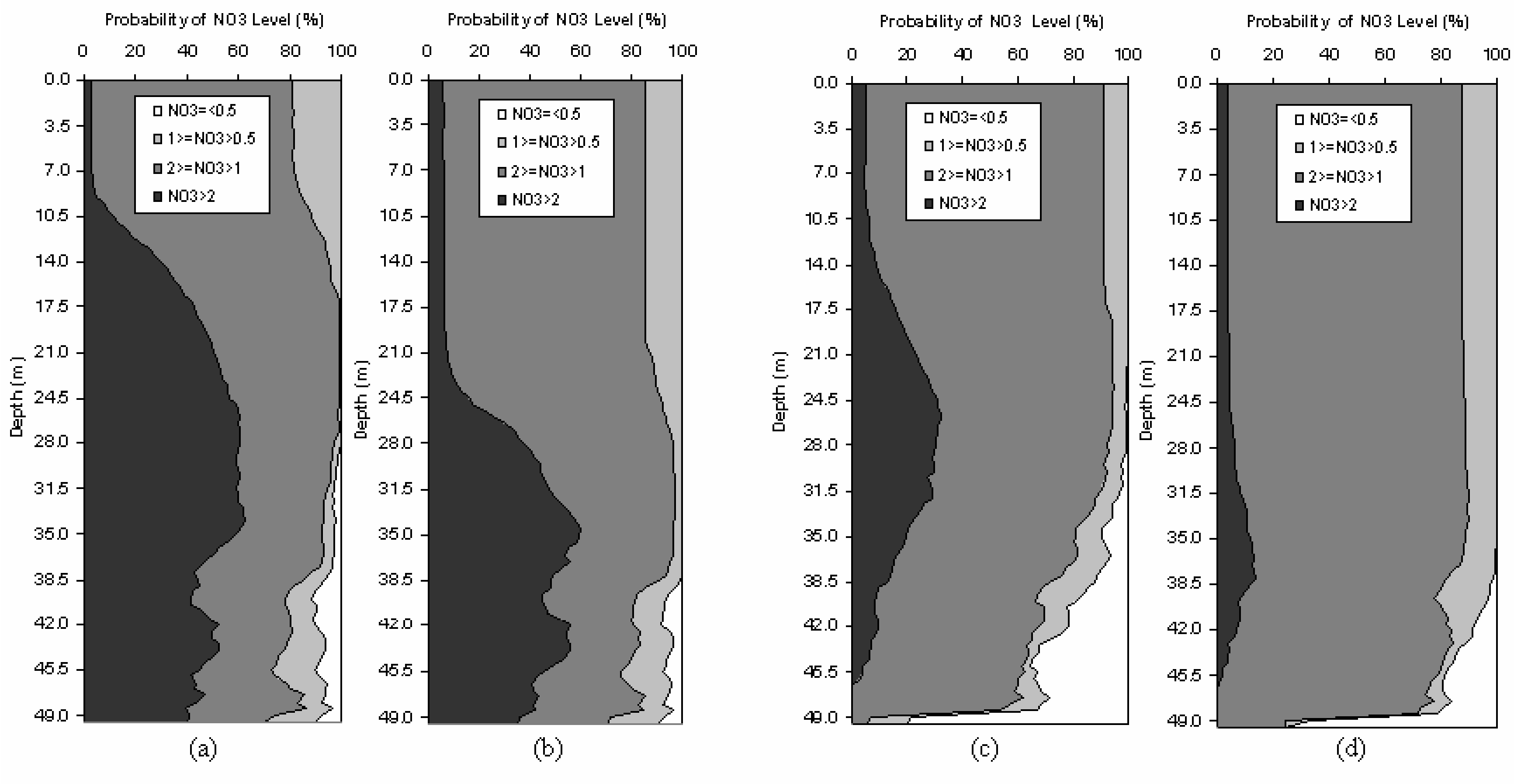



Figure 7.15 Probability occurrences of nitrate ($NO_3$) levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

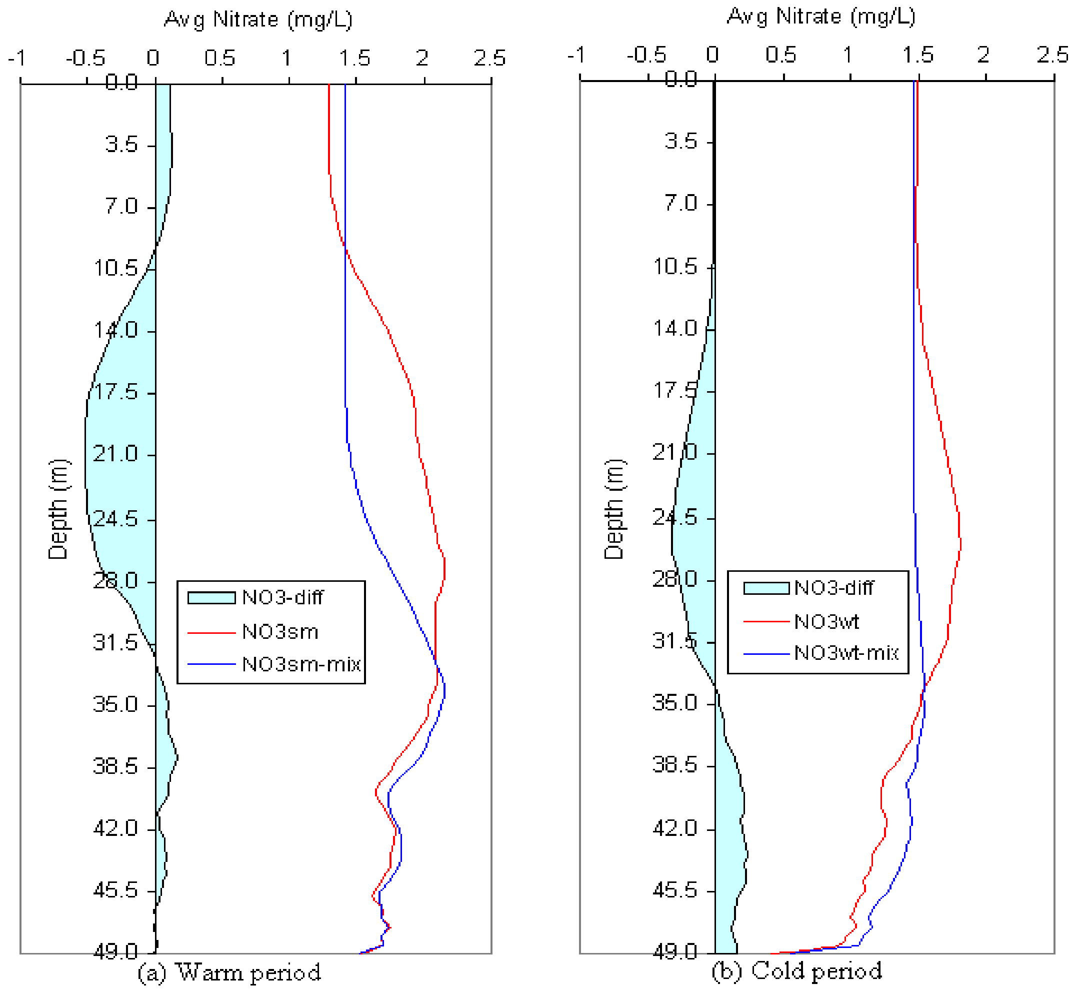



Figure 7.16 Profiles of average value of Nitrate ($NO_3$) through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

### *7.2.5 Total phosphorus*

Phosphorus is another important nutrient in a water body. It has been managed to control the cyanobacterial growth (phos-lock method) in some reservoirs (Florida LAKEWATCH 2000; Sas 1989). Reducing the sediment phosphorus load to water column can starve the cyanobacterial of nutrient (Department of Land and Water Conservation NSW 2002).

Total phosphorus concentrations were classified into four states which are: very low ($TP \leq 0.05$ mg $L^{-1}$), low (0.05 mg $L^{-1}$ < $TP \leq 0.10$ mg $L^{-1}$), high (0.10 mg $L^{-1}$ < TP

$\leq 0.15$ mg $L^{-1}$), very high (TP > 0.15 mg $L^{-1}$). These states were used to simplify the presentation of probability of occurrence results for phosphorus in the water column.

A very high total phosphorus condition can only occur in the hypolimnion layer (below 9 m depth) with a probability of less than 40 per cent. In the epilimnion, low or very low total phosphorus states are always present shown in Figure 7.17(a).

The operation of mixers during this period will reduce the probability of a high level of total phosphorus in the hypolimnion. However, it increases the likelihood of very high phosphorus concentrations in the epilimnion layer. The mixers distribute the total phosphorus uniformly through the water column as clearly seen in Figure 7.17(b).

During the cold period, a low total phosphorus state is dominant through the water column (about 70 per cent of time). The highest state (TP > 0.15 mg $L^{-1}$) only occurs in the deeper layer of the reservoir with a probability of less than 20 per cent. The mixers in the storage act to distribute the total phosphorus throughout the whole water column, reducing total phosphorus concentrations in the hypolimnion. On the other hand, high state concentrations between 0.1 mg $L^{-1}$ and 0.15 mg $L^{-1}$ appear in all layers shown in Figure 7.17(d).

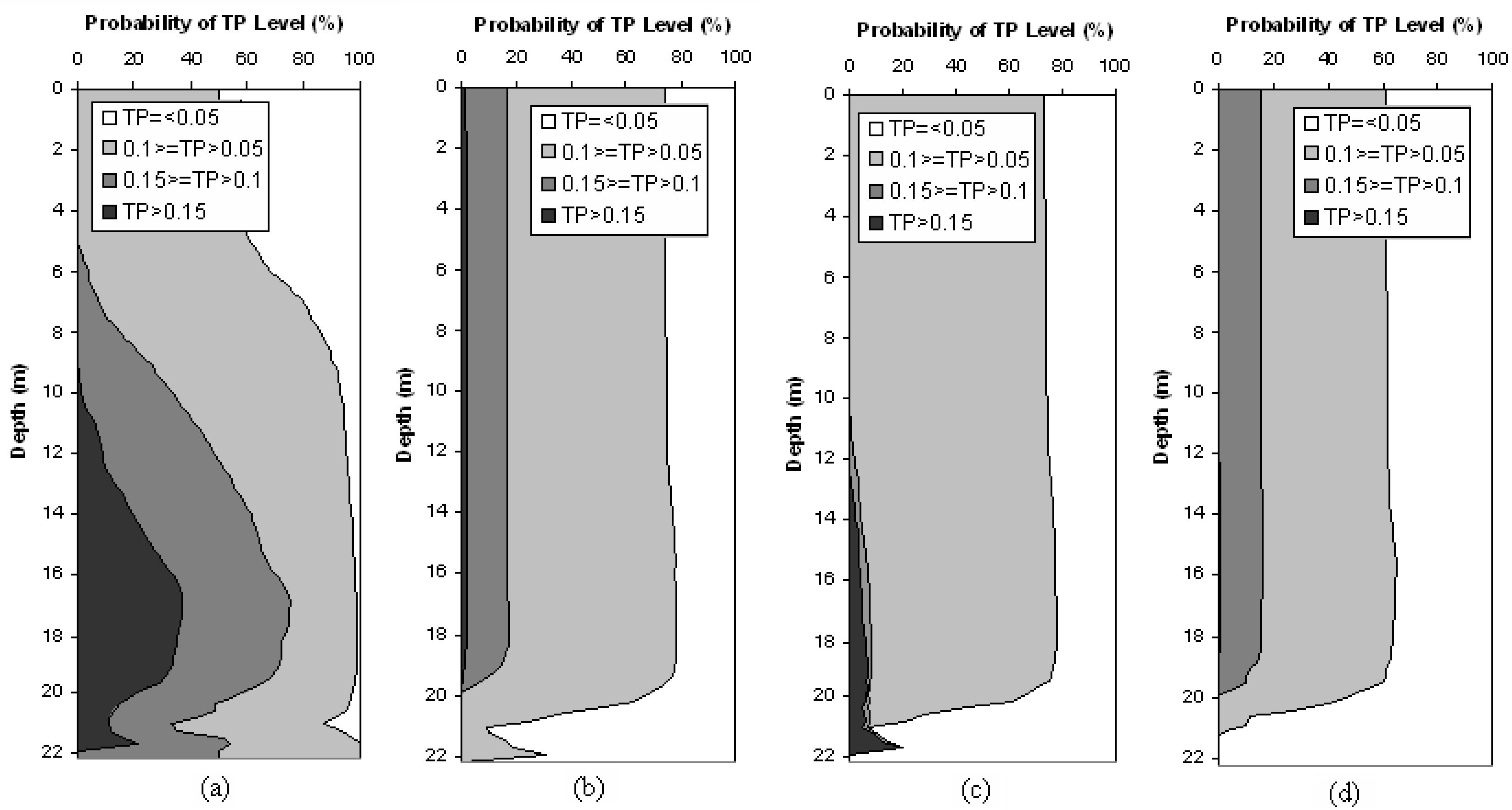



Figure 7.17 Probability occurrences of total phosphorous levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

The effect of the mechanical destratifiers is also shown by the average value of total phosphorus concentration through the water column, shown in Figure 7.18. The mixers homogenise the concentrations from the surface to their working depth. They effectively transport phosphorus from the hypolimnion to the epilimnion. As a result, the total phosphorus concentration increases in the epilimnion layer and decreases in the hypolimnion layer. The difference can be a 0.02 mg $L^{-1}$ increase in the epilimnion layer or a drop of 0.08 mg $L^{-1}$ in the hypolimnion during the warm period (see Figure 7.18(a)).

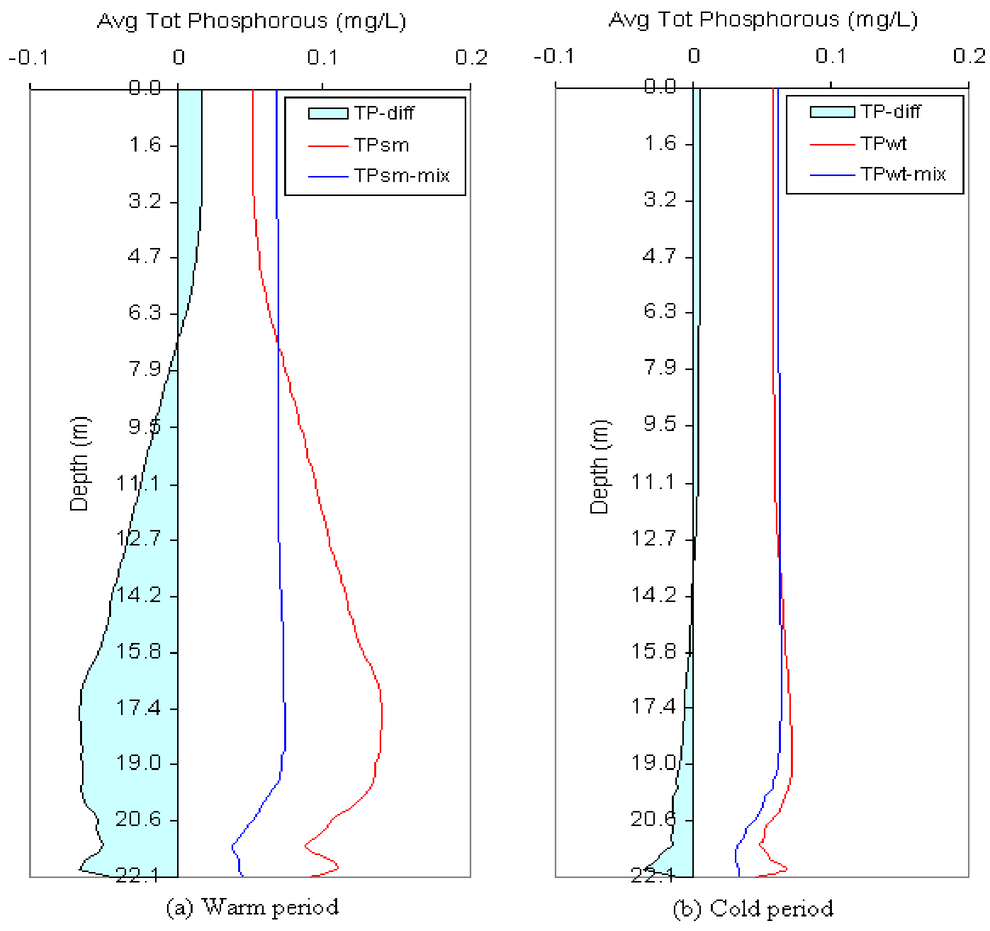



Figure 7.18 Profiles of average value of total phosphorus through the water column with and without mixers in Cooby reservoir during warm and cold periods.

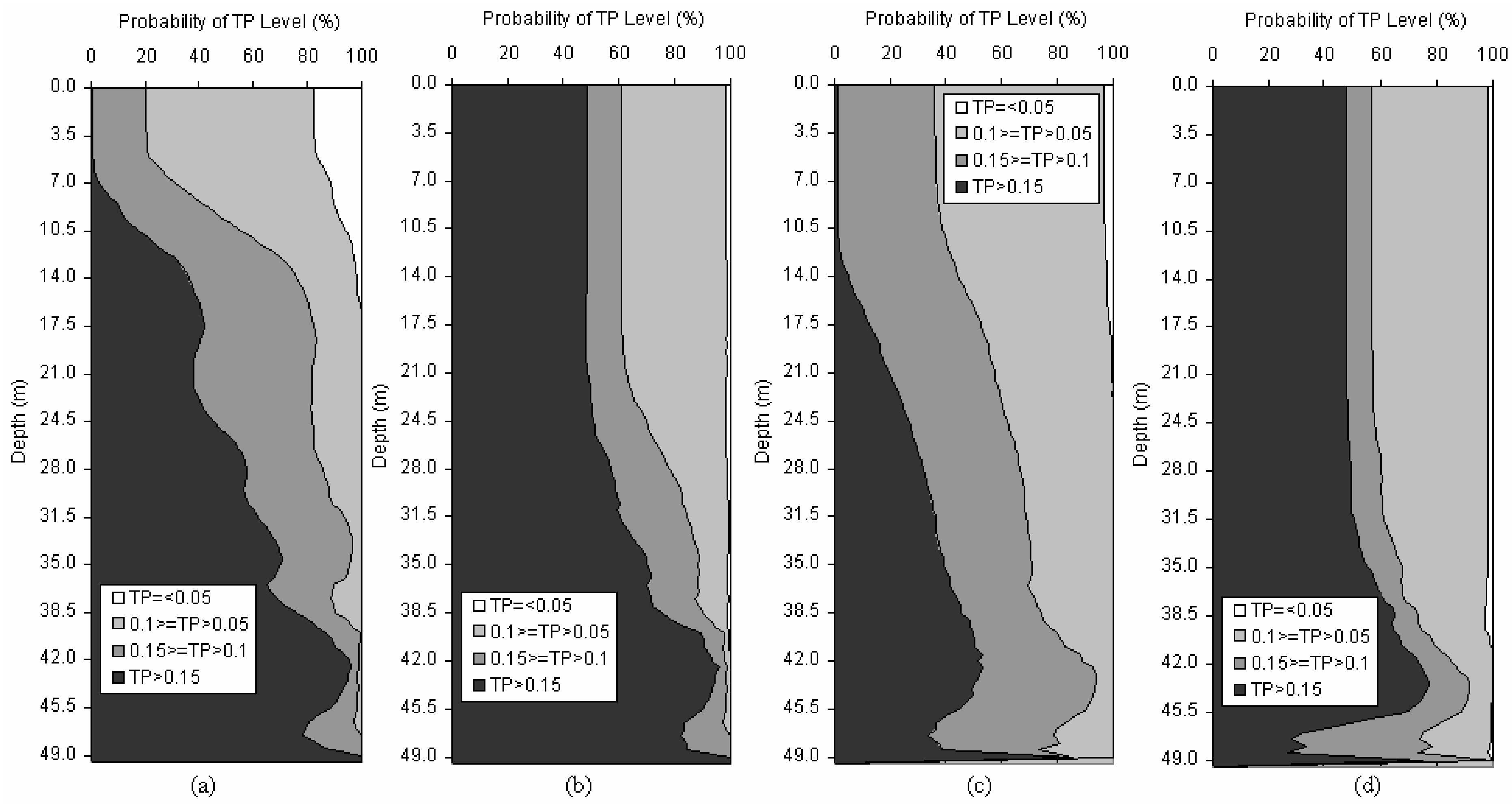
The vertical profile of time averaged total phosphorus concentrations in the storage during the cold period shows little effect from the mixers' operation. Figure

7.18(b) shows that the average concentration in the water column is less than 0.07 mg $L^{-1}$ with and without mixers operating. The mixers increase the average total phosphorus concentration by 0.01 mg $L^{-1}$ in the epilimnion and reduce it by 0.02 in the bottom layers.

The probability profiles for total phosphorus levels in Cressbrook reservoir are shown in Figure 7.19. They are quite different to that previously discussed for Cooby reservoir. The probability of very high level of total phosphorus concentration during the warm period increases dramatically from less than 1 per cent at 7 m depth to 97 per cent at 42 m depth under natural conditions. The mixers raise this probability in the epilimnion layer, as shown in Figure 7.19(a) and (b). The probability of very high level of phosphorus (TP > 1.5 mg $L^{-1}$) tends to increase in the layers from the surface to the 25 m depth with the addition of mixing energy.

During the cold period, very high concentrations (> 0.15 mg $L^{-1}$) occur in the hypolimnion layer 45% of the time, but lower states are found to a depth of 11 m for 95% of the time. The mixers increase the probability of occurrence of very high total phosphorus concentrations in the epilimnion layer to approximately 50 per cent, as shown in Figures 7.1.9(c) and (d).

Figure 7.20 summarises the effect of mixers on the time averaged total phosphorus concentration in the water column. It compares the profiles with and without mixers for both periods. The mixers increase the average total phosphorus concentration in the whole water column by up to 0.08 mg $L^{-1}$ during the warm period of the year. During the cold period, however, the mixers reduce the concentration below 28 m depth by up to 0.05 mg $L^{-1}$. However, artificial mixing increases the averaged total phosphorus concentration from the water surface to 28 m by 0.06 mg$L^{-1}$.




F Figure 7.19 Probability occurrences of total phosphorous levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

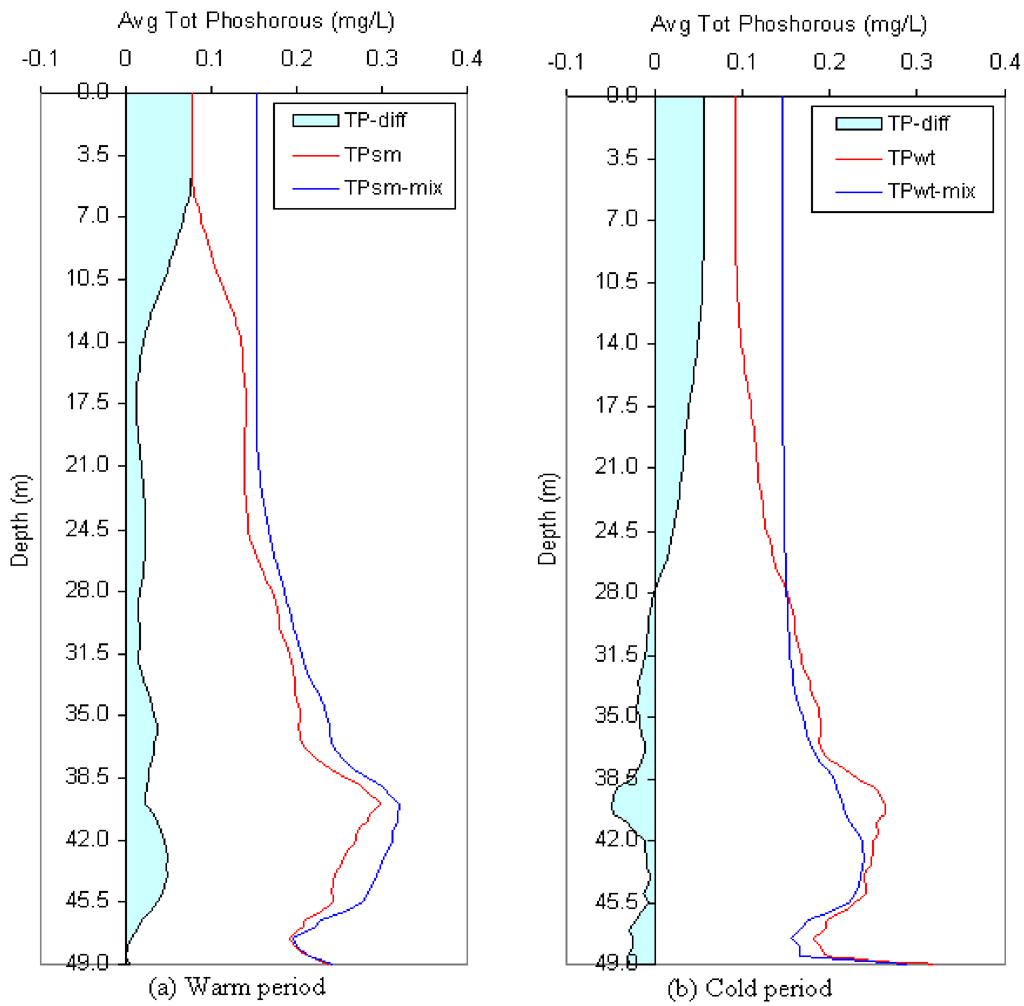



Figure 7.20 Profiles of average value of total phosphorous through water column with and without mixers in Cressbrook reservoir during warm and cold periods.

### *7.2.6 pH*

The pH of water has a significant effect on chemical transformations in water bodies (Bowie et al. 1985). In the DYRESM-CAEDYM water quality model, pH levels are used when simulating transformation processes including sediment nutrient fluxes (the change in phosphorus and ammonium concentrations in the bottom layer of the water column) and the equilibrium balance for reduced and oxidised phases of iron, manganese and aluminium (Herzfeld & Hamilton 2000).

The pH levels were classified into four levels: acidic (pH < 6.5), slightly acidic (6.5 ≤ pH ≤ 8.0), slightly alkaline (8.0 < pH ≤ 10.0), and alkaline (pH ≥ 10.0). An acceptable range for pH of water is slightly acidic (6.5 and 8.0) (EPA Queensland 2005).

The probability of occurrences for these pH levels are presented in Figure 7.21 for Cooby Dam. The desired slightly acidic pH level occurs for only about 30 per cent of the time between the water surface and 19 m depth at any time of the year, but is always present in the deepest layers of the water column. The probability of alkaline state is about 70 per cent. This pH profile is not significantly affected by artificial mixing process.

The time averaged value pH profiles are shown in Figure 7.22, confirming the lack of effect from artificial mixers on pH in the water column.

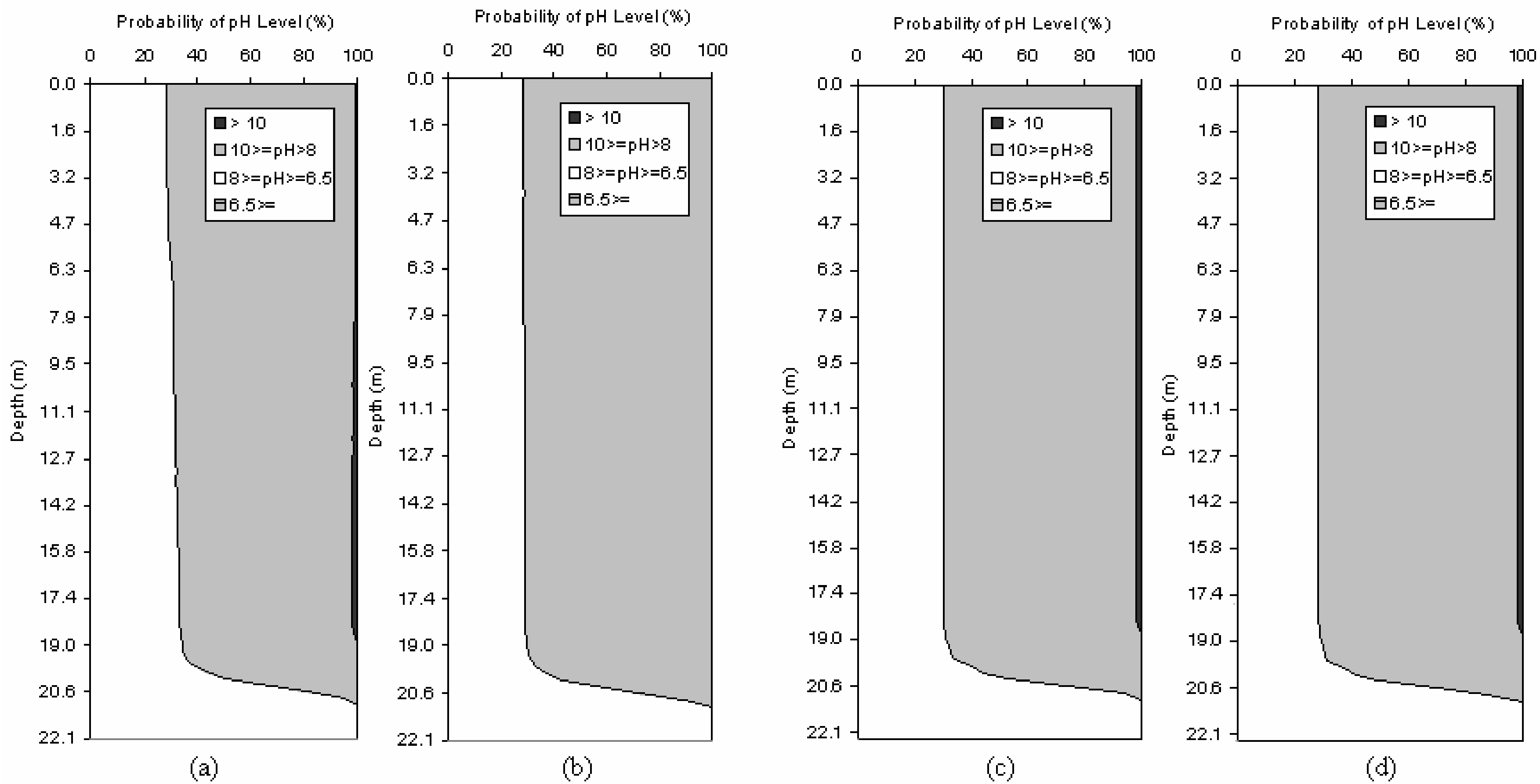



Figure 7.21 Probability occurrences of pH levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

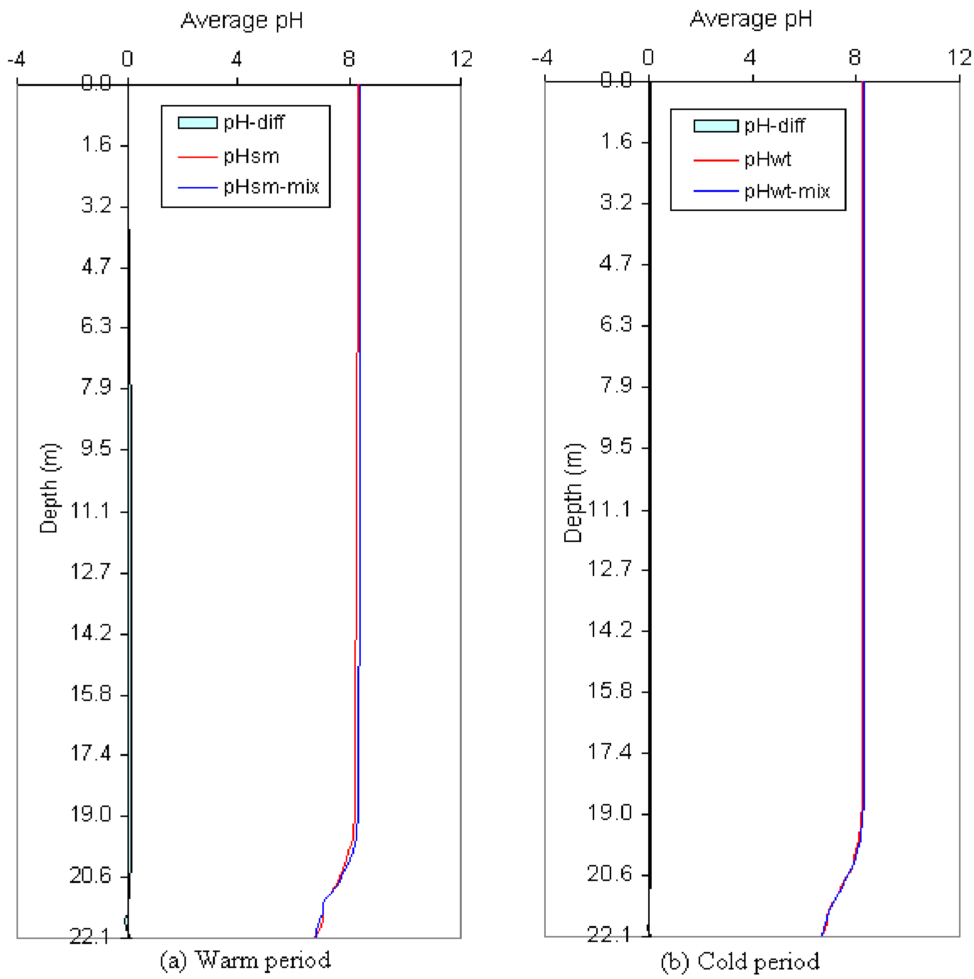



Figure 7.22 Profiles of average value of pH through the water column with and without mixers in Cooby reservoir during warm and cold periods.

The occurrence of desirable, slightly acidic water in Cressbrook Dam is less likely than in Cooby Dam. The probability of occurrence is less than 10 per cent compared to the 30 per cent in Cooby storage. Figure 7.23 indicates that slightly alkaline or alkaline water occurs most of the time with probabilities of occurrence of 70% and 20% respectively.

The operation of mixers in Cressbrook reservoir has a small effect at the epilimnion and hypolimnion layers during the warm period from November – April (see Figure 7.23(a) and (b)). The probability of an alkaline level of pH in the epilimnion layer decreases from 22 per cent to about 18 per cent with the use of artificial mixers.

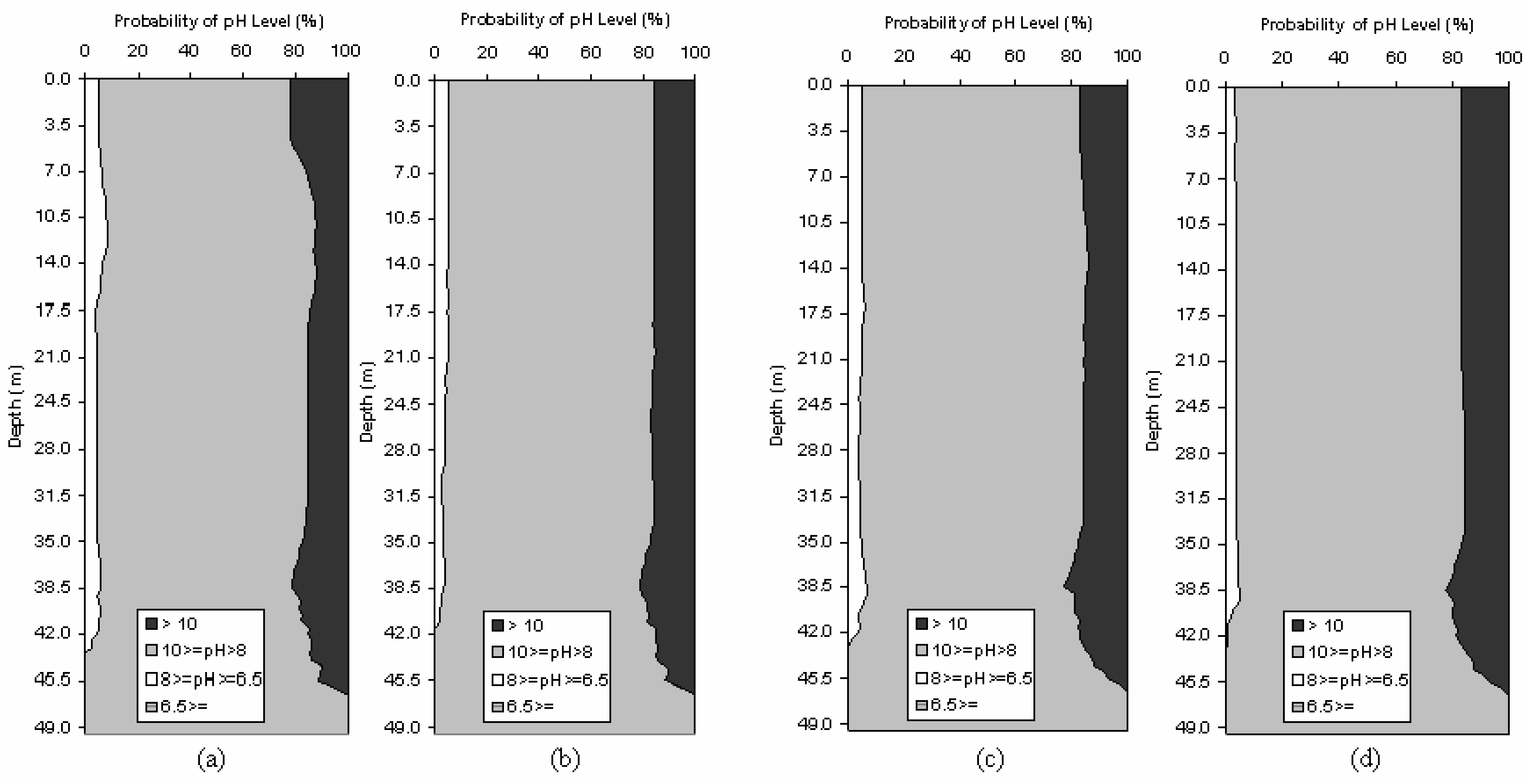



Figure 7.23 Probability occurrences of pH levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

In contrast, the mixers slightly increase the likelihood of alkaline water in the metalimnion layer (by 1 per cent). During the cold period, there is an 80% chance of slightly alkaline water occurring throughout the water body. The artificial mixers cause only a very small change in the pH levels (see Figure 7.23(c) and (d)).

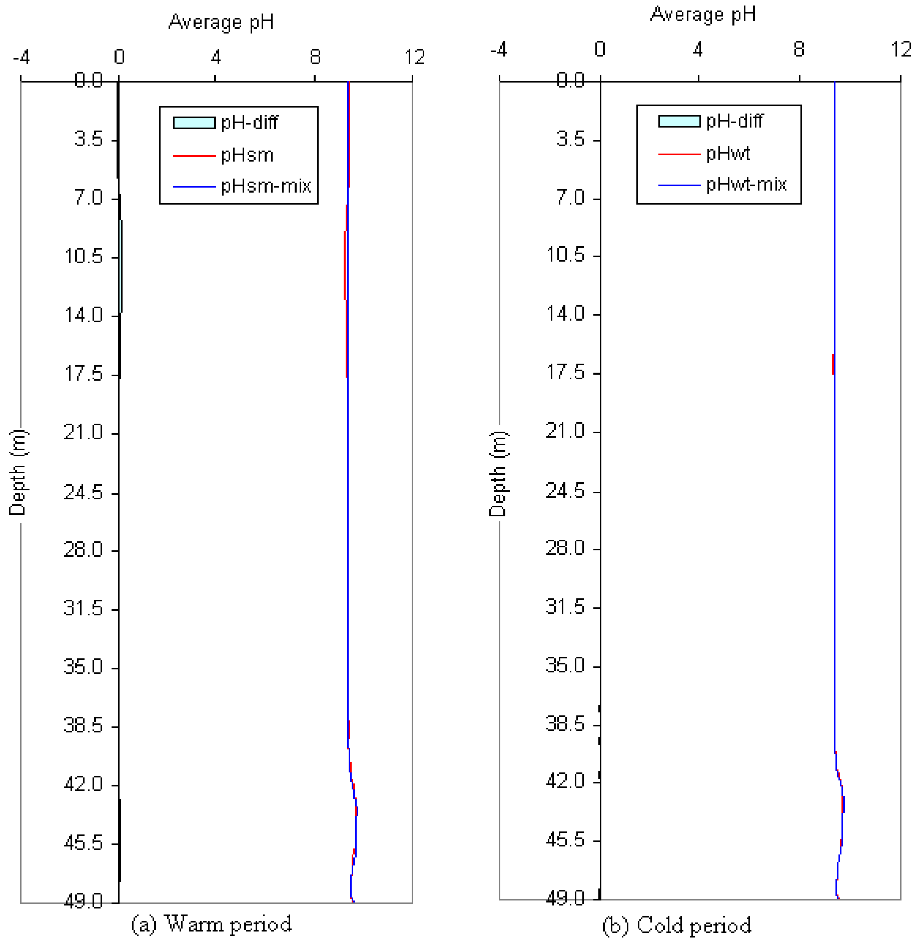



Figure 7.24 Profiles of average value of pH through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

The time averaged values of pH in Cressbrook reservoir are summarised in Figure 7.24 to show an insignificant effect of artificial mixers on pH. The pH is 9.5 from the water surface to 40 m depth. The time averaged values of pH then increase by 0.5 at layers below 40 m.

### *7.2.7 Salinity*

The salinity level of inland freshwater in Australia is not usually a major problem. For aquaculture purposes, the EPA Queensland (2005) recommends a salinity level below 5 psu. Most freshwater fish species can growth optimally in water below this value.

Historically, salinity levels in Toowoomba's storages have been lower than 1 psu. Therefore, salinity was classified into four small ranges to describe the environment in Toowoomba's reservoirs. The levels are: excellent (salinity below 0.5 psu), very good (0.5 to 0.6 psu), good (0.6 to 0.7 psu), and poor (>0.7 psu). All these levels are associated with acceptable water in multi purpose reservoirs.

In Cooby Dam, very good and good levels of salinity occur most of the time except in the bottom layers. They have probability of occurrence values of about 40 per cent and 55 per cent, respectively.

Figure 7.25(a) and (b) presents the probability profiles for salinity in Cooby storage with and without mixers during the warm period. Mixers serve to distribute the salinity from the water surface to 18 m depth, changing the probability of the two dominant levels. The probability of good levels of salinity increases in the epilimnion layer. Conversely, the probability of good salinity levels decrease in the hypolimnion layer.

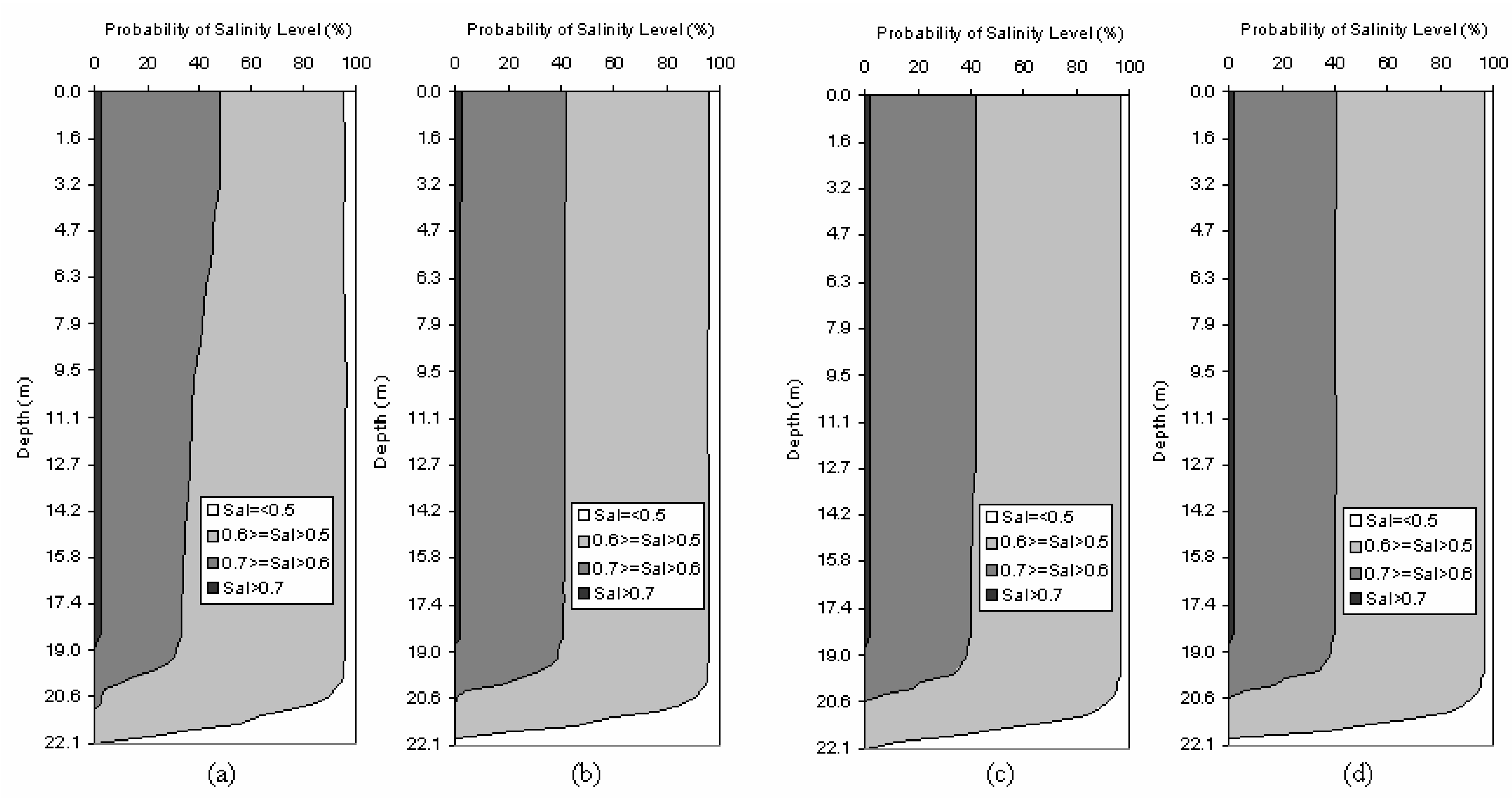



Figure 7.25 Probability occurrences of salinity levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

In the cold period, artificial mixing does not change the likelihood of different salinity levels in the water column as shown by Figure 7.25(c) and (d).

Figure 7.26 shows that the mixers do not affect the time averaged values of salinity in the reservoir. The time averaged values of salinity varies from about 0.58 psu at the water surface to about 0.47 psu at the bottom of the reservoir.

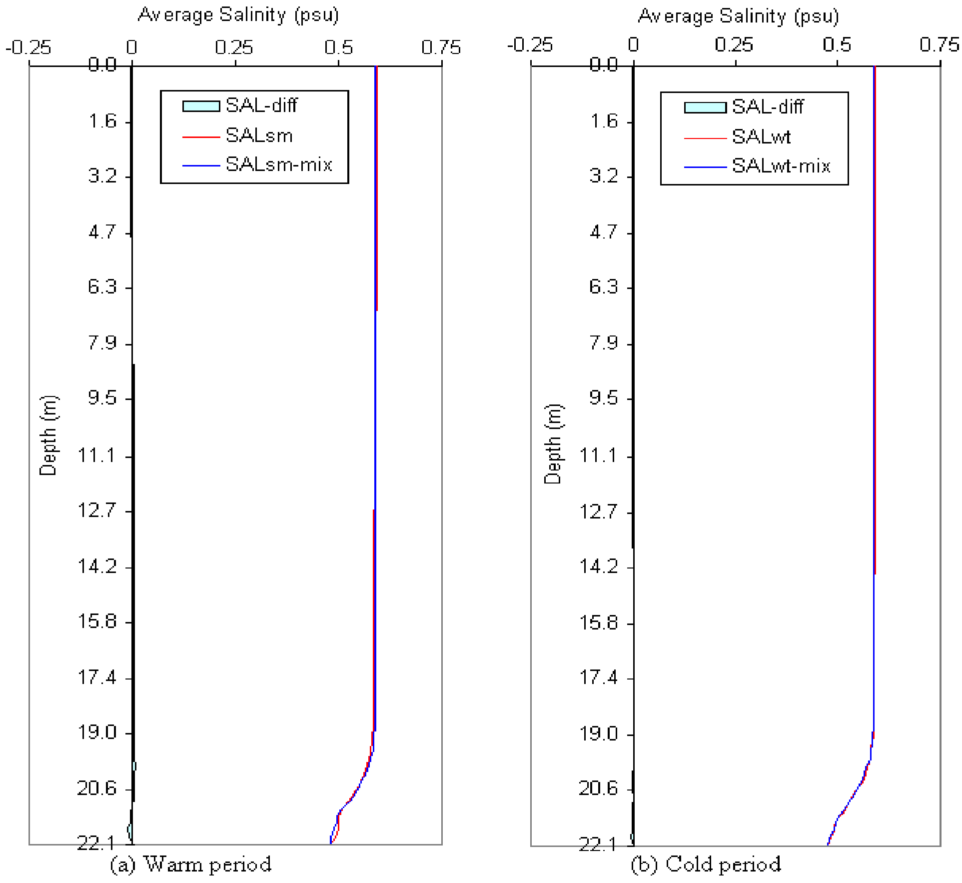



Figure 7.26 Profiles of average value of Salinity through the water column with and without mixers in Cooby reservoir during warm and cold periods.

The poor salinity levels (above 0.7 psu) are more likely to occur in Cressbrook than in Cooby storage. During the warm period, a poor salinity level occurs up to 40 per cent of the time in the epilimnion layer and about 35 per cent in the hypolimnion layer of Cressbrook Dam. The good levels occur from the water surface to a depth of 34 m for almost 40 per cent of the time.

The artificial mixers decrease the probability of occurrence of poor salinity levels to about 30 per cent from the water surface to 34 m depth during the warm period. During the cold period, good and poor salinity levels occur for almost 80 per cent of the time. The salinity probability profile is slightly different with the use of the mixers. Poor salinity levels, for example, are 4 per cent less likely to occur when using the mechanical mixers as shown in Figure 7.27(d).

Figure 7.28 presents the time averaged salinity concentration profiles. It shows that the averaged salinity concentration in the epilimnion layer is 0.65 psu. The averaged salinity concentration below 8 m depth during the warm period is 0.015 lower than the averaged concentration in the epilimnion layer of Cressbrook reservoir. Any artificial mixing in the storage only affects a part of the epilimnion layer (water surface to the depth of 8 m) as shown in Figure 7.28(a).

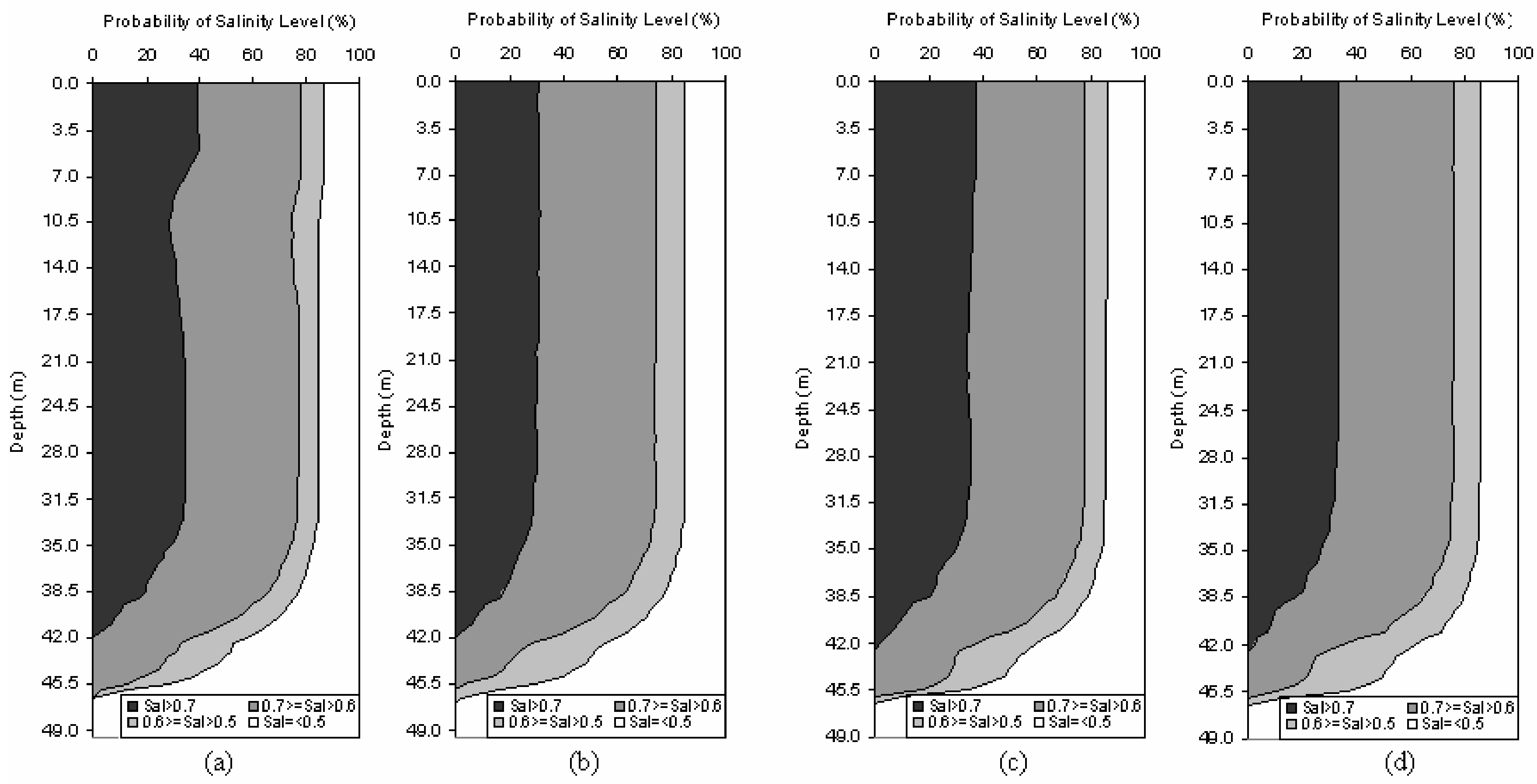



Figure 7.27 Probability occurrences of salinity levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

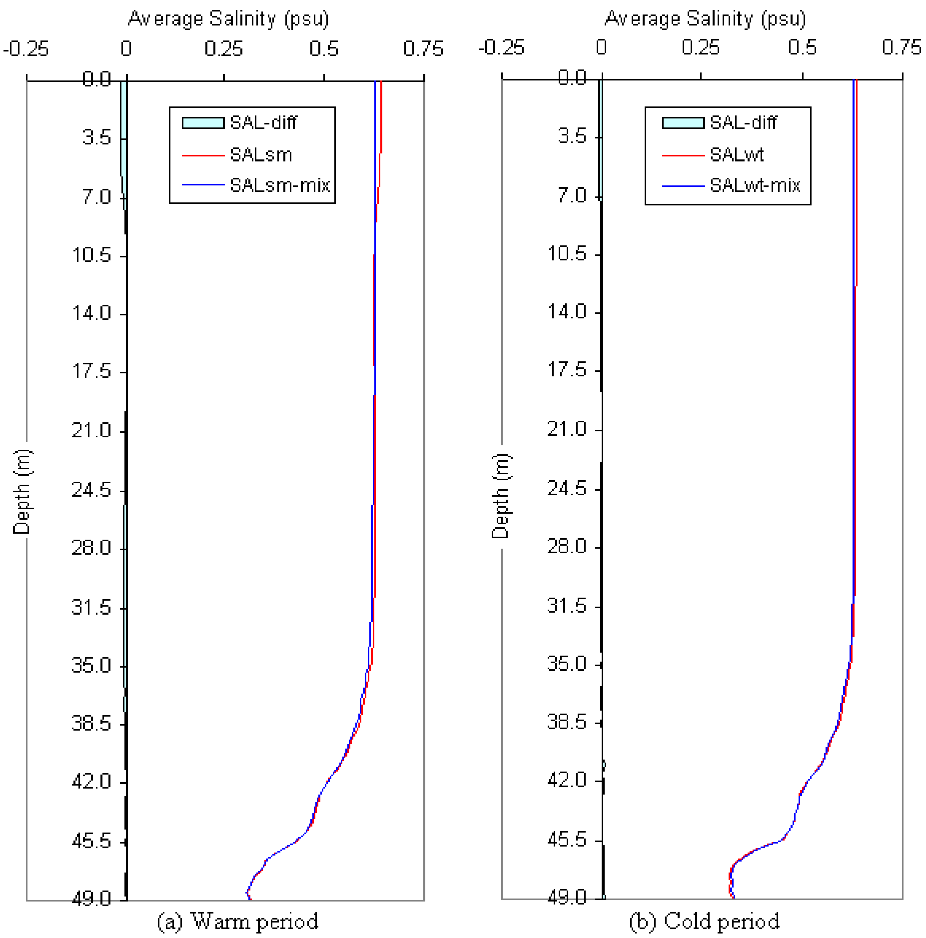



Figure 7.28 Profiles of average value of salinity through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

### *7.2.8 Total iron*

A high concentration of total iron in water bodies can create nuisance odours in a domestic water supply. The EPA Queensland (2005) recommends that the concentration of total iron be below 0.1 mg $L^{-1}$ for optimal growth of freshwater species.

Four levels of total iron concentration defined to represent the levels occurring in Cooby reservoir. These are: very low (TFe $\leq$ 0.01 mg $L^{-1}$), low (0.01 < TFe $\leq$ 0.1 mg $L^{-1}$), high (0.1 < TFe $\leq$ 0.5 mg $L^{-1}$), and very high (TFe > 0.5 mg $L^{-1}$).

During the warm period from November to April, a high level total iron occurs in the epilimnion layer of Cooby storage up to 70 per cent of the time as presented in Figure 7.29(a). However a very low occurrence of total iron concentration is found in the hypolimnion layer for up to 90 per cent of the time. Figure 7.29(b) shows the probability of occurrence profile for total iron levels in the water column during the warm period with artificial mixers in use. The mixers' operation transports the iron deeper into the reservoir.

In the cold period from May to October, there is at least a 65% chance of very low total iron status throughout the water column. The use of artificial mixers at this time reduces the probability levels of all total iron above 0.01 mg $L^{-1}$. A detail presentation of the probability of occurrence of total iron levels with and without artificial mixers during the cold period is presented in Figure 7.29(c) and (d).

The time averaged profiles of total iron for the 50-year prediction period with and without artificial mixers in the water column are shown in Figure 7.30. Figure 7.30(a) shows that the mixers reduce the average total iron concentration by 0.17 mg $L^{-1}$ from the surface to a depth of 11 m during the warm period. In the cold period from May to October, the mixers improve water quality by reducing the time averaged concentration of total iron throughout the storage. The reduction in concentration is just below 0.1 mg $L^{-1}$.

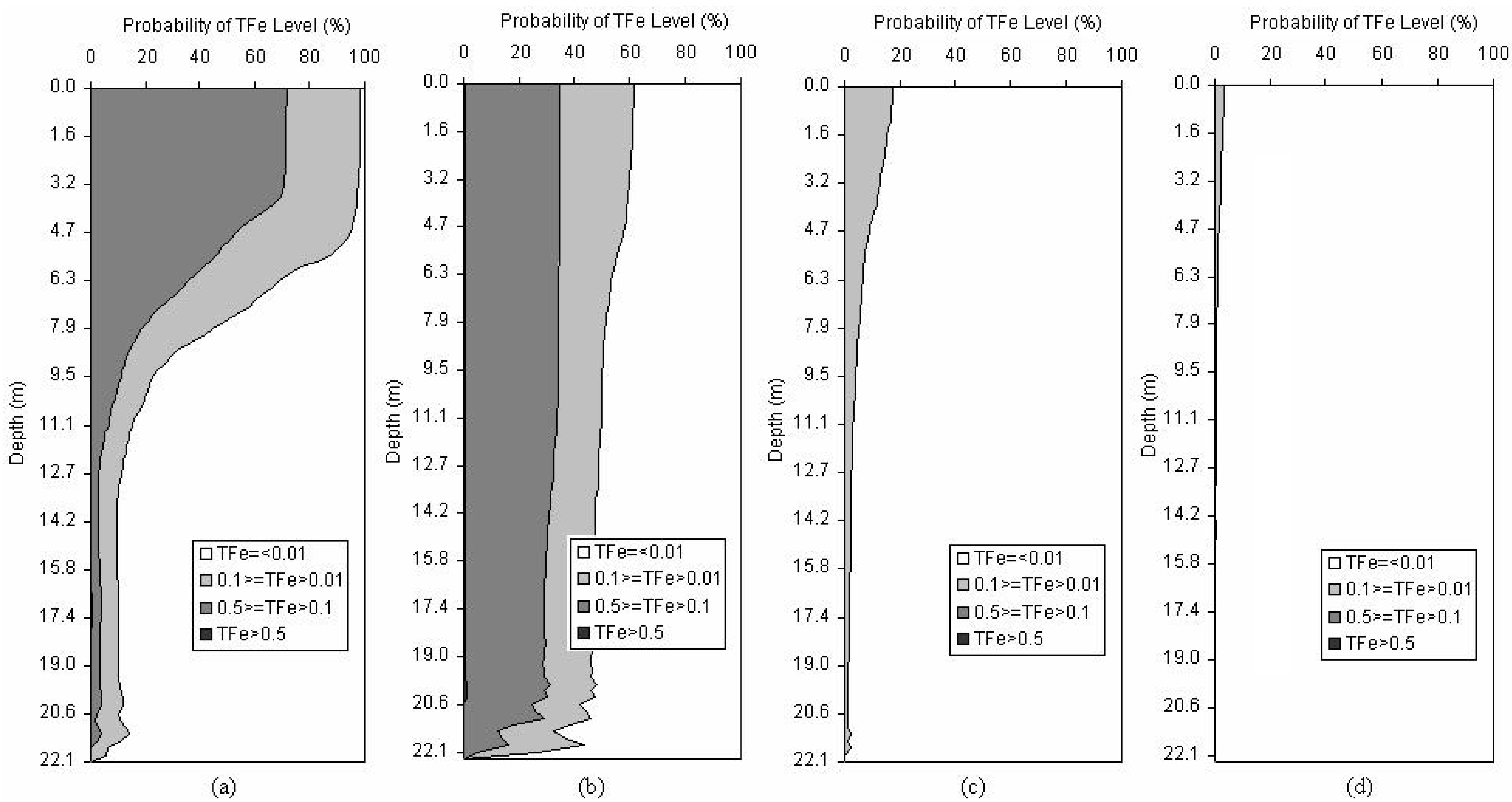
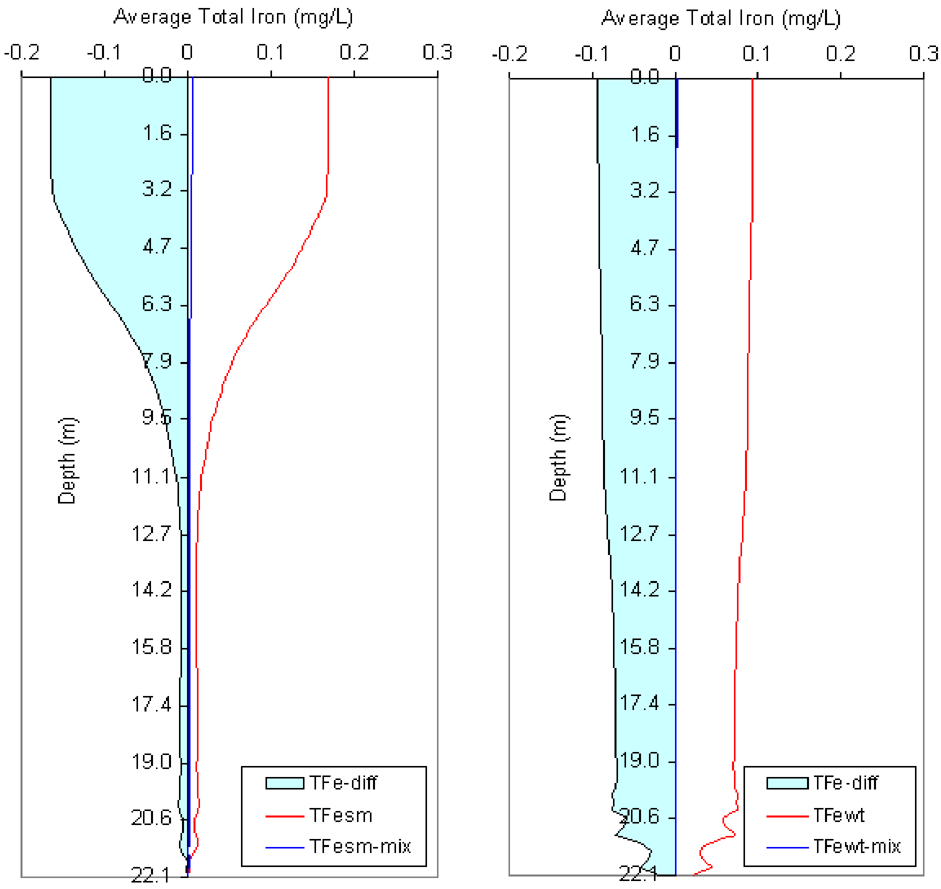



Figure 7.29 Probability occurrences of total iron levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.




(a) Warm period (b) Cold period

Figure 7.30 Profiles of average value of total iron through the water column with and without mixers in Cooby reservoir during warm and cold periods.

Total iron concentrations in Cressbrook storage are lower than those in Cooby Dam, it was necessary to adopt smaller concentration ranges for Cressbrook reservoir. The levels were set at very small (TFe $\leq$ 0.001 mg $L^{-1}$), small (0.001 < TFe $\leq$ 0.005 mg $L^{-1}$), large (0.005 < TFe $\leq$ 0.010 mg $L^{-1}$), and very large (TFe > 0.010 mg $L^{-1}$).

The probabilities of having small, large or very large total iron in the epilimnion layer during the warm period are 27, 15 and 24 per cent of the time, respectively. The water layer below 14 m depth is most likely to have a very small concentration of total iron as shown in Figure 7.31(a).

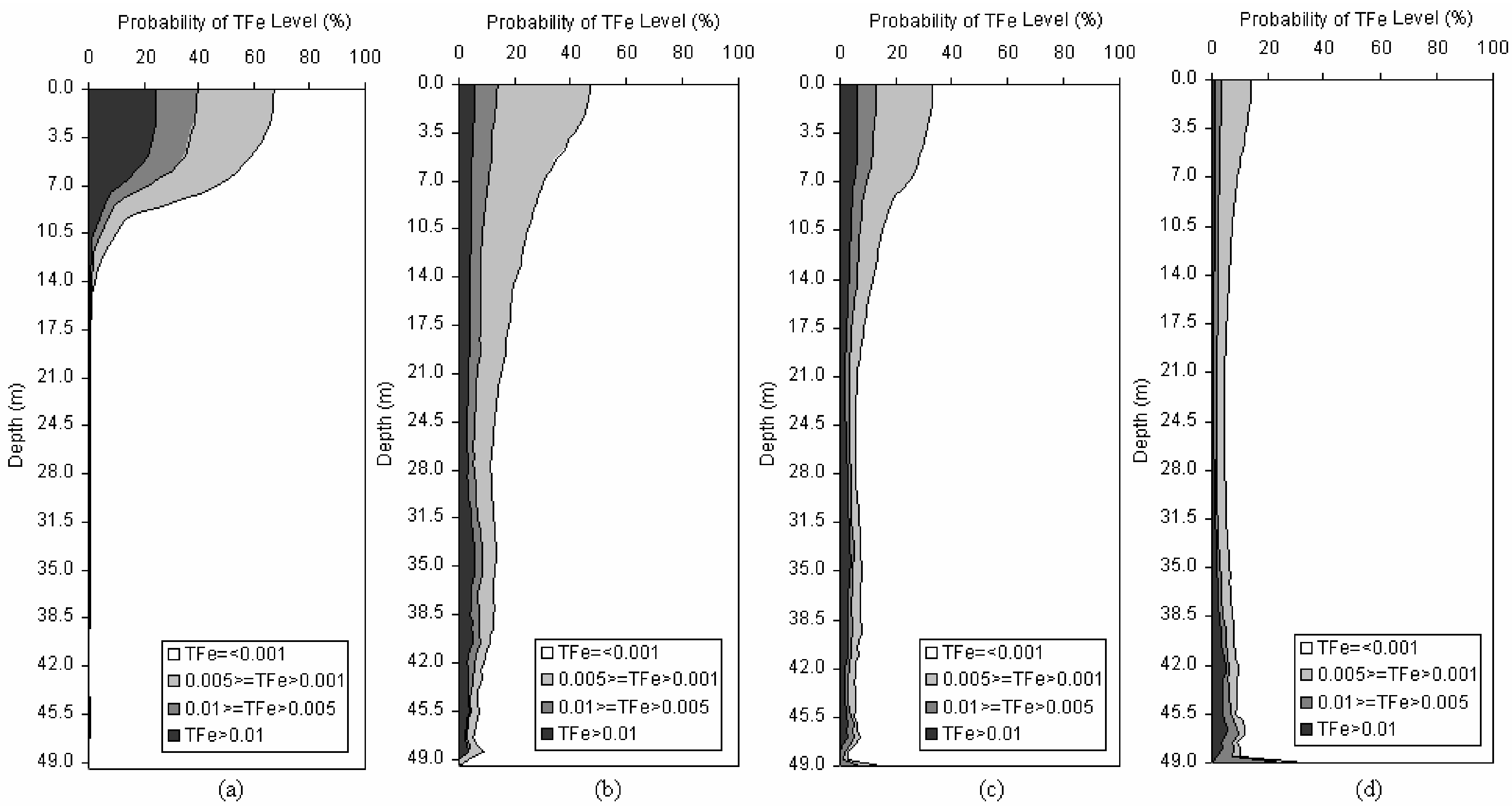



Figure 7.31 Probability occurrences of total iron levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

The artificial mixers affect the vertical profile of total iron levels. High risks of large iron content in the epilimnion layer decrease because of vertical circulation in the storage. Conversely, the risk in the hypolimnion layer increases. There is about 5 per cent probability of very large total iron in the water column as shown in Figure 7.31(b).

Figure 7.31(c) and (d) show the incidence of total iron levels in the storage with and without artificial mixers during the cold period. The probability of occurrence of the very small total iron (below 0.001 mg $L^{-1}$) is about 65 per cent in the water surface and up to 95 per cent in the hypolimnion layer.

Profiles of time averaged values of total iron concentration are presented for the separate periods (warm and cold periods) with and without mixers in Figure 7.32. During the warm period, the mixers reduce the average concentration of total iron by up to 0.005 mg $L^{-1}$ in the epilimnion layer. In contrast, the average concentrations increase by 0.003 mg $L^{-1}$ in the hypolimnion layer.

During the cold period, the mixers reduce the time averaged concentration of total iron by 0.002 mg $L^{-1}$ at the water surface to the 39 m depth. Below 39 m depth, the use of mechanical mixers tends to increase the averaged concentrations of total iron.

### *7.2.9 Total manganese*

Manganese concentrations in the DYREMS-CAEDYM model follow an identical mathematical formulation to iron, but with different parameter representations (Herzfeld & Hamilton 2000). Aeration allows manganese ions in reservoirs to be oxidised manganese dioxide. An aeration system is commonly used in a water treatment plant as a pre-treatment process to reduce manganese levels (Raveendran, Ashworth & Chatelier 2001).

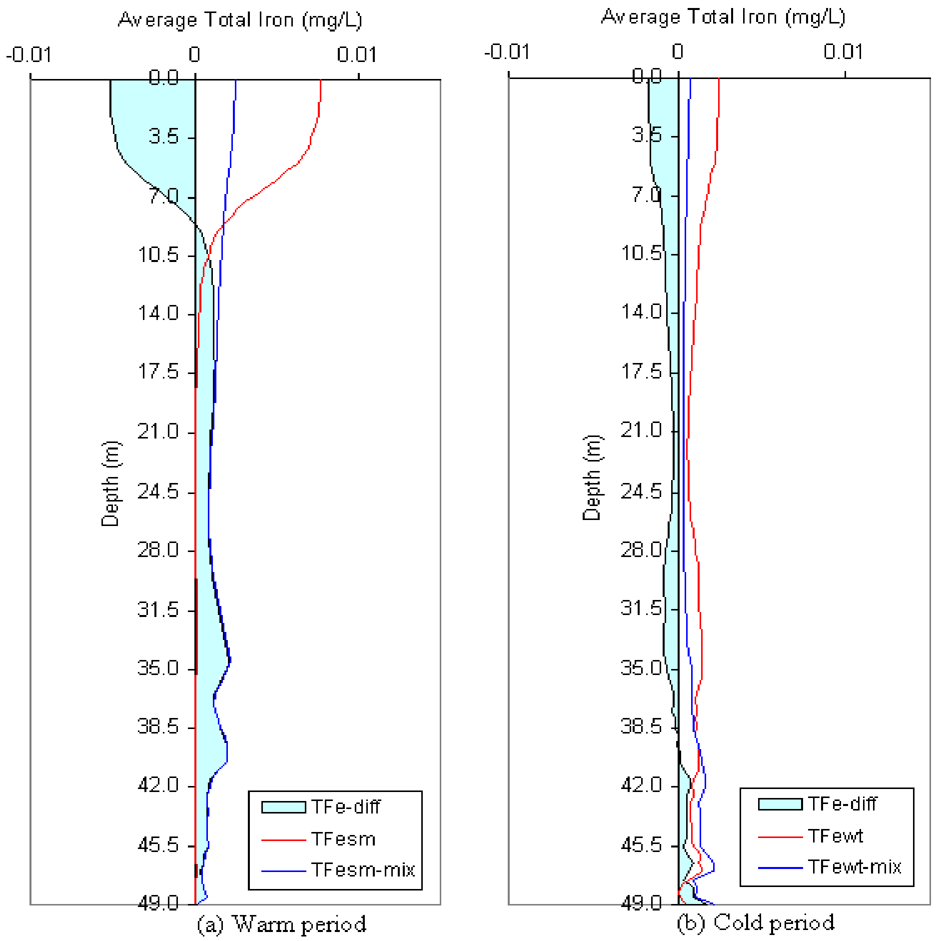



Figure 7.32 Profiles of average value of total iron through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

The ranges of total manganese concentrations are similar to those for iron in Cooby and Cressbrook reservoirs. Figure 7.33 details probability of occurrence of total manganese in Cooby's water column during the warm and the cold period with and without mechanical destratifiers. Total manganese concentrations above 0.1 mg $L^{-1}$ are about 70 and 10 per cent likely to occur in the epilimnion and hypolimnion layers, respectively during the warm period in Cooby.

During the cold period, total manganese levels above 0.1 mg $L^{-1}$ are about 35 per cent likely to occur above the hypolimnion layer.

Surface mixers are able to remove the high levels of total manganese concentrations during the warm period by acting as oxygenation tools. Concentrations

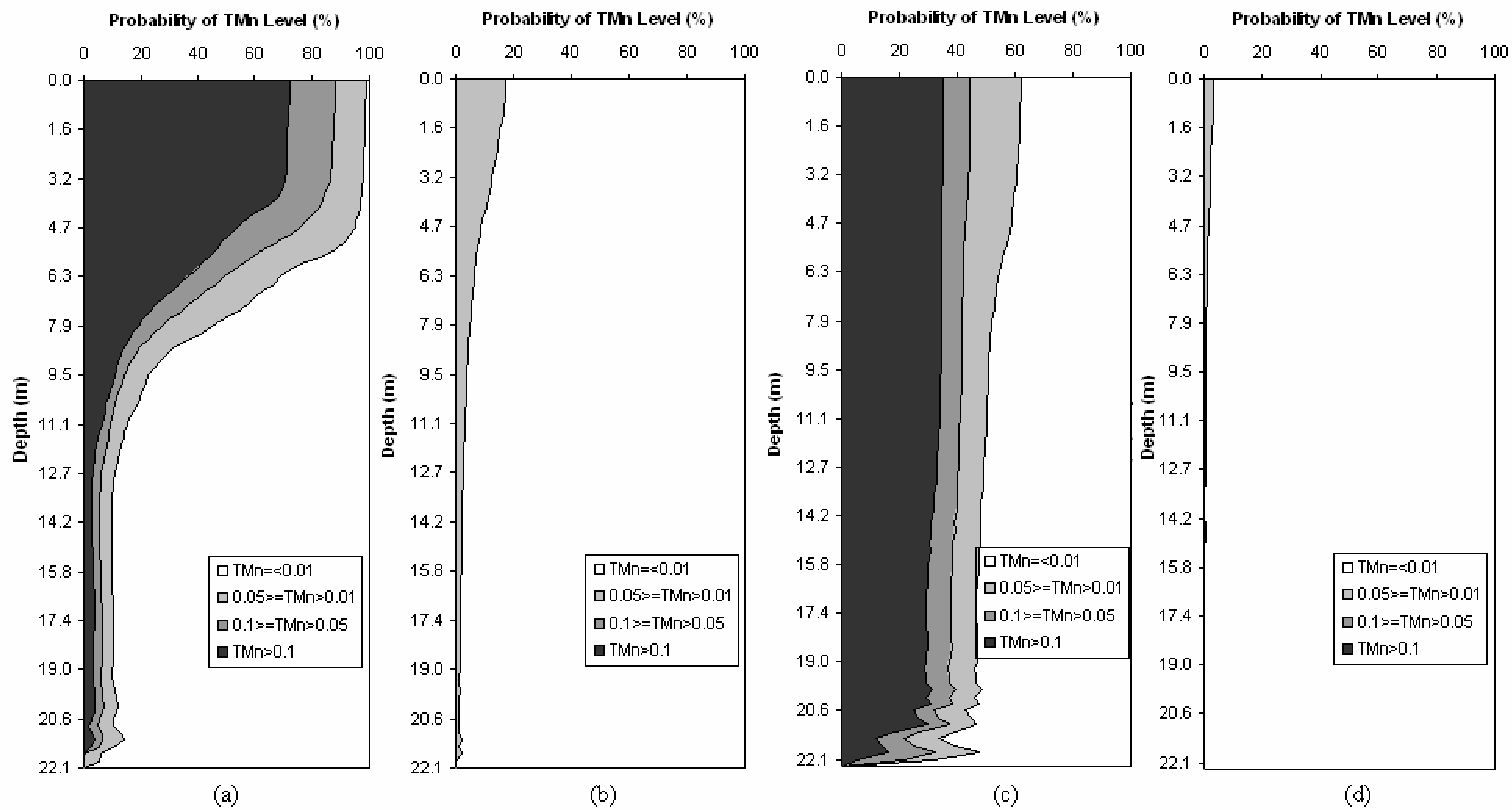



Figure 7.33 Probability occurrences of total manganese levels in Cooby reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

between 0.01 mg L$^{-1}$ and 0.05 mg L$^{-1}$ can occur with a probability below 20 per cent while concentrations below 0.01 mg L$^{-1}$ are shown in Figure 7.33(b). High total manganese concentrations are simply not found during the cold period if mixers are operated in Cooby storage (see Figure 7.33(d)).

Time averaged total manganese concentrations in the water column also show the effect of mixers in Cooby storage. Figure 7.34 shows that the mixers reduce the average total manganese concentration by 0.17 mg L$^{-1}$ and 0.09 mg L$^{-1}$ in the water column during the warm and the cold periods, respectively.

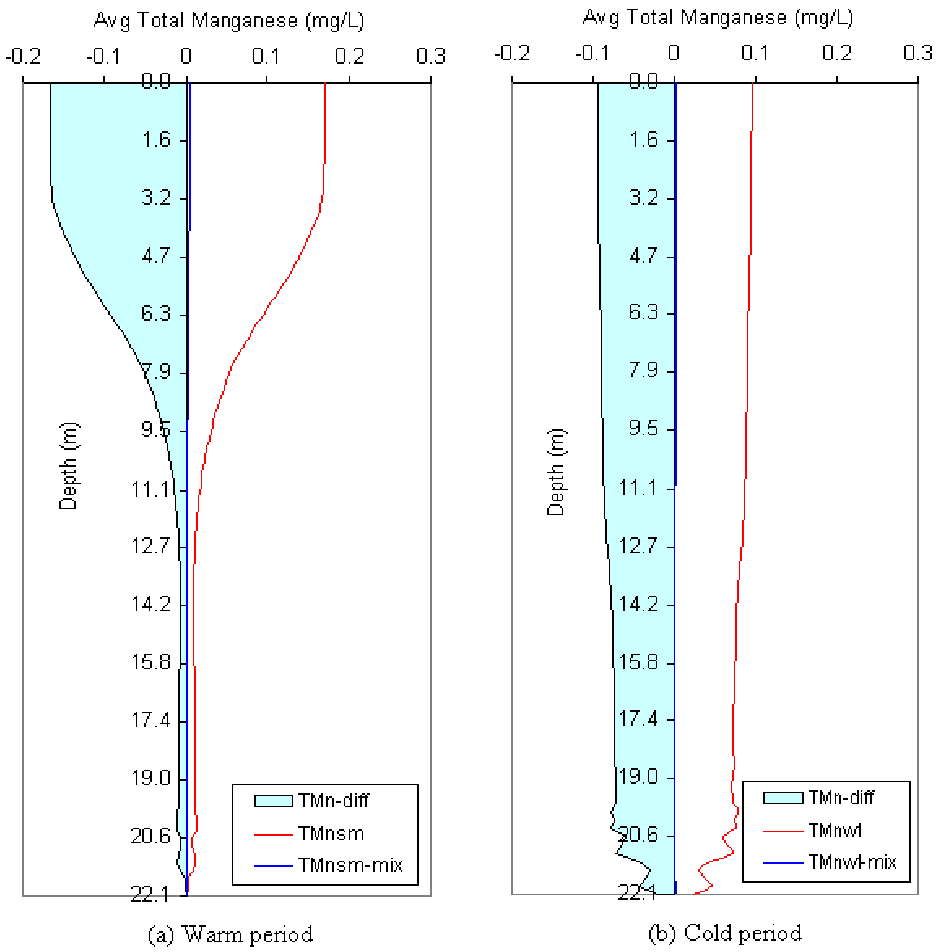



Figure 7.34 Profiles of average value of total manganese through the water column with and without mixers in Cooby reservoir during warm and cold periods.

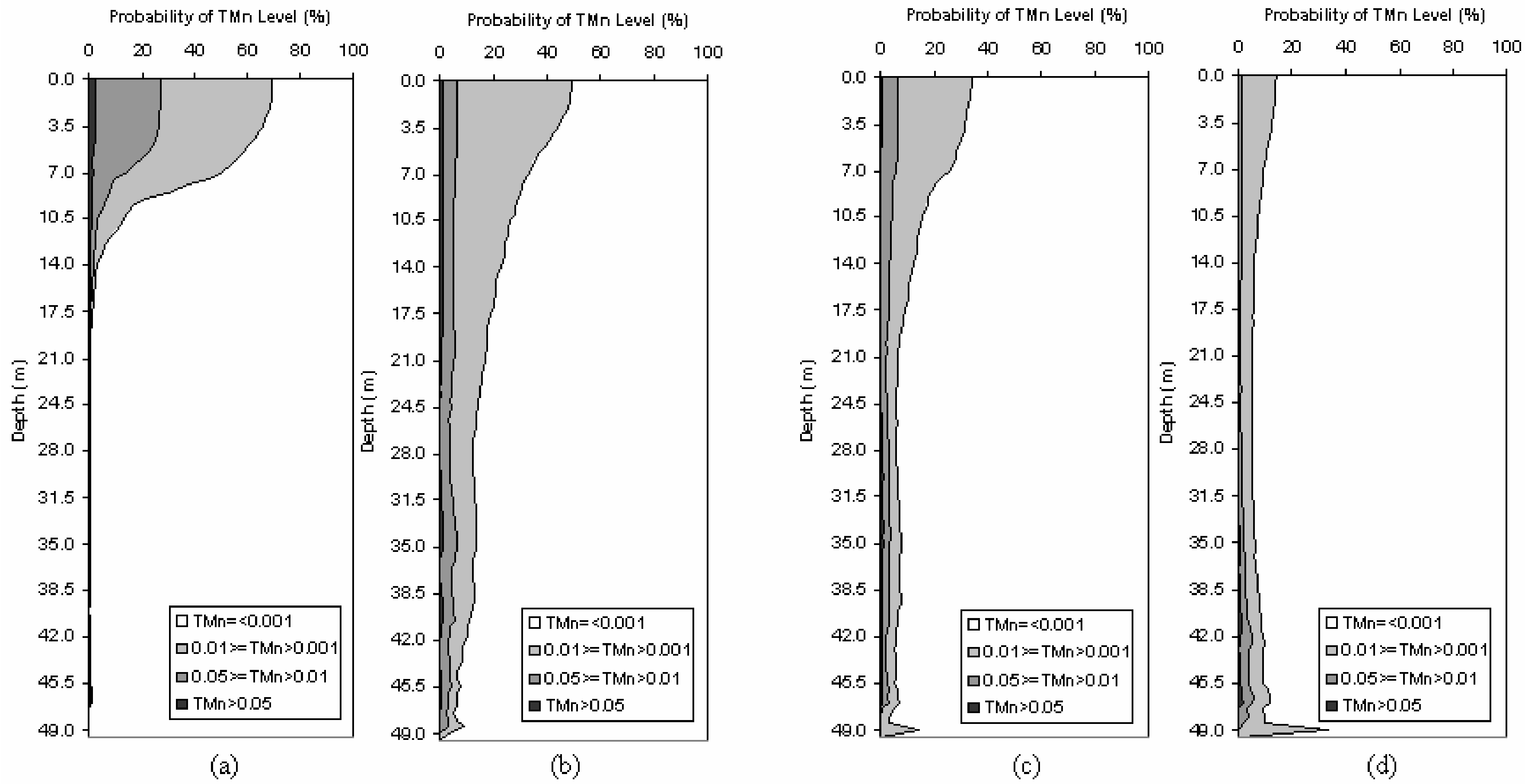



Figure 7.35 Probability occurrences of total manganese levels in Cressbrook reservoir. (a) warm period without mixers, (b) warm period with mixers, (c) cold period without mixers, and (d) cold period with mixers.

The small range of total manganese concentrations in Cressbrook storage is similar to that for total iron in the storage. The probability of occurrences of raised total manganese levels in the epilimnion layer during the warm period from November to April is higher than in the hypolimnion layer as shown in Figure 7.35(a). Artificial mixers distribute manganese down through the hypolimnion layer and change the probability of occurrence of different levels. The likelihood of total manganese concentrations above 0.001 mg $L^{-1}$ drops by 20 per cent in the top layers but increases by 20 per cent below 17.5 m depth.

During the cold period, the total manganese concentration is relatively lower. The possibility of total manganese occurring above 0.001 mg $L^{-1}$ is about 33 per cent in the epilimnion layer and only about 15 per cent below 17.5 m depth. The mixers reduce the probability of levels above 0.001 mg $L^{-1}$ occurring to about 15 per cent in the epilimnion layer. A complete probability profile for a range of total manganese levels can be seen in Figure 7.35(c) and (d).

Detailed profiles of time averaged total manganese concentration in the reservoir can be seen in Figure 7.36. The time averaged value of total manganese concentrations can be influenced by mixers in the reservoir. During the warm period, the time averaged concentration is just below 0.01 mg $L^{-1}$ in the surface water. The mixers reduce the concentration by 0.006 mg $L^{-1}$. However, the concentration then increases in the layers below 9 m depth as the manganese is distributed in the column of water. In the cold period, the time averaged concentrations decrease as a result of the of mixers’ action. The concentrations increase only in the layer close to the bottom of the reservoir.

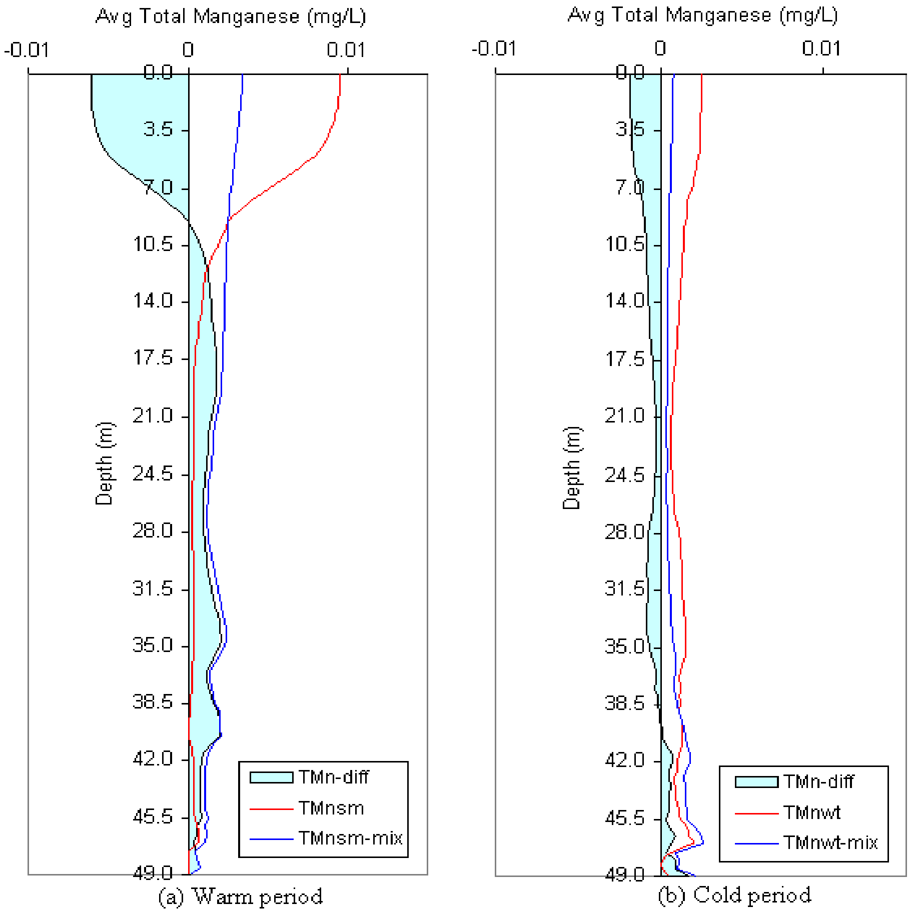



Figure 7.36 Profiles of average value of total manganese through the water column with and without mixers in Cressbrook reservoir during warm and cold periods.

## 7.3 Summary of the Effect of Artificial Mixers on Water Quality

This section presents a summary of the changes of water quality levels to evaluate the overall effect of the mixers in the water column. There are some benefits from using mechanical mixers in the storages. Unfortunately, the water quality parameters do become worse in some layers.

### *7.3.1 Cooby Dam*

The benefits from using artificial mixers in Cooby Dam during the warm period from November to April are: improved dissolved oxygen levels, warmer temperatures deeper in the water column, reduced nutrient concentrations in the hypolimnion layer, and reduced cyanobacterial concentrations in the epilimnion layer.

There are also some negative impacts of the mixers. The cyanobacterial concentrations in the hypolimnion layer are increased as are the nutrient concentrations in the epilimnion layer. A detailed summary of the impact of the mixers in Cooby Dam during the warm period is presented in Table 7.1.

Table 7.1 A summary of the changes in average water quality parameters with and without mixers during the period November to April in Cooby Dam.

| Depth | Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **BGA** µg $L^{-1}$ | **DO** mg $L^{-1}$ | **Tw** $^{o}$C | **$NO_3$** mg $L^{-1}$ | **TP** mg $L^{-1}$ | **pH*** - | **Sal*** psu | **TFe** mg $L^{-1}$ | **TMn** mg $L^{-1}$ |
| 0-2 | 0 | 0 | 0 | +0.05 | +0.016 | +0.010 | -0.004 | -0.160 | -0.160 |
| 3-4 | -2.5 | +0.1 | +0.2 | +0.05 | +0.015 | +0.020 | -0.003 | -0.150 | -0.150 |
| 5-6 | +1.5 | +0.4 | +1.0 | -0.05 | +0.007 | +0.045 | -0.001 | -0.100 | -0.100 |
| 7-8 | +1.0 | +0.7 | +2.5 | -0.10 | -0.006 | +0.078 | +0.001 | -0.049 | -0.049 |
| 9-10 | +0.8 | +1.0 | +3.5 | -0.20 | -0.019 | +0.097 | +0.002 | -0.022 | -0.022 |
| 11-12 | +0.6 | +1.5 | +5.0 | -0.30 | -0.030 | +0.110 | +0.003 | -0.010 | -0.010 |
| 13-14 | +0.4 | +1.8 | +6.5 | -0.45 | -0.041 | +0.119 | +0.003 | -0.008 | -0.008 |
| 15-16 | +0.2 | +2.1 | +7.0 | -0.50 | -0.054 | +0.124 | +0.004 | -0.008 | -0.008 |
| 17-18 | +0.2 | +3.5 | +7.0 | -0.60 | -0.065 | +0126 | +0.004 | -0.010 | -0.010 |
| 19-20 | +0.2 | +3.9 | +7.0 | -0.50 | -0.064 | +.0120 | +0.004 | -0.010 | -0.010 |
| 21-22 | +0.2 | +3.7 | +5.5 | -0.35 | -0.063 | -0.080 | -0.004 | -0.007 | -0.007 |

Note: BGA is Cyanobacteria, DO is Dissolved Oxygen, Tw is Water Temperature, $NO_3$ is Nitrate, TP is Total Phosphorus, pH is the degree of alkalinity, Sal is Salinity, TFe is Total Iron, and TMn is Total Manganese. Grey colour indicates that the layers gain a positive impact from the mixers;
*) insignificant parameter (the different is less than 1 per cent).

The impact of artificial mixers on water quality during the cold period is not so great, as summarised in Table 7.2. The mixers cause no significant difference in the pH and salinity concentrations through the water column, nor in dissolved oxygen and water temperatures in the epilimnion layer. Water quality improvement does result from a small reduction of nitrate, total iron and total manganese concentrations in all layers, a small increase in dissolved oxygen concentrations in the hypolimnion layer, temperature changes below 5 m depth, and a reduction of cyanobacterial concentrations in the layers 3 – 6 m depth and 9 – 16 m depth. Negative impacts from the mixers during the cold period are shown by the increase in total phosphorus in the epilimnion layer and the Cyanobacteria at the water surface, 7 – 8 m depth, and 17 – 22 m depth.

Table 7.2 A summary of the changes in average water quality parameters with and without mixers during the period May to October in Cooby Dam.

| Depth | Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **BGA** µg $L^{-1}$ | **DO** mg $L^{-1}$ | **Tw** $^{o}C$ | **$NO_3$** mg $L^{-1}$ | **TP** mg $L^{-1}$ | **pH*** - | **Sal*** psu | **TFe** mg $L^{-1}$ | **TMn** mg $L^{-1}$ |
| 0-2 | +0.05 | 0 | 0 | -0.05 | +0.004 | 0 | 0 | -0.09 | -0.09 |
| 3-4 | -1.50 | 0 | 0 | -0.05 | +0.004 | 0 | 0 | -0.09 | -0.09 |
| 5-6 | -0.80 | 0 | +0.2 | -0.05 | +0.004 | 0 | 0 | -0.09 | -0.09 |
| 7-8 | +0.11 | 0 | +0.4 | -0.05 | +0.004 | 0 | 0 | -0.09 | -0.09 |
| 9-10 | 0 | 0 | +0.4 | -0.05 | +0.004 | 0 | 0 | -0.09 | -0.09 |
| 11-12 | 0 | 0 | +0.4 | -0.05 | +0.003 | 0 | 0 | -0.08 | -0.08 |
| 13-14 | -0.01 | +0.2 | +0.4 | -0.07 | +0.001 | 0 | 0 | -0.08 | -0.08 |
| 15-16 | 0 | +0.4 | +0.3 | -0.08 | -0.003 | 0 | 0 | -0.07 | -0.07 |
| 17-18 | +0.05 | +0.6 | +0.4 | -0.09 | -0.007 | 0 | 0 | -0.07 | -0.07 |
| 19-20 | +0.04 | +0.5 | +0.4 | -0.09 | -0.015 | 0 | 0 | -0.07 | -0.07 |
| 21-22 | +0.02 | +1.1 | +0.8 | -0.10 | -0.020 | 0 | 0 | -0.03 | -0.03 |

Note: BGA is Cyanobacteria, DO is Dissolved Oxygen, Tw is Water Temperature, $NO_3$ is Nitrate, TP is Total Phosphorus, pH is the degree of alkalinity, Sal is Salinity, TFe is Total Iron, and TMn is Total Manganese. Grey colour indicates that the layers gain a positive impact from the mixers;
*) insignificant parameter (the different is less than 1 per cent).

Table 7.2 also shows that the layers between 13 m and 16 m depth have the maximum benefit from the use of the mechanical surface mixers. The mixers reduce the cyanobacterial concentration in the 13 – 14 m layer but there is a small increase in total phosphorus concentration. In the 15 – 16 m layer, there is no change of cyanobacterial concentration but an improvement in other water quality parameters.

### *7.3.2 Cressbrook Dam*

Cressbrook water storage quality gains from the use of mechanical mixers during the warm period by increased dissolved oxygen concentrations and improved water temperature levels below 5 m depth. The mixers also decrease the concentrations of total iron and total manganese in the epilimnion layer and cyanobacterial concentrations in the surface layer. Conversely, some parameters are made worse by continuous operation of mixers. The cyanobacterial concentrations in the middle layers are increased as are total iron and total manganese concentrations in the hypolimnion layer. Nitrate concentrations in the surface and the bottom layers of the reservoir and total phosphorus throughout the water column are also increased when mixers are used.

Table 7.3 A summary of the changes in average water quality parameters with and without mixers during the period November to April in Cressbrook Dam.

| Depth | Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **BGA** µg $L^{-1}$ | **DO** mg $L^{-1}$ | **Tw** $^oC$ | **$NO_3$** mg $L^{-1}$ | **TP** mg $L^{-1}$ | **pH*** - | **Sal*** psu | **TFe** mg $L^{-1}$ | **TMn** mg $L^{-1}$ |
| 0-5 | -0.41 | -0.02 | -0.01 | +0.12 | +0.08 | -0.09 | -0.02 | -0.005 | -0.006 |
| 6-10 | +0.28 | +0.54 | +1.19 | +0.07 | +0.06 | +0.02 | -0.01 | -0.001 | -0.002 |
| 11-15 | +1.70 | +1.44 | +4.99 | -0.19 | +0.03 | +0.10 | 0 | -0.001 | +0.001 |
| 16-20 | +1.20 | +1.27 | +8.66 | -0.46 | +0.01 | +0.03 | 0 | +0.001 | +0.002 |
| 21-25 | +0.61 | +0.91 | +8.57 | -0.51 | +0.02 | -0.01 | 0 | +0.001 | +0.001 |
| 26-30 | +0.21 | +1.16 | +4.70 | -0.36 | +0.02 | -0.01 | -0.01 | +0.001 | +0.001 |
| 31-35 | +0.09 | +1.28 | +2.13 | -0.02 | +0.02 | -0.01 | -0.01 | +0.001 | +0.002 |
| 36-40 | +0.03 | +1.00 | +0.79 | +0.11 | +0.03 | -0.01 | -0.01 | +0.001 | +0.002 |
| 41-45 | 0 | +0.50 | +0.25 | +0.06 | +0.04 | 0 | 0 | +0.001 | +0.001 |
| 46-50 | 0 | +0.06 | +0.12 | +0.01 | +0.01 | +0.02 | 0 | +0.001 | +0.001 |

Note: BGA is Cyanobacteria, DO is Dissolved Oxygen, Tw is Water Temperature, $NO_3$ is Nitrate, TP is Total Phosphorus, pH is the degree of alkalinity, Sal is Salinity, TFe is Total Iron, and TMn is Total Manganese. Grey colour indicates that the layers gain a positive impact from the mixers;
*) insignificant parameter (the different is less than 1 per cent).

During the cold period, the artificial mixers improve most water quality parameters, except Cyanobacteria and nitrate in the hypolimnion layer and total phosphorus in the epilimnion layer. The mixers do not affect the time averaged pH or salinity concentrations in the water column. The reservoir gains maximum benefit from the mixers in the layer between 11 m and 15 m depth as shown in Table 7.4.

Table 7.4 A summary of the changes in average water quality parameters with and without mixers during the period May to October in Cressbrook Dam.

| Depth | Parameters | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | BGA µg $L^{-1}$ | DO mg $L^{-1}$ | Tw $^{o}C$ | $NO_3$ mg $L^{-1}$ | TP mg $L^{-1}$ | pH* - | Sal* Psu | TFe mg $L^{-1}$ | TMn mg $L^{-1}$ |
| 0-5 | -1.12 | +0.03 | +0.01 | -0.02 | +0.06 | 0 | -0.01 | -0.002 | -0.002 |
| 6-10 | -1.35 | -0.01 | +0.36 | -0.02 | +0.06 | +0.01 | -0.01 | -0.001 | -0.001 |
| 11-15 | -0.17 | +0.12 | +1.26 | -0.04 | +0.05 | +0.03 | -0.01 | -0.001 | -0.001 |
| 16-20 | +0.29 | +0.64 | +1.98 | -0.14 | +0.04 | +0.04 | 0 | 0 | -0.001 |
| 21-25 | +0.38 | +1.23 | +2.11 | -0.27 | +0.03 | +0.03 | 0 | 0 | 0 |
| 26-30 | +0.28 | +1.88 | +1.88 | -0.29 | +0.01 | +0.01 | 0 | 0 | -0.001 |
| 31-35 | +0.21 | +2.44 | +1.64 | -0.12 | -0.01 | 0 | 0 | +0.001 | -0.001 |
| 36-40 | +0.15 | +2.50 | +1.25 | +0.10 | -0.02 | -0.01 | 0 | 0 | 0 |
| 41-45 | +0.05 | +2.09 | +0.79 | +0.21 | -0.02 | 0 | 0 | 0 | 0 |
| 46-50 | +0.02 | +1.36 | +0.45 | +0.15 | -0.02 | 0 | 0 | +0.001 | -0.001 |

Note: BGA is Cyanobacteria, DO is Dissolved Oxygen, Tw is Water Temperature, $NO_3$ is Nitrate, TP is Total Phosphorus, pH is the degree of alkalinity, Sal is Salinity, TFe is Total Iron, and TMn is Total Manganese. Grey colour indicates that the layers gain a positive impact from the mixers;
*) insignificant parameter (the different is less than 1 per cent).

## 7.4 Risk Management of Water Quality in the Reservoirs

Risk management requires decision makers to analyse the future likelihood of hazards and to make management decisions with regard to these risks (Beck & Straten 1983). Quantitative analysis of uncertainty and variability is used extensively in risk assessment (Wilson & Shlyakhter 1997). Risk represents the probability of an undesired event for which the probability distribution is known. Accordingly, risk analysis must determine the outcomes of decisions together with their probability levels.

Risks to water quality in a reservoir can be managed through an understanding of water quality behaviour in the water column. For a domestic water supply, risk management addresses the level of acceptable water quality for treatment plants. A intake level is often varied as a way of managing for optimum water quality. The raw water quality determines the cost of treatment to acceptable drinking levels. Thus, decision making focuses on alternatives available within the limitations of natural and capital resources.

The vertical variations in some water quality parameters in Cooby and Cressbrook reservoirs would allow such a selective pumping level layer system to be adopted. However, it is not obvious where the optimal pumping elevation would be as some parameters improve and some worsen with the use of mixers. Probability level for satisfactory or “safe” levels for different water quality parameters were investigated to assist in such decision management. The layer which is most likely (highest probability) to have safe levels is considered to offer an appropriate pumping elevation in the reservoirs.

Three water quality parameters were eliminated in this risk assessment based on the results in sections 7.2 and 7.3. Salinity, water temperature, and pH were determined not to affect the treatment requirements. Salinity levels in the reservoirs remained at safe levels (less than 5 psu) throughout the historic and simulated data. The variation in pH level in the reservoirs showed no significant variations as explained in Section 7.2.6. And the raw water temperature does not affect water treatment processes. Water treatment is based on the atmosphere temperature for most physical treatment processes and a controlled temperature level (pre-heating/cooling) for most chemical treatment processes.

### *7.4.1 Risks in Cooby Dam*

#### 7.4.1.1 Risks without artificial mixers

Suitable or safe levels of water quality Cooby Dam is based on six parameters. They are the concentrations of Cyanobacteria, dissolved oxygen, nitrate, total phosphorus, total iron, and total manganese.

With no artificial mixing during the warm period, three parameters (dissolved oxygen, nitrate and total phosphorus) are always within their safe levels in the epilimnion layer (surface to 5.5 m depth). This is not always the case in the hypolimnion layer. The probability of occurrence of safe levels of total phosphorus drops to about 25 per cent at 16 – 18 m depth. The opposite solution applies with total iron and total manganese. They have low probability of safe levels occurring in the epilimnion layer (about 12 per cent) but are relatively higher values in the hypolimnion layer (more than 90 per cent). A safe level of cyanobacterial concentration occurs least often (has the lowest probability) in the layer between 2 m and 5 m below the water surface. The highest probability can be found in the layer below 8 m depth. A detail of the probability of safe levels of selected parameters is shown in Figure 7.37.

Figure 7.37 shows that the six indicators have safe levels above 60 per cent of the time in the layer between 8 m and 10 m depth. From the surface to 8 m depth, at least two indicators have safe levels for less than 60 per cent of the time with no artificial mixer in operation. The water is best drawn for 8 to 10 m below the surface

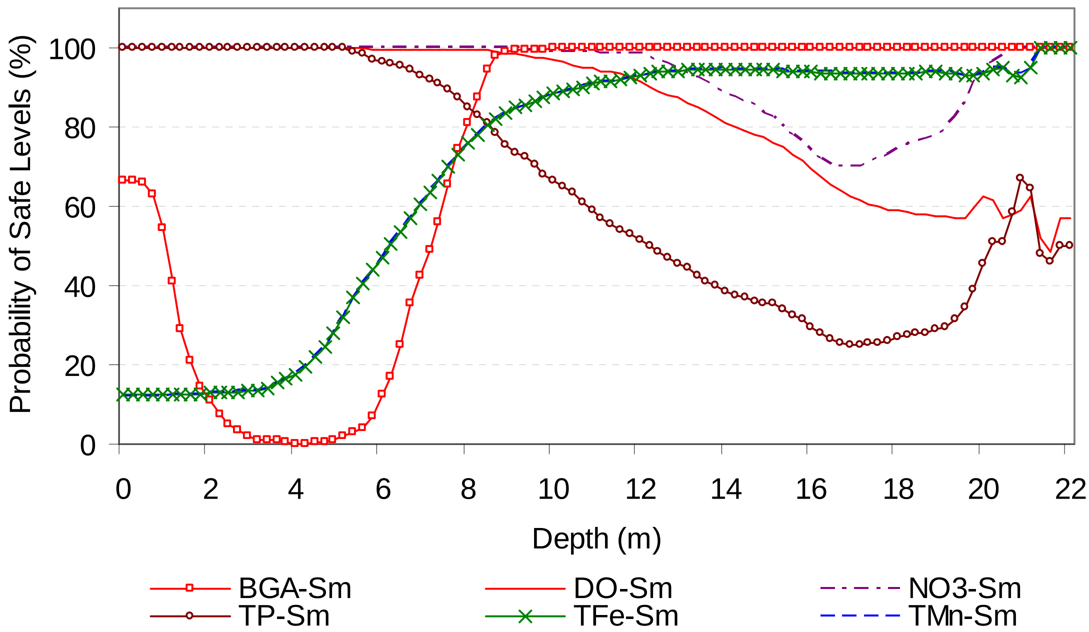



Figure 7.37 Probability of safe levels of analysed parameters occurring through the water column without artificial mixers during the warm period in Cooby Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

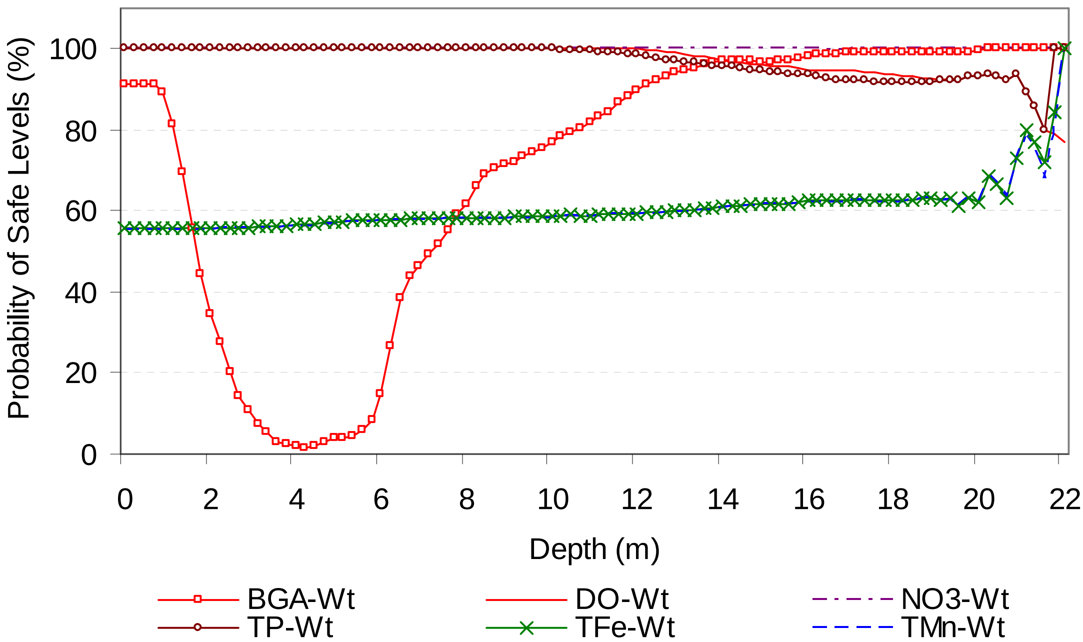



Figure 7.38 Probability of safe levels of analysed parameters occurring through the water column without artificial mixers during the cold period in Cooby Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

During the cold period from May to October, the probability of suitable levels of the six parameters changes to that presented in Figure 7.38. Three of the parameters (dissolved oxygen, nitrate and total phosphorus) occur at safe levels for more than 90 per cent of the time from surface to 20 m depth. Total iron and total manganese have safe levels occurring for 55 per cent of the time at the water surface increasing to about 62 per cent at 20 m depth. A safe level of Cyanobacteria can be found in the top of the reservoir or in the layer below 8 m depth.

The six indicators together suggest that acceptable water quality occurs for more than 60 per cent of the time below 8 m depth. However, the layer close to the bottom of the storage can have a high concentration of suspended solid which is not shown on these graphs. Therefore, the pumping layer during the cold period is recommended between 8 m and 20 m depth. An optimum layer is suggested by Figure 7.38 at 13.5 m below the surface.

7.4.1.2 Risks with the use of artificial mixers

When surface mixers are used during the warm period, four indicators (dissolved oxygen, nitrate, total iron and total manganese) always exist at safe levels (100 per cent of time). A safe level of total phosphorus occurs for about 83 per cent of the time at all depths.

The likelihood of safe levels of Cyanobacteria varies with depth through the water column, as shown in Figure 7.39. Safe levels occur for at least 60 per cent of the time below 9 m depth. The layer just above the bottom of the storage may have high concentrations of suspended solid which were not simulated in this study. Therefore, the recommended pumping level during the period from November to April would lie at the surface or between 9 m and 20 m depth. An optimum layer is indicated at 15 m depth where the cyanobacterial concentration has above 95 per cent probability of being at a safe level.

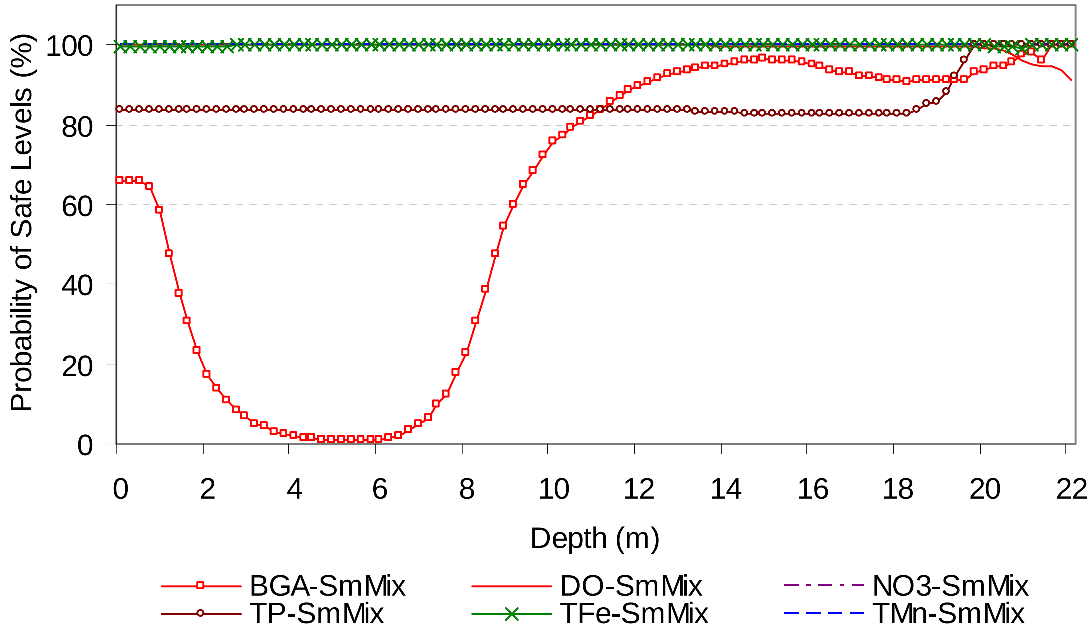



Figure 7.39 Probability of safe levels of analysed parameters occurring through the water column with artificial mixers during the warm period in Cooby Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

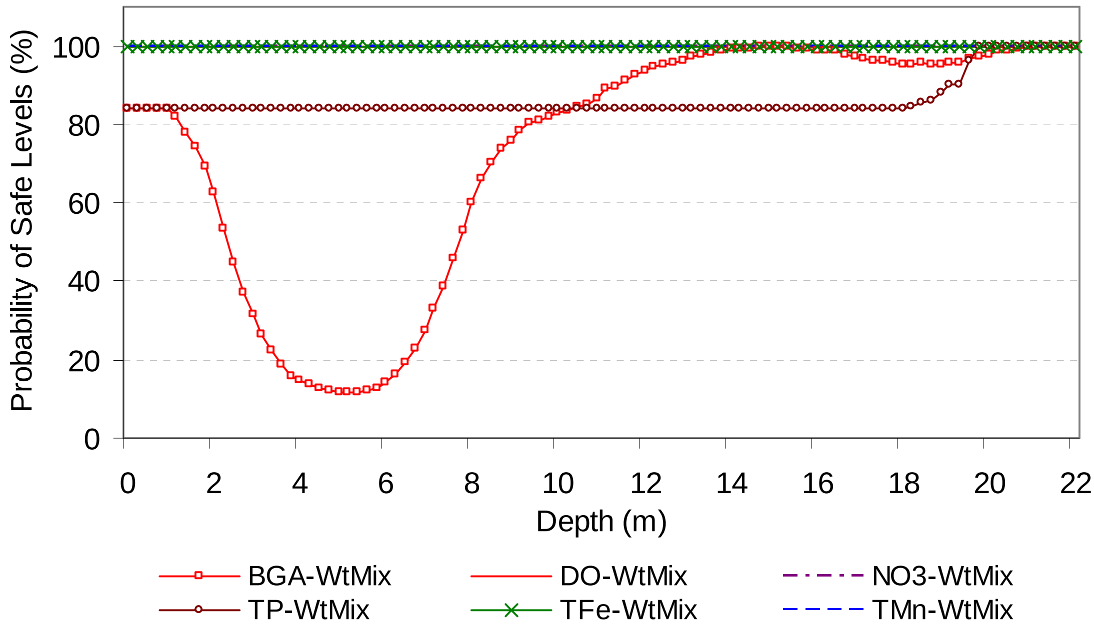



Figure 7.40 Probability of safe levels of analysed parameters occurring through the water column with artificial mixers during the cold period in Cooby Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

Figure 7.40 shows that most indicators have a high probability of safe levels during the May to October period, except for Cyanobacteria at 2 m to 8 m depth. The cyanobacterial safe levels only occur for 11 to 60 per cent of the time at this depth. Four indicators (dissolved oxygen, nitrate, total iron and total manganese) show a remarkably high probability of safe levels. Safe levels of total phosphorus occur for about 84 per cent of the time from the water surface to the 18 m depth.

The pumping elevation is suggested to be at the surface layer or between 8 m and 20 m depth during this cold period. The layer between 13.5 m and 16.5 m would give optimum water quality.

A general summary recommended pumping elevations in the storage can be made as shown in Figure 7.41. The figure presents matrices of recommended and optimal layers of pumping elevation. With no artificial mixing, the chance of attaining safe levels of water quality is best at 8 to 10 m depth over the whole year. The best/optimal layers differ between the warm and cold periods of the year but the 8 to 10 m level provides a sound management solution. Artificial mixers can extend the range of the recommended pumping levels and so give the authority more flexibility in managing withdrawals. An optimal water quality can be achieved throughout the year with a fixed pumping elevation at 15 m depth.

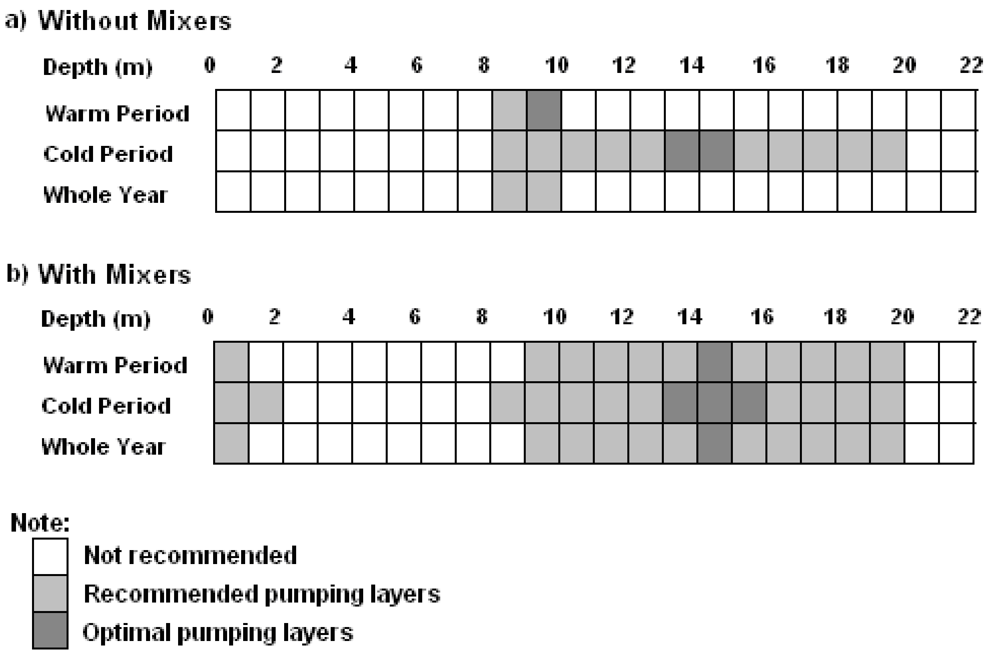



Figure 7.41 Matrix of recommended and optimal layers for the pumping elevation in Cooby reservoir.

### *7.4.2 Risks in Cressbrook Dam*

The same six parameters were used to assess the optimum water quality management strategy for Cressbrook Dam. Water depths with the highest probability of safe levels of quality were considered as potential pumping levels. To date, there has been no artificial mixer installed in the reservoir but the simulations show the impact of mixing. The risk analysis which follows describes the probability of future conditions in the vertical profile as a result of artificial mixing.

7.4.2.1 Risks without artificial mixer

The probability profiles for the occurrence of safe levels of the six parameters are presented in Figure 7.42. Total iron and total manganese are always at acceptable, or “safe”, levels in all parts of the profile. Safe levels of nitrate and total phosphorus occur frequently only from the surface to about 8 m depth. They only occur for about 19 per cent of the time at 15 – 30 m depth and then between 0 and 12 per cent or between 13 and 43 per cent of the time respectively for total phosphorus and nitrate. A high probability of safe levels of dissolved oxygen exists from the surface to about 32 m depth. In contrast, cyanobacterial levels are not likely to be at safe in the epilimnion layer. However the cyanobacterial concentration will be safe below a depth of 15 m.

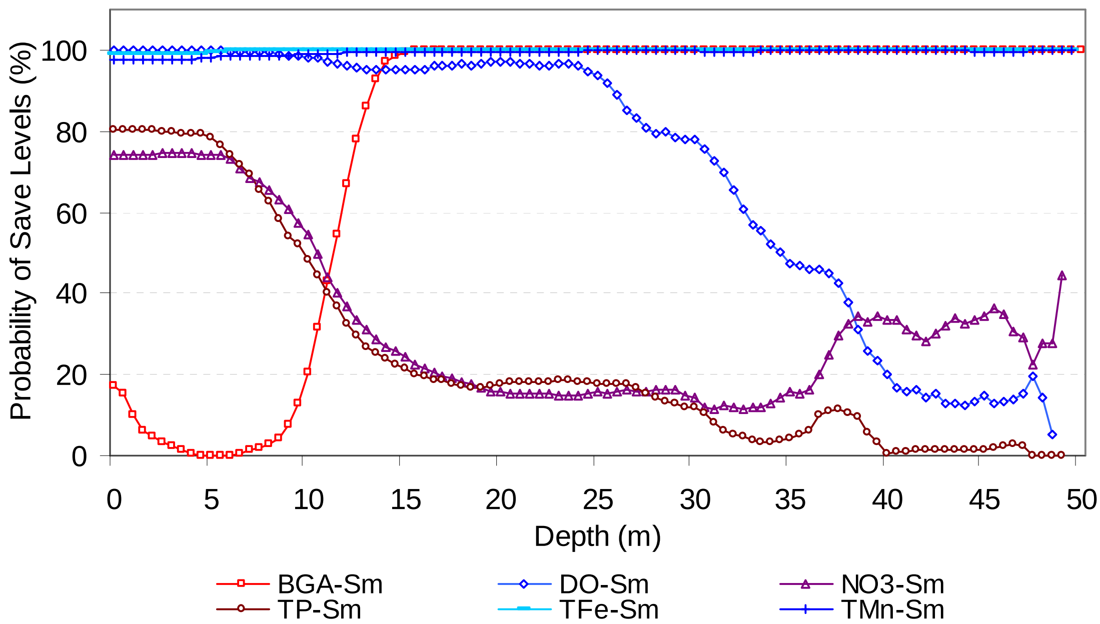



Figure 7.42 Probability of safe levels of analysed parameters occurring through the water column without artificial mixers during the warm period in Cressbrook Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

Figure 7.42 shows that no single layer simultaneously achieves an acceptable probability of safe levels for all indicators. The epilimnion has a high risk of excessive Cyanobacteria while the layer between 13 m and 30 m has a high risk of unacceptable nitrate and total phosphorus concentrations. The treatment of nitrate and phosphorus is easier to do than cyanobacterial treatment and the removal of algal toxins. The consumption of water with a high cyanobacterial concentration also represents a high risk to human health. Based on this consideration, the layer between 12 m and 30 m is suggested for the pumping intake level during the warm period without artificial mixers.

During the cold period from May to October, total iron and total manganese remain at safe levels throughout the water column as shown in Figure 7.43. Similarly, the dissolved oxygen concentration is always acceptable in the epilimnion layer. The probability of safe levels of total phosphorus occurring in the epilimnion layer (0 – 10 m depth) is just above 60 per cent but decreases in lower levels. Safe levels of nitrate are not as reliable, ranging between 27 per cent and 65 per cent in the hypolimnion layer and staying constant at about 45 per cent in the epilimnion. The cyanobacterial level tends to be unsafe in the epilimnion layer but the probability of safe levels rises to greater than 60 per cent of the time in the hypolimnion (below 14 m depth).

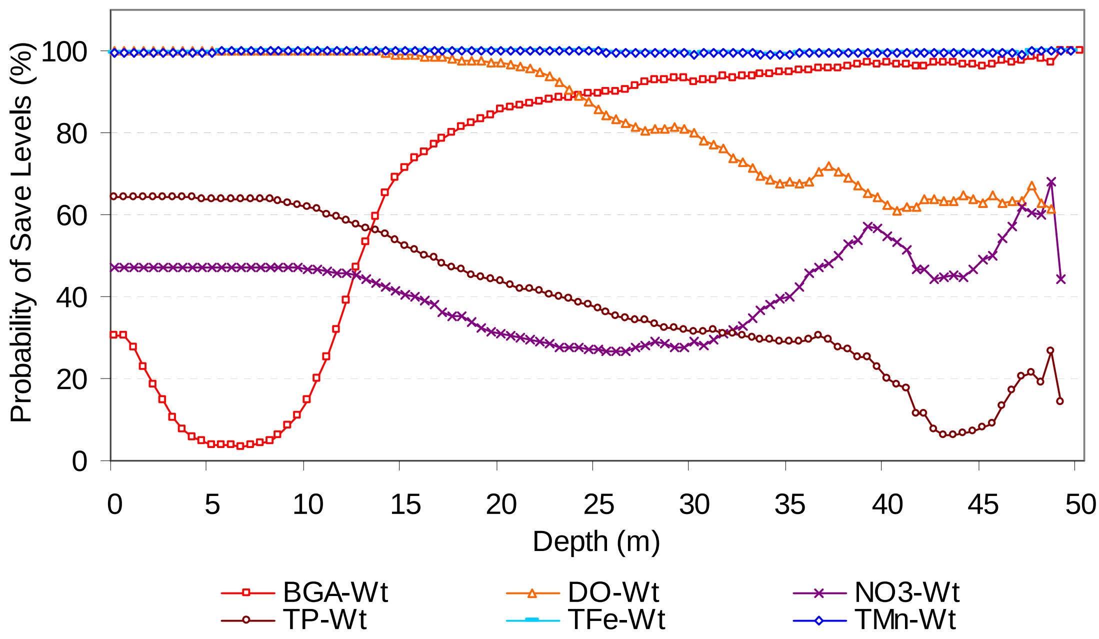



Figure 7.43 Probability of safe levels of analysed parameters occurring through the water column without artificial mixers during the cold period in Cressbrook Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

Figure 7.43 shows that no single layer has the probability of safe levels above 60 per cent for all six parameters at once. In selecting a recommended pumping depth, the cyanobacterial level should be given the highest priority. The layer between 14 m and 36 m was adopted as the appropriate position for withdrawals from the storage during the cold period.

### 7.4.2.2 Risks with the use of the artificial mixers

The limnology of Cressbrook Dam is different to that of Cooby because of its greater depth.

During the warm period, the existence of safe levels of the six indicators is more variable through the water column. In the top layer (0 – 15 m depth), the dissolved oxygen, total iron and total manganese indicators always exist at a safe level. The other three indicators have acceptable levels for less than 60 per cent of the time. From 15 to 37 m below water surface, the cyanobacterial concentration is increasingly safe with depth. The probability ranges from 60 per cent to just below 100 per cent. There are four indicators at a safe level (Cyanobacteria, dissolved oxygen, total iron and total manganese) with a high probability of occurrence in this layer.

Below 37 m depth, the probabilities of safe levels of dissolved oxygen, nitrate and total phosphorus decrease to about 5 per cent, 0 per cent, and 12 per cent, respectively. These results are summarised in Figure 7.44.

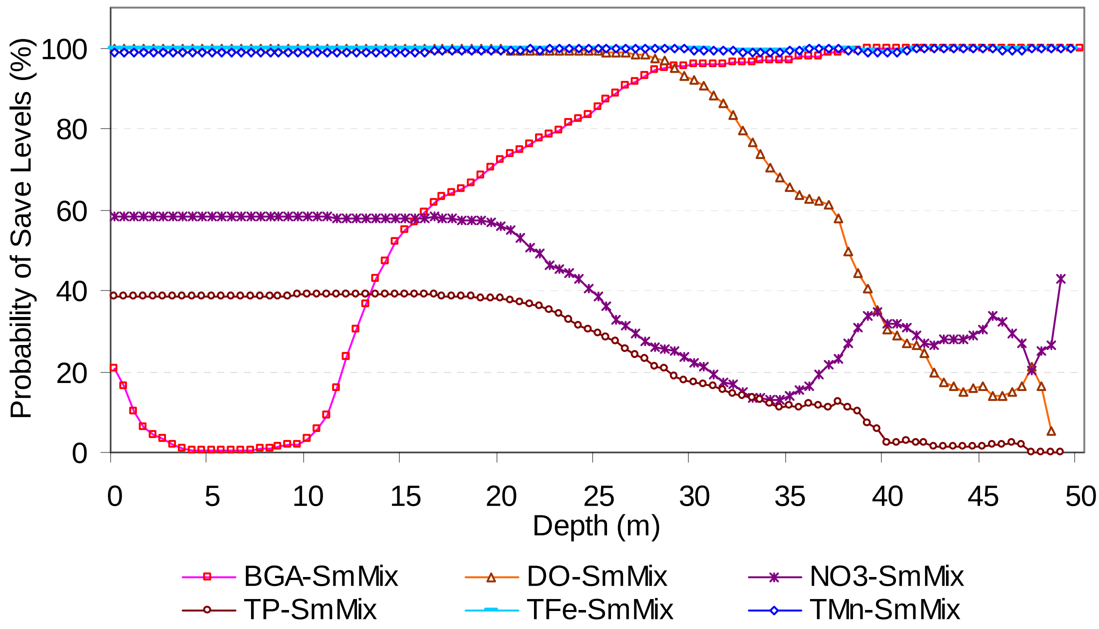



Figure 7.44 Probability of safe levels of analysed parameters occurring through the water column with artificial mixers during the warm period in Cressbrook Dam. BGA is Cyanobacteria, DO is Dissolved Oxygen, $NO_3$ is Nitrate, TP is Total Phosphorus, TFe is Total Iron, and TMn is Total Manganese.

Figure 7.44 shows that each layer of the reservoir has a high probability of at least one of the indicators being at an unsafe level. As before, the management of cyanobacterial blooms is a major objective of this project, and because of the significant health risks it poses this parameter becomes a main priority (the biggest weighting factor value). As a result, the layer between 16 m and 37 m is concluded to be the appropriate pumping elevation in the storage during the period November to April.

During the cold period, the probability profile for safe levels of the indicators changes as shown in Figure 7.45. Cyanobacteria, dissolved oxygen, nitrate and total phosphorus show significant changes while total iron and total manganese remain the same as during the warm period. The safe level for dissolved oxygen possibly occurs for at least 60 per cent of the time at all depths. The cyanobacterial level is likely to be unsafe in the epilimnion layer but safe in the hypolimnion layer.

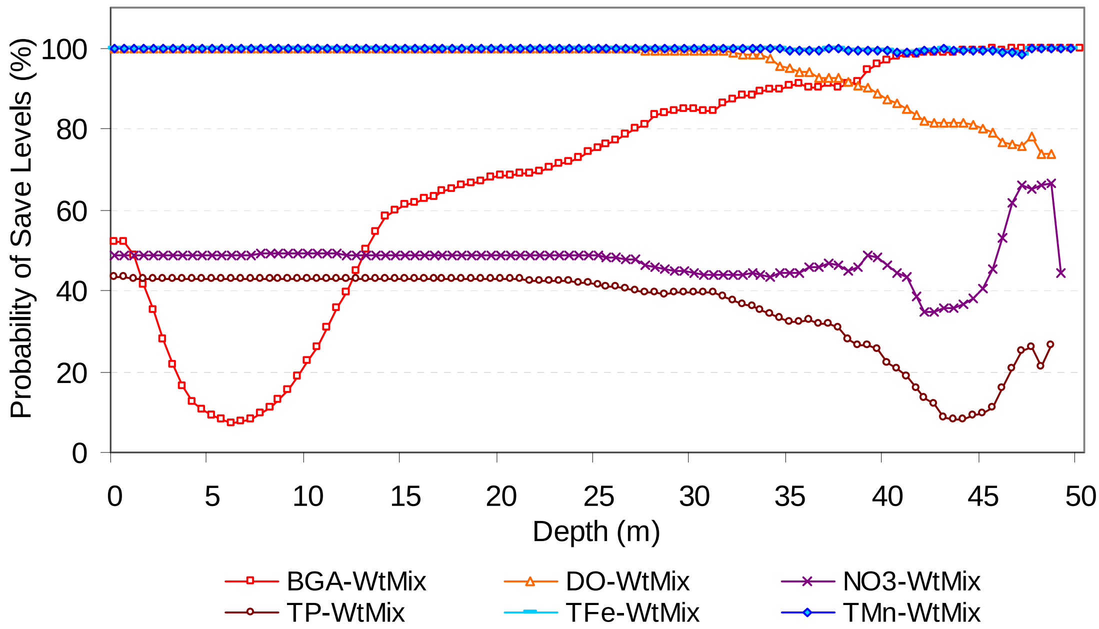



Figure 7.45 Probability of safe levels of analysed parameters occurring through water column with artificial mixers during the cold period in Cressbrook Dam. BGA is Cyanobacteria, DO is dissolved oxygen, $NO_3$ is nitrate, TP is total phosphorus, TFe is total iron, and TMn is total manganese.

The layer between 16 m and 38 m gives the most reliable quality for withdrawal and the cyanobacterial level is expected to be safe from occurrences for most of the time.

A summary of recommended pumping layers in the storage is presented in Table 7.46. The matrix recommends pumping layers for during the cold and the warm period, and the two groupings overlap intersection as shown in Figure 7.46. Without an artificial mixer, safe levels can be reliably attained at between 14 m and 30 m depth throughout the year.

The pumping position is located at 22 m from the bottom of the reservoir. With an average depth of 44 m, this means that the pump is located at 22 m below the water surface (in the range of suggested pumping layers 14 – 30 m). The use of the artificial mixers increases the range of recommended pumping elevations which then lies between 16 m and 37 m depth.

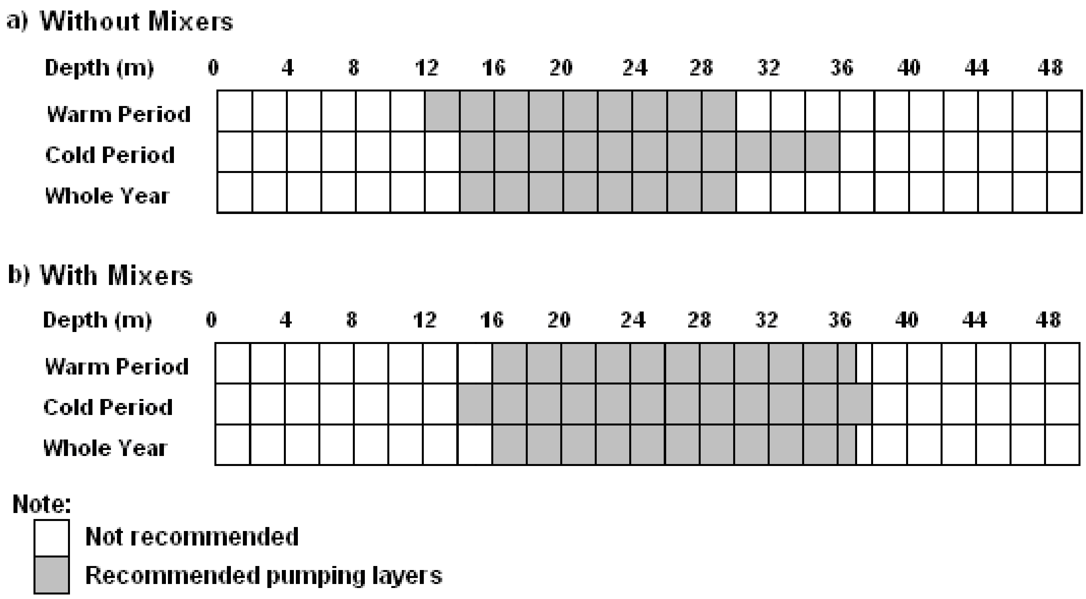



Figure 7.46 Matrix of recommended pumping layers in Cressbrook reservoir.

# Chapter 8

# CONCLUSIONS

I would start with a statement that the project objective has been met, and repeat the wording of that objective from Chapter One. Then move to specific conclusions.

Historically, the behaviour of Cooby and Cressbrook reservoirs differs during the warm and the cold periods. Thermal stratification can be strong in the reservoir during the summer season (the warm period) as is indicated by a high value of the stratification index (SI). The concentration of Cyanobacteria is also relatively higher at this time. The frequency of level 3 algal alerts was also calculated from 1998 to 2002 in the reservoirs.

The volume in storage is trending down under current management procedures. Cooby reservoir would need to reduce the evaporation loss by 5.7 per cent or increase rainfall by 5 per cent to sustain the reservoir. To sustain Cressbrook storage, the surface evaporation would need to be reduced by at least 12 per cent. The distributions of time averaged water quality parameters in both storages show significant difference of the reservoirs' behaviour between the warm and the cold periods over a 50 years simulation period.

The DYRESM-CAEDYM model was adopted and calibrated for simulating the quantity and quality of water in the reservoirs. The model was used for predicting water quality over a 50-year period in the reservoirs.

The mechanical destratifiers can improve the average quality of water in the reservoirs. There is however no effect from the mixers on pH or salinity concentrations.

A WQI was developed to integrate the following parameters: cyanobacterial concentration, dissolved oxygen, pH, water temperature, total phosphorus, nitrate, salinity, total manganese, and total iron.

The WQI values for Cooby Dam decrease from excellent to good, during the warm period in particular. The mixers increase the WQI values by up to 15 grade points at the surface layer, the pumping layer, and on average through the whole profile.

The WQI values for Cressbrook Dam follow a decadal pattern. Every decade, the WQIs follow a decreasing trend and then step up again in a sawtooth pattern. In general, the WQI tends to increase from good to excellent within a 50-year period. The surface mixers increase the WQI by only 4 grade points on average.

Safe water quality levels are most likely to be found at 8 – 10 m depth for the whole year in Cooby Dam in the absence of artificial mixers. The best water quality can not be attained from a single pumping elevation as the depth changes. Therefore, managed multi-level withdrawals would provide a best/optimal water quality from the storage. Artificial mixers are able to extend the acceptable range of pumping elevations to 9 – 20 m depth. The optimal water quality can be achieved with a single fixed pumping elevation at 15 m depth when the mixers are used.

In Cressbrook reservoir, safe levels of water quality are reliably found at the layer between 14 m and 30 m depth in the absence of artificial surface mixers. An appropriate water quality can be achieved throughout the year with a multi-level withdrawal. This is because nitrate and total phosphorus ratings have a low probability of occurring at the safe level. The current pumping position is located 22 m from the bottom of the reservoir. With an average depth of 44 m, the location of the pump is 22 m below the water surface (in the range of suggested pumping layers 14 – 30 m). The use of the artificial mixers will lower the recommended pumping elevation range to 16 – 37 m depth.

To sum up, mechanical mixers can be a benefit for both reservoirs. In Cooby, dissolved oxygen, water temperature and nitrate are the parameters which gain most improvement from the mixers. In Cressbrook, most parameters are improved except for cyanobacterial concentrations below 15 m depth.

The vertical circulation from mixers in both reservoirs decreases the cyanobacterial concentrations at its optimal growth layer. However, it increases the concentration of Cyanobacteria in deeper layers because of the increased availability of oxygen and the introduction of warmer water.

A multi-level withdrawal is recommended to attain optimal quality of the raw water for the Mt. Kynoch Water Treatment Plant.

The results presented in this thesis represent the maximum amount of information that can be extracted from existing data. Extra measured data on the quantity and quality of inflow to the reservoirs would be needed to improve the accuracy of the water quality simulations. With actual inflow data, the assumption of constant quality inflow can be tested. It is also suggested to have a fixed water quality measurement point for each reservoir to minimise inaccuracy in the recorded data.

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# Appendices

# Appendix A.1 Files of water quality simulations of Cooby reservoir

### *Batch file|*

```
createDYref CoobyPWQ.stg CoobyPWQ.met CoobyPWQ.inf CoobyPWQ.wdr DYref.nc
createDYsim CoobyPWQ.pro CoobyPWQ.par CoobyPWQ.con DYsim.nc
extractDYinfo DYref.nc DYsim.nc CoobyPWQ.cfg
dycd>log.txt
```

### *Configuration file*

```
<#4>
! DYRESM-CAEDYM configuration file for Cooby
2004001                 # Simulation start day
18263                   # Simulation length (unit=days)
.TRUE.                  # Run CAEDYM (.TRUE. or .FALSE.)
7                       # Output Interval (in days, or -9999 for every time step)
0.4                     # Light extinction coefficient (m-1)
0.00                    # Benthic Boundary Thickness (m)
0.5                     # Min layer thickness (m)
3.0                     # Max layer thickness (m)
7200                    # Time Step (s)
10                      # Number of Output Selections
SALINITY TEMPTURE DENSITY DO NO3 TP TFE TMN CYANO PH  # List of Output Selections
.FALSE.                      # Activate destrat system (.TRUE. or .FALSE.)
.TRUE.                  # Activate non-neutral atmospheric stability
(.TRUE. or .FALSE.)
```

*Note*: If the mixers are operated, the destratification system is set to .TRUE.

### *Morphometry file*

```
<#3>
! WQCooby morphometry
-27.40                            # latitude
465                               # height above MSL
2                                  # number of inflowing streams
20 87  0.16  0.015  Geham          # 1/2-angle, slope, drag coeff, name
20 89  0.16  0.015  Cooby          # 1/2-angle, slope, drag coeff, name
0                                  # zero height elevation (m)
22.60                              # crest elevation    (m)
1                                  # no.  of outlets.
10.06                              # outlet elevation (m)
9                                  # number of stg survey points
Elev(m) Area(m2)
1.26   16270
4.31   81976
7.36   336977
10.41  591977
13.46  1143280
16.50  1679564
19.55  2273419
22.60  3010575
25.50 4200000
```

## *Initial physical file*

```
WQCooby day 2003365
21       # number of layers
DEPTH  TEMP   SAL
0.6    24.90  0.50
1.5    24.90  0.50
3.5    24.90  0.50
4.5    24.90  0.50
5.5    24.90  0.50
6.5    24.90  0.50
7.5    24.90  0.50
8.5    24.60  0.50
9.5    23.00  0.50
10.5   21.50  0.50
11.5   20.30  0.50
12.5   18.00  0.50
13.5   17.80  0.50
14.5   17.60  0.50
15.5   17.50  0.50
16.5   17.10  0.50
17.5   17.00  0.50
18.5   17.00  0.50
19.5   17.00  0.50
20.5   17.00  0.50
21.15  17.00  0.50
```

## *Initial water quality file*

```
3D DATA
CYANO
 IN_I
 4
 0.6   9.14   16.46  20
 10.0       10.0          5.5       2.0
 0.05
IC_CYA
 CO_I
 0.01
 0
DN_CYA
 CO_I
 996
 996
CHLOR
 CO_I
 -50
 0
IC_CHL
 CO_I
 -50
 0
FDIAT
 CO_I
 9
 0
IC_FDI
 CO_I
 -50
 0
SIZE1
 CO_I
 0.03
 0
SIZE2
 CO_I
 0.003
 0
DO
```

```
 IN_I
 12
 1     2      3      4      5      6      7      8      9      10     11     12
 5.2   5.3    5.4    5.5    5.5    5.5    5.3    4.6    0.2    0.1    0.1    0
 0.05
PO4
 CO_I
 0.0075
 0
IP_CYA
 CO_I
 0.002
 0.08
TP
 IN_I
 4
 0.6   9.14   16.46  20
 0.01  0.01   0.01   0.01
 0
NO3
 IN_I
 4
 0.6   9.14   16.46  20
 0.05  0.2    0.19   0.05
 0
NH4
 CO_I
 0.05
 0
IN_CYA
 CO_I
 0.001
 0.5
TN
 IN_I
 4
 0.6   9.1    16.46  20
 0.75  0.1    0.1    0.1
 0.8
PH
 IN_I
 12
 1     2      3      4      5      6      7      8      9      10     11     12
 7     7      7      7      7      7      7      7      7      7      7      7
 0
SSOL1
 CO_I
 1.3
 4
SSOL2
 CO_I
 8
 0
FBOD
 CO_I
 3
 -10
SBOD
 CO_I
 2
 -10
SiO2
 CO_I
 0.5
 0
FE2
 IN_I
 3
 0.6   16.46  20
 0.02  0.02   0.03
 0
TFE
```

```
 IN_I
 3
 0.6   16.46  20
 0.07  0.04   0.1
 0
MN2
 IN_I
 3
 0.6   16.46  20
 0.005 0.05   0.51
 0
TMN
 IN_I
 3
 0.6   16.46  20
 0.03  0.02   0.58
 0
COL
 CO_I
 5
 0
2D DATA
EOF
```

### *Basic hydrodynamic file*

```
<#5>
Cooby Parameters File.
1.3E-3       # bulk aerodynamic mmt. transport coeff.
0.08         # mean albedo of water
0.96         # emissivity of a water surface           (Imberger & Patterson
[1981,p316])
3.00         # critical wind speed [m s^-1]
36000        # time of day for output (in seconds from midnight)
0.002        # entrainment coefficient constant
0.012        # bubbler entrainment coefficient         (Alexander 2000)
0.083        # buoyant plume entrainment coefficient   (Fischer et al. 1979)
0.080        # shear production efficiency
0.20         # potential energy mixing efficiency
0.06         # wind stirring efficiency (0.06)
1.0E+7       # effective surf. area coeff.
200          # vertical mix coeff.
```

### *Water quality configuration file*

```
 11              ! Transport scheme invoked (0 = external advection)
 0               ! Open boundary condition type (0 = no open boundaries)
 1               ! Method of sediment nutrient flux calculation
 T               ! Simulate colour / tracer
 T               ! Simulate iron
 T               ! Simulate manganese
 F               ! Simulate aluminum
 T               ! Simulate pH
 F               ! Simulate turbulence quantities
 F               ! Print progress messages
 T               ! Print debug information
 CoobyPWQ.int    ! Initialisation file
 CoobyPWQ.dat    ! Constants file
 NULL            ! Inflow forcing file
 NULL            ! 3D forcing file
  1.0            ! Print time step (days)
  360.0          ! Time series time step (minutes)
  1.0            ! Benthic time step (days)
 1               ! Number of phytoplankton groups to simulate
 2               ! Phytoplankton groups to simulate
```

```
 2              ! Number of zooplankton groups to simulate
 1 2              ! Zooplankton groups to simulate
 0              ! Number of jellyfish groups to simulate
 0              ! Number of fish groups to simulate
 0              ! Number of seagrass groups to simulate
 0              ! Number of macroalgae groups to simulate
 0              ! Number of invertebrate groups to simulate
   1  1  -0.25  ! Time series location
 0              ! Phytoplankton time series group
 0              ! Zooplankton time series group
 0              ! Jellyfish time series group
 0              ! Fish time series group
 0              ! Seagrass time series group
 0              ! Macroalgae time series group
 0              ! Invertebrate time series group
 0                ! Number of salinity divisions for time series output
 -1.  10. 25. 99. ! Salinity bounds for time series output
! DYRESM-CAEDYM Cooby configuration.
```

### *Constant water quality parameter file*

```
^@
!-------------------------------------------------------------------------------!
! GENERAL constants                                                             !
!-------------------------------------------------------------------------------!
! Base extinction coefficient                                                   !
     0.39000
!-------------------------------------------------------------------------------!
! PHYTOPLANKTON constants                                                       !
!-------------------------------------------------------------------------------!
! Pmax (/day) : Maximum potential growth rate of phytoplankton                  !
     0.28000           : dinoflagellatte growth rate
     0.46000           : cyanobacteria growth rate
     0.90000           : nodularia growth rate
     1.20000           : chlorophyte growth rate
     0.70000           : cyrptophyte growth rate
     1.90000           : marine diatom growth rate
     1.80000           : freshwater diatom growth rate
! Ycc (mg C/mg chla) : Average ratio of C to chlorophyll a                      !
    85.00000
    40.00000
    40.00000
    25.00000
    47.00000
    42.00000
    60.00000
!-------------------------------------------------------------------------------!
! Light limitation (2=no photoinhibition, 3=photoinhibition)                    !
! algt (no units) : Type of light limitation algorithm                          !
           2
           2
           2
           3
           2
           2
           3
! IK (microE/m^2/s) : Parameter for initial slope of P_I curve                  !
    60.00000
    95.00000
    95.00000
    80.00000
    60.00000
    90.00000
    100.0000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                    !
   150.00000
   200.00000
   200.00000
```

```
   200.00000
   200.00000
   400.00000
   140.00000
! Kep (ug chlaL^-1m^-1) : Specific attenuation coefficient                     !
     0.02000
     0.04000
     0.02000
     0.02000
     0.02000
     0.02000
     0.02000
!------------------------------------------------------------------------------!
! Nutrient limitation                                                          !
! KP (mg/L) : Half saturation constant for phosphorus                          !
     0.00500
     0.00600
     0.01000
     0.01000
     0.00500
     0.00500
     0.01000
! Po (mg/L) : Low concentrations of PO4 at which uptake ceases                 !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! KN (mg/L) : Half saturation constant for nitrogen                            !
     0.02000
     0.00300
     0.00300
     0.07000
     0.02300
     0.01500
     0.03500
! No (mg/L) : Low concentrations of N at which uptake ceases                   !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! Sicon : Constant internal Silica concentration                               !
     0.00000            dinoflagellates
     0.00000            f'water cyanobacteria
     0.00000            nodularia
     0.00000            chlorophytes
     0.00000            cryptophytes
     0.00000            marine diatoms
     0.00000            f'water diatoms
! KSi (mg/L) : Half saturation constant for silica                             !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.14000
     0.14000
! No (mg/L) : Low concentrations of Si at which uptake ceases                 !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! KCa (mg/L) : Half saturation constant for carbon                             !
     2.00000
```

```
      2.00000
      2.00000
      2.00000
      2.00000
      2.00000
      2.00000
! INmin (mg N/mg Chla) : Minimum internal N concentration                      !
      2.80000
      2.50000
      2.50000
      3.50000
      2.50000
      2.50000
      3.50000
! INmax (mg N/mg Chla) : Maximum internal N concentration                      !
      6.50000
      5.00000
      6.00000
      6.00000
      6.00000
      6.00000
      6.00000
! IPmin (mg P/mg Chla) : Minimum internal P concentration                      !
      1.00000
      0.10000
      1.00000
      1.00000
      1.00000
      1.00000
      1.00000
! IPmax (mg P/mg Chla) : Maximum internal P concentration                      !
      0.68000
      1.20000
      1.20000
      1.24000
      1.20000
      1.20000
      1.20000
! ICmin (mg C/mg Chla) : Minimum internal C concentration                      !
     48.00000
     15.00000
     15.00000
     25.00000
     15.00000
     15.00000
     15.00000
! ICmax (mg C/mg Chla) : Maximum internal C concentration                      !
     80.00000
     80.00000
     80.00000
     80.00000
     80.00000
     80.00000
     80.00000
! UCmax (mg C/mg Chla/day) : Maximum rate of carbon uptake                     !
     50.00000
      1.50000
      1.50000
      1.50000
      1.50000
      1.50000
      1.50000
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
      1.08000
      1.09000
      1.08000
      1.05000
      1.08000
      1.08000
      1.04000
```

```
! Tsta (Deg C) : Standard temperature                                        !
    20.00000
    26.00000
    20.00000
    22.00000
    20.00000
    19.00000
    19.00000
! Topt (Deg C) : Optimum temperature                                         !
    33.00000
    33.00000
    33.00000
    28.00000
    33.00000
    27.00000
    22.00000
! Tmax (Deg C) : Maximum temperature                                         !
    39.00000
    40.00000
    39.00000
    36.00000
    39.00000
    32.00000
    34.00000
!----------------------------------------------------------------------------!
! Respiration, mortality, and excretion.
!
! kr (/day) : Respiration rate coefficient                                  !
     0.03000
     0.15000
     0.10000
     0.20000
     0.15000
     0.12000
     0.14000
! vR (no units) : Temperature multiplier (no units)                          !
     1.08000
     1.09000
     1.08000
     1.10000
     1.08000
     1.08000
     1.05000
!----------------------------------------------------------------------------!
! Salinity limitation                                                        !
! maxSP (psu) : Maximum potential salinity                                   !
    36.00000  dinoflagellates
    36.00000            f'water cyanobacteria
    36.00000            nodularia
    36.00000            chlorophytes
    36.00000            cryptophytes
    36.00000            marine diatoms
    36.00000            f'water diatoms
! phsal (no units) : Type of water environment (Angeline 23/08/2000)
!
    0
    0
    2
    0
    1
    1
    0
! Sop (psu) : Minimum bound of salinity tolerance                            !
    18.00000
     3.00000
    28.00000
    14.00000
    20.00000
    30.00000
     1.00000
! Bep (no units) : Salinity limitation value at S=0 and S=maxSP              !
     2.00000
```

```
     3.00000
     2.00000
     2.50000
     2.00000
     5.00000
     5.00000
! Aep (no units) : Salinity limitation value at S=Sop                          !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
!-------------------------------------------------------------------------------!
! Vertical migration and settling  (0-stokes, 1-constant, 2-motile w/o
photoinhibition 3-motile w/ photoinhibition         !
! phvel (no units) : Type of vertical migration algorithm                      !
           3
           3
           0
           1
           1
           1
           1
! c1 (kgm^-3min^-1) : Rate coefficient for density decrease                    !
     0.90000            dinoflagellates
     0.90000            f'water cyanobacteria
     0.90000            nodularia
     0.20000            chlorophytes
     0.90000            cryptophytes
     0.90000            marine diatoms
     0.90000            f'water diatoms
! c3 (kgm^-3min^-1) : Minimum rate of density decrease with time               !
     0.04150            dinoflagellates
     0.04150            f'water cyanobacteria
     0.04150            nodularia
     0.040              chlorophytes
     0.04150            cryptophytes
     0.04150            marine diatoms
     0.04150            f'water diatoms
! c4 (mhr^-1) : Rate for light dependent migration velocity                    !
     2.50000  dinoflagellates
     0.85000            f'water cyanobacteria
     0.85000            nodularia
     0.800              chlorophytes
     0.85000            cryptophytes
     0.85000            marine diatoms
     0.85000            f'water diatoms
! c5 (mhr^-1) : Rate for nutrient dependent migration velocity                 !
     0.20000  dinoflagellates
     0.65000            f'water cyanobacteria
     0.65000            nodularia
     0.15000            chlorophytes
     0.65000            cryptophytes
     0.65000            marine diatoms
     0.65000            f'water diatoms
! IKm (uEm^-2s^-1) : Half saturation constant for density increase             !
    26.00000  dinoflagellates
    25.00000            f'water cyanobacteria
    25.00000            nodularia
    25.00000            chlorophytes
    25.00000            cryptophytes
    25.00000            marine diatoms
    25.00000            f'water diatoms
! min_pd (kg/m^3) : Minimum phytoplankton density
   980.00000  dinoflagellates
   980.00000            f'water cyanobacteria
   980.00000            nodularia
   980.00000            chlorophytes
   980.00000            cryptophytes
   980.00000            marine diatoms
```

```
   980.00000            f'water diatoms
! max_pd (kg/m^3) : Maximum phytoplankton density
  1050.00000  dinoflagellates
  1050.00000            f'water cyanobacteria
  1050.00000            nodularia
  1030.00000            chlorophytes
  1050.00000            cryptophytes
  1050.00000            marine diatoms
  1050.00000            f'water diatoms
! pw20 (kgm^-3) : Density of water at 20 deg C                                 !
  1000.00000
! dia (m) : Diameter of phytoplankton                                          !
 0.10000E-04
 0.40000E-04      (range 0.25-0.60E-04m)
 0.50000E-04
 0.10000E-04
 0.10000E-04
 0.10000E-04
 0.20000E-04
! ws (ms^-1) : Constant settling velocity                                      !
 0.10000E-04
 0.69440E-04
 0.50000E-04
 -2.00000E-06
 0.10000E-04
 0.10000E-04
 -3.5000E-06
! oth (mg/l) dissolved oxgyen threshold for migration of motile phytoplankton  !
 0.0
 0.0
 0.0
 0.0
 0.0
 0.0
 0.0
!------------------------------------------------------------------------------!
! Resuspension                                                                !
! tcpy (N/m^2) : Critical shear stress
     0.02000  dinoflagellates
     0.03000            f'water cyanobacteria
     0.05000            nodularia
     0.05000            chlorophytes
     0.05000            cryptophytes
     0.05000            marine diatoms
     0.05000            f'water diatoms
! alpPy (mg Chla/m^2/s) : Resuspension rate constant                           !
 0.23000E-03
! KTPy (mg Chla/m^2) : Controls rate of resuspension                           !
     1.00000  dinoflagellates
     2.00000            f'water cyanobacteria
     2.00000            nodularia
     2.00000            chlorophytes
     2.00000            cryptophytes
     2.00000            marine diatoms
     2.00000            f'water diatoms
! DTphy (days) : Phytoplankton sediment survival time                          !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! JELLYFISH constants                                                          !
!------------------------------------------------------------------------------!
! Jmax (/day) : Maximum potential growth rate of jellyfish                     !
     0.40000
! Ycj (mg C/mg medusae) : Carbon meduase ratio                                 !
     0.00400
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
```

```
! vT (no units) : Temperature multiplier                                      !
     1.08000
! Tsta (Deg C) : Standard temperature                                         !
    20.00000
! Topt (Deg C) : Optimum temperature                                          !
    33.00000
! Tmax (Deg C) : Maximum temperature                                          !
    39.00000
!-----------------------------------------------------------------------------!
! Salinity limitation                                                         !
! Sop (psu) : Minimum bound of salinity tolerance                             !
    25.00000
! Bep (no units) : Salinity limitation value at S=0 and S=maxSP               !
    27.00000
! Aep (no units) : Salinity limitation value at S=Sop                         !
     1.00000
!-----------------------------------------------------------------------------!
! Light limitation.                                                           !
! algt (no units) : Type of light limitation algorithm                        !
           2
! IK (microE/m^2/s) : Parameter for initial slope of P-I curve                !
    90.00000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                  !
    90.00000
!-----------------------------------------------------------------------------!
! Nutrient limitation                                                         !
! KP (mg/L) : Half saturation constant for phosphorus                         !
     0.01000
! Po (mg/L) : Low concentrations of PO4 at which uptake ceases                !
     0.00000
! KN (mg/L) : Half saturation constant for nitrogen                           !
     0.02500
! No (mg/L) : Low concentrations of N at which uptake ceases                  !
     0.00000
!-----------------------------------------------------------------------------!
! Respiration mortality and excretion.                                        !
! krj (/day) : Respiration rate coefficient                                   !
     0.10000
! ke (/day) : Excretion rate coefficient                                      !
     0.10000
! KBODj (mg BOD/L) : Half saturation constant for organic nutrition           !
     2.00000
! vuk (m/s) : Upward swimming velocity constant                               !
     0.01000
! vdk (m/s) : Downward sinking velocity constant                              !
     0.00000
!-----------------------------------------------------------------------------!
! ZOOPLANKTON constants                                                       !
!-----------------------------------------------------------------------------!
! az (no units) : assimilation rate                                           !
     0.30000  : rotifers/small cladocerans
     0.30000  : large cladocerans/copepods
     0.30000
     0.30000
     0.30000
!-----------------------------------------------------------------------------!
! Respiration mortality and excretion.                                        !
! fzz (no units) : Fraction of loss contributing to excretion only            !
     0.20000
! kz (/day) : Respiration rate coefficient                                    !
     0.10000
     0.05000
     0.05000
     0.05000
     0.05000
!-----------------------------------------------------------------------------!
! Salinity limitation                                                         !
! Smxz (psu) : Maximum salinity, or optimum salinity for SIZE5                !
    50.00000
    50.00000
    28.00000
    28.00000
```

```
    27.00000
! Smnz (psu) : Minimum salinity                                               !
     0.00000
     0.00000
     6.00000
     6.00000
     0.00000
! Bez (no units) : Salinity intercept (for S=0)                               !
     0.00000
     0.00000
     2.00000
     2.00000
     2.00000
!-----------------------------------------------------------------------------!
! Dissolved oxygen limitation                                                 !
! DOmz (mg/L) : Minimum DO tolerance                                          !
     0.00000
     0.00000
     0.00000
     1.00000
     1.00000
!-----------------------------------------------------------------------------!
! Temperature representation                                                  !
! vT (no units) : Temperature multiplier for growth NOTE SET TO 1.08 in
params.dat regardless of value HERE though this is the value used  !
     1.06000
     1.10000
     1.10000
     1.10000
     1.10000
! Tsta (Deg C) : Standard temperature                                         !
    20.00000
    20.00000
    20.00000
    20.00000
    20.00000
! Topt (Deg C) : Optimum temperature                                          !
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
! Tmax (Deg C) : Maximum temperature                                          !
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
!-----------------------------------------------------------------------------!
! Grazing                                                                     !
! ki (g phyto C/m^3)/(g zoo C/m^3)/day) : Grazing rate                        !
     1.00000            : SIZE1 grazing rate
     0.40000          : SIZE2 grazing rate
     0.72000
     0.20000
     0.20000
! vZ (no units) : Grazing/Respiration temperature dependence                  !
     1.12000
     1.06000
     1.07000
     1.07000
     1.07000
! Pij (no units) : Preference of zooplankton for phytoplankton                !
     0.11000    : SIZE1 on DINOF
     0.25000    : SIZE2 on DINOF
     0.28000    : SIZE3 on DINOF
     0.00000    : SIZE4 on DINOF
     0.00000    : SIZE5 on DINOF
     0.00000    : SIZE1 on CYANO
     0.00000    : SIZE2 on CYANO
     0.00000    : SIZE3 on CYANO
     0.20000    : SIZE4 on CYANO
```

```
     0.20000    : SIZE5 on CYANO
     0.00000    : SIZE1 on NODUL
     0.00000    : SIZE2 on NODUL
     0.00000    : SIZE3 on NODUL
     0.00000    : SIZE4 on NODUL
     0.00000    : SIZE5 on NODUL
     1.00000    : SIZE1 on CHLOR
     0.00000    : SIZE2 on CHLOR
     0.00000    : SIZE3 on CHLOR
     0.00000    : SIZE4 on CHLOR
     0.00000    : SIZE5 on CHLOR
     0.00000    : SIZE1 on CRYPT
     0.00000    : SIZE2 on CRYPT
     0.00000    : SIZE3 on CRYPT
     0.00000    : SIZE4 on CRYPT
     0.00000    : SIZE5 on CRYPT
     0.00000    : SIZE1 on MDIAT
     0.00000    : SIZE2 on MDIAT
     0.00000    : SIZE3 on MDIAT
     0.00000    : SIZE4 on MDIAT
     0.00000    : SIZE5 on MDIAT
     0.00000    : SIZE1 on FDIAT
     0.00000    : SIZE2 on FDIAT
     0.00000    : SIZE3 on FDIAT
     0.00000    : SIZE4 on FDIAT
     0.00000    : SIZE5 on FDIAT
! Pzij (no units) : Preference of zooplankton for zooplankton                    !
     0.00000    : SIZE1 prey of SIZE1
     0.00000    : SIZE1 prey of SIZE2
     0.23000    : SIZE1 prey of SIZE3
     0.00000    : SIZE1 prey of SIZE4
     0.00000    : SIZE1 prey of SIZE5
     0.00000    : SIZE2 prey of SIZE1
     0.00000    : SIZE2 prey of SIZE2
     0.00000    : SIZE2 prey of SIZE3
     0.00000    : SIZE2 prey of SIZE4
     0.00000    : SIZE2 prey of SIZE5
     0.00000    : SIZE3 prey of SIZE1
     0.00000    : SIZE3 prey of SIZE2
     0.00000    : SIZE3 prey of SIZE3
     0.00000    : SIZE3 prey of SIZE4
     0.00000    : SIZE3 prey of SIZE5
     0.00000    : SIZE4 prey of SIZE1
     0.00000    : SIZE4 prey of SIZE2
     0.00000    : SIZE4 prey of SIZE3
     0.00000    : SIZE4 prey of SIZE4
     0.00000    : SIZE4 prey of SIZE5
     0.00000    : SIZE5 prey of SIZE1
     0.00000    : SIZE5 prey of SIZE2
     0.00000    : SIZE5 prey of SIZE3
     0.00000    : SIZE5 prey of SIZE4
     0.00000    : SIZE5 prey of SIZE5
! Pbij (no units) : Preference of zooplankton for detritus                       !
     0.00000    : FBOD by SIZE1
     0.00000    : FBOD by SIZE2
     0.00000    : FBOD by SIZE3
     0.00000    : FBOD by SIZE4
     0.00000    : FBOD by SIZE5
     0.00000    : SBOD by SIZE1
     0.00000    : SBOD by SIZE2
     0.00000    : SBOD by SIZE3
     0.00000    : SBOD by SIZE4
     0.00000    : SBOD by SIZE5
! Kj (g C/m^3) : Half saturation constant for grazing                            !
     1.32000
     0.24000
     0.62000
     1.00000
     1.00000
!--------------------------------------------------------------------------------!
! Predation                                                                      !
! kk (/day) : Grazing rate of fish on zooplankton                                !
```

```
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
! PFi (no units) : Preference of fish for zooplankton                       !
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
! KFk (g/m^3) : Half saturation constant for grazing                        !
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
!---------------------------------------------------------------------------!
! FISH constants                                                            !
!---------------------------------------------------------------------------!
! swin (m/s) : Swimming speed                                               !
     0.02000
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
! mfl (/day) : Threshold of fish mortality                                  !
     0.30000
     0.30000
     0.30000
     0.30000
     0.30000
     0.30000
     0.30000
     0.30000
     0.30000
! mtol (%) : Mortality migration tolerance                                  !
     2.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
!---------------------------------------------------------------------------!
! Temperature representation                                                !
! vT (no units) : Temperature multiplier                                    !
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
! Tsta (Deg C) : Standard temperature                                       !
    20.00000
```

```
    20.00000
    20.00000
    20.00000
    20.00000
    20.00000
    20.00000
    20.00000
    20.00000
! Topt (Deg C) : Optimum temperature                                         !
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
! Tmax (Deg C) : Maximum temperature                                         !
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
!----------------------------------------------------------------------------!
! Salinity limitation                                                        !
! maxS (psu) : Maximum potential salinity                                    !
    45.00000
! SL (psu) : Optimal salinity growth for fish                                !
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
! SU (psu) : Salinity response for S>Slim (not including MULLT)              !
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
! cfs (no units) : Max. fractional salinity respiration increment            !
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
!----------------------------------------------------------------------------!
! Dissolved oxygen limitation.                                               !
! DOmin (mg/L) : Lower dissolved oxygen tolerance                            !
     0.00000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
```

```
     0.50000
     0.50000
! KDO (mg/L) : Dissolved oxygen response for DO>=DOmin (mg/L)                  !
     0.40000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! ofl (no units) : Max. fractional oxygen respiration increment                 !
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
!------------------------------------------------------------------------------!
! Predation response to light.                                                 !
! dfs (no units) : Max. fractional light respiration increment                 !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! Ikf (uE/m^2/s) : Half saturation constant for light                          !
   400.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! Grazing constants                                                            !
! FZ (/day) : Grazing rate                                                     !
     0.14000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
! KFb (g C/m^2) : Half saturation constant for grazing on benthos              !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! PFij (no units) : Preference of fish grazing on invertabrates                !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
```

```
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! PFij (no units) : Preference of fish grazing on detritus                     !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
!------------------------------------------------------------------------------!
! Respiration, mortality and excretion                                         !
! kf (/day) : Respiration rate coefficient                                     !
     0.07000
     0.08000
     0.08000
     0.08000
     0.08000
     0.08000
     0.08000
     0.08000
     0.08000
! vF (no units) : Temperature multiplier for respiration                       !
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
!------------------------------------------------------------------------------!
! Biomass size distribution                                                    !
! Ft1 (mg C change/mg fish C/day) : Threshold biomass for adults               !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! Ft2 (mg C change/mg fish C/day) : Threshold biomass for juveniles            !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
```

```
     1.00000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! SEAGRASS constants                                                           !
!------------------------------------------------------------------------------!
! Yes (no units) : Ration of epiphyte C to seagrass C                          !
     1.00000
! Vmax (/day) : Maximum growth rate                                            !
     0.12500
!------------------------------------------------------------------------------!
! Light limitation                                                             !
! IK (microE/m^2/s) : Parameter for initial slope of P-I curve                 !
   120.00000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                   !
    90.00000
!------------------------------------------------------------------------------!
! Respiration                                                                  !
! kb (/day) : Respiration rate coefficient                                     !
     0.01250
! vB (no units) : Temperature multiplier                                       !
     1.08000
!------------------------------------------------------------------------------!
! Salinity limitation                                                          !
! Sop (psu) : Minimum bound of salinity tolerance                              !
    26.00000
! Bep (no units) : Salinity limitation value at S=0 and S=2 x Sop              !
     5.11600
! Aep (no units) : Salinity limitation value at S=Sop                          !
     0.58200
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
     1.08000
! Tsta (Deg C) : Standard temperature                                          !
    20.00000
! Topt (Deg C) : Optimum temperature                                           !
    25.00000
! Tmax (Deg C) : Maximum temperature                                           !
    30.00000
!------------------------------------------------------------------------------!
! MACROALGAE constants                                                         !
!------------------------------------------------------------------------------!
! Vmax (/day) : Maximum growth rates                                           !
     0.35000
     0.30000
     0.30000
     0.30000
! Ycc (mg C/mg chla) : Average ratio of C to chlorophyll a                     !
    50.00000
    50.00000
    50.00000
    50.00000
!------------------------------------------------------------------------------!
! Light limitation.                                                            !
! algt (no units) : Type of light limitation algorithm                         !
           2
           2
           2
           2
! IK (microE/m^2/s) : Parameter for initial slope of P-I curve                 !
    90.00000
    90.00000
    90.00000
    90.00000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                   !
    90.00000
    90.00000
    90.00000
    90.00000
! Hmac (m/(gm^2)) : Conversion macroalgae biomass to height                    !
```

```
      0.01000
      0.01000
      0.01000
      0.01000
! Kmac (g C/m^2/m) : Specific light attenuation coefficients                   !
      1.00000
      3.00000
      3.00000
      3.00000
!------------------------------------------------------------------------------!
! Nutrient limitation                                                          !
! KP (mg/L) : Half saturation constant for phosphorus                          !
      0.01000
      0.01000
      0.01000
      0.01000
! Po (mg/L) : Low concentrations of PO4 at which uptake ceases                 !
      0.00000
      0.00000
      0.00000
      0.00000
! KN (mg/L) : Half saturation constant for nitrogen                            !
      0.05000
      0.05000
      0.05000
      0.05000
! No (mg/L) : Low concentrations of N at which uptake ceases                   !
      0.00000
      0.00000
      0.00000
      0.00000
! INmin (mg N/mg Chla) : Minimum internal N concentration                      !
      0.00500
      0.00500
      0.00500
      0.00500
! INmax (mg N/mg Chla) : Maximum internal N concentration                      !
      0.02000
      0.02000
      0.02000
      0.02000
! IPmin (mg P/mg Chla) : Minimum internal P concentration                      !
      0.00100
      0.00100
      0.00100
      0.00100
! IPmax (mg P/mg Chla) : Maximum internal P concentration                      !
      0.00000
      0.00000
      0.00000
      0.00000
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
      1.08000
      1.08000
      1.08000
      1.08000
! Tsta (Deg C) : Standard temperature                                          !
     20.00000
     20.00000
     20.00000
     20.00000
! Topt (Deg C) : Optimum temperature                                           !
     33.00000
     33.00000
     33.00000
     33.00000
! Tmax (Deg C) : Maximum temperature                                           !
     39.00000
     39.00000
     39.00000
```

```
    39.00000
!----------------------------------------------------------------------------!
! Salinity limitation                                                        !
! Sop (psu) : Minimum bound of salinity tolerance                            !
    25.00000
    25.00000
    25.00000
    25.00000
! Bep (no units) : Salinity limitation value at S=0 and S=2 x Sop            !
     2.00000
     2.00000
     2.00000
     2.00000
! Aep (no units) : Salinity limitation value at S=Sop                        !
     1.00000
     1.00000
     1.00000
     1.00000
!----------------------------------------------------------------------------!
! Respiration                                                                !
! kb (/day) Respiration rate coefficient                                     !
     0.07000
     0.07000
     0.07000
     0.07000
! vB (no units) : Temperature multiplier for respiration                     !
     1.08000
     1.08000
     1.08000
     1.08000
!----------------------------------------------------------------------------!
! Grazing                                                                    !
! PCm (no units) : Preference of crustaceans grazing on macroalgae           !
     0.20000
     0.20000
     0.20000
     0.20000
!----------------------------------------------------------------------------!
! INVERTABRATE constants                                                     !
!----------------------------------------------------------------------------!
! IZ (g C consumed/(g invert. C)/day) : Maximum consumption rate             !
     0.00000
     0.00000
     0.00000
! KIZ (g C/m^3) : Half saturation constant for grazing                       !
     0.00000
     0.00000
     0.00000
! KDOI (mg/L) : Half saturation for dissolved oxygen limitation              !
     0.00000
     0.00000
     0.00000
! BDOi (no units) : Basal respiration increase from DO limitation            !
     0.00000
     0.00000
     0.00000
!----------------------------------------------------------------------------!
! Salinity limitation                                                        !
! Minimum salinity tolerance for bivalves                                    !
     8.00000
! Maximum salinity tolerance for bivalves                                    !
    35.00000
! Sop (psu) : Minimum bound of salinity tolerance                            !
     8.00000
     8.00000
    25.00000
! Bep (no units) : Salinity limitation value at S=0 and S=2 x Sop            !
     2.00000
     2.00000
     2.00000
! Aep (no units) : Salinity limitation value at S=Sop                        !
     1.00000
```

```
     1.00000
     1.00000
!-------------------------------------------------------------------------------!
! Respiration                                                                   !
! kb (/day) : Respiration rate coefficient                                      !
     0.10000
     0.10000
     0.08000
! vB (no units) : Temperature multiplier                                        !
     1.08000
     1.08000
     1.08000
!-------------------------------------------------------------------------------!
! SUSPENDED SOLID constants                                                     !
!-------------------------------------------------------------------------------!
! denSS (g/m^3) : Mean density of suspended solid in the sediment               !
 0.25000E+07      : SSOL1 sediment density
 0.25000E+07      : SSOL2 sediment density
! des (kg/m^3) : Density of suspended solid particles                           !
 0.11500E+04      : SSOL1 particle density
 0.12500E+04      : SSOL2 particle density
! diaSS (m) : Diameter of suspended solids groups                               !
 0.10000E-04      : SSOL1 particle diameter
 0.10000E-04      : SSOL2 particle diameter
! KeSS (mg^L-1m^-1) : Specific attenuation coefficient                          !
 0.05000E+00      : SSOL1 particle specific attenuation
 0.05000E+00      : SSOL2 particle specific attenuation
!-------------------------------------------------------------------------------!
! Resuspension constants                                                        !
! tcs (N/m^2) : Critical shear stress                                           !
 0.50000E-01
 0.50000E-01
! alpS (g/m^2/s) : Resuspension rate constants                                  !
 0.30000E-03
 0.30000E-03
! KTS (g/m^2) : Controls rate of resuspension                                   !
 0.40000E+00
 0.40000E+00
!-------------------------------------------------------------------------------!
! pH constants                                                                  !
!-------------------------------------------------------------------------------!
     0.00000      kpho (m^3/g O)  : Photosynthetic / respiration pH constant
     0.00000      kphp (m^3/g O)  : BOD pH constant
     1.00000      KDOS (g/m^3)    : Controls release of sediment nutrients via O
     7.00000      KpHS (no units) : Controls release of sediment nutrient via pH
!-------------------------------------------------------------------------------!
! Colour / tracer constants                                                     !
!-------------------------------------------------------------------------------!
     0.00000      decr (/day) : Decay rate for colour/tracer
!-------------------------------------------------------------------------------!
! DISSOLVED OXYGEN constants                                                    !
!-------------------------------------------------------------------------------!
     1.08000   vOP    (no units) : Temperature multiplier for phytoplankton
     1.08000   vON    (no units) : Temperature multiplier for nitrification
     1.60000   KSO    (mg_O/L) : Half saturation cons. for sediment BOD uptake
    50.00000   PCmax  (g/m^2) : Maximum limit of polychaete biomass
     2.66667   YOC    (mg C/mg O) : Respiration stoichiometric ratio of C to
oxygen
     1.00000   YOZ    (mg zooC/mg O) Stoichiometric factor, zooplankton C : DO
     0.10000   fox    (no units) : Fraction of net DO allocated to seagrass roots
     2.66667   YSG    (mg seagC/mg O) : Stoichiometric factor, seagrass C : DO
     2.66667   YOJ    (mg jelC/mg O) : Stoichiometric factor, jellyfish C : DO
     0.05000   koNH   (/day) : Nitrification rate coefficient
     3.42857   YNH    (mg N/mg O) : Ratio for O2 to N during nitrification
     1.50000   KOn    (mg O/L) : Half saturation constant for nitrification
     1.60000   DOs    (cm^2/day) : Molecular diffusion of the sediments
    24.80000   DOb    (cm^2/day) : Diffusivity due to bioturbation
     0.00500   doxmin (m) : Minimum depth of the oxic layer
     0.30000   doxmax (m) : Sediment depth=max depth of the oxic layer
     0.03000   oxmin  (mg/L) : Minimum DO in the bottom layer (mg/L)
     0.10000   rSOs   (g/m^2/day) : Static sediment exchange rate
     2.00000   KSOs   (mg O/L) : 1/2 sat constant for static DO sediment flux
```

```
     0.14000   prc    (no units) : Photo-respiration phytoplankton DO loss
! Fraction of P respiration relative to total loss rate                       !
 0.70000E+00
 0.70000E+00
 0.70000E+00
 0.80000E+00
 0.70000E+00
 0.70000E+00
 0.70000E+00
 0.80000E+00
 0.80000E+00
 0.80000E+00
 0.80000E+00
 0.80000E+00
!-----------------------------------------------------------------------------!
! BOD Cconstants                                                              !
!-----------------------------------------------------------------------------!
     0.12000E+07   denB (g/m^3)    : Mean density of BOD in the sediment
     1.08000   vOB  (no units) : Temperature multiplier for BOD
! dib (m) : Diameter of BOD particles                                         !
    0.1000E-04                    : SBOD diameter
    0.1000E-04             : FBOD diameter
! deb (kg/m^3) : Density of BOD particles                                     !
    0.11000E+04            : SBOD density
    0.10500E+04            : FBOD density
! tc (N/m^2) : Critical shear stress                                          !
     0.05000               : SBOD shear streass
     0.05000               : FBOD shear stress
! Kmass (g/m^2) : Controls rate of resuspension                               !
     0.10000               : SBOD control on rate of resuspension
     0.10000               : FBOD control on rate of resuspension
! alp (g/m^2/s) : Resuspension rate                                           !
    0.12500E-03            : SBOD resuspension rate
    0.12500E-03            : FBOD resuspension rate
! tref (N/m^2) : Reference shear stress                                       !
     1.00000
! koB (/day) : Water column  mineralisation rate                              !
     0.01000               : SBOD mineralization rate
     0.10000               : FBOD mineralization rate
! KBOD (mg BOD/L) : Half saturation constant for mineralisation               !
     5.0000
! kan (no units) : Anerobic relative to aerobic decomposition                 !
     0.30000
! kdB (/day) : Sediment decay rate                                            !
     0.00010               : SBOD sediment decay rate
     0.08000               : FBOD sediment decay rate
! KeBOD (m^2/g) : Specific attenuation coefficient                            !
     0.01000               : SBOD specific attenuation
     0.01000               : FBOD specific attenuation
!-----------------------------------------------------------------------------!
     2.66667   YCBOD  (mg C/mg BOD)    : BOD to C ratio
     2.66667   YBODZ  (mg BOD/mg zooC) : Zooplankton C to BOD ratio
     2.66667   YBODJ  (mg BOD/mg jelC) : Jellyfish C to BOD ratio
     2.66667   YBODPC (mg BOD/mg polC) : Polychaete C to BOD ratio
     2.66667   YBODBV (mg BOD/mg bivC) : Bivalve C to BOD ratio
     2.66667   YBODMB (mg BOD/mg macC) : Macroalgae C to BOD ratio
     0.90000   mabw   (no units)       : Macroalgae beach wrack constant
!-----------------------------------------------------------------------------!
! NITROGEN constants                                                          !
!-----------------------------------------------------------------------------!
! UNmax (mg N/mg Chla/day) : Maximum rate of nitrogen uptake                  !
 0.15000E+01           : uptake rate for dinoflagellates
 0.25000E+01           : uptake rate for cyanobacteria
 0.15000E+01           : uptake rate for nodularia
 0.20000E+01           : uptake rate for chlorophytes
 0.15000E+01           : uptake rate for crptophytes
 0.15000E+01           : uptake rate for marine diatoms
 0.20000E+01           : uptake rate for freshwater diatoms
! UNmax (mg N/mg C/day) : Maximum rate of nitrogen uptake                     !
 0.20000E-02
 0.20000E-02
 0.20000E-02
```

```
 0.20000E-02
! INcon (mg N/mg Chla) : Phytoplankton constant internal nitrogen            !
     3.00000
! INZcon (mg N/mg C) : Zooplankton constant internal nitrogen                !
     7.00000      INZconF : Freshwater systems
     7.00000      INZconM : Marine systems
     7.00000      INZconE : Estuarine systems
   -99.00000      INZcon  : If INZcon/=-99, then use the specified value
!----------------------------------------------------------------------------!
     1.08000      vN2  (no units)  : Temperature multiplier for denitrification
     0.18500      koN2 (/day)      : Denitrification rate coefficient
     0.20000      KN2  (mg/L)      : Half saturation const for denitrification
     0.0100       KMAN (/day)      : Anaerobic organic mineralisation rate
     0.0200       KMN  (/day)      : Aerobic organic mineralisation rate
     1.08000      vM   (no units)  : Temp. multiplier for mineralisation
     1.50000      kONm (mg O/L)    : Half saturation for mineralisation
    -0.10E-5      Nset (m/s)       : Settling velocity for particulate N
     2.50000      tcn  (N/m^2)     : Critical shear stress
     0.00005      alpN (g/m^2/s)   : Resuspension rate constants
     0.50000      KTNr (g/m^2)     : Controls rate of resuspension
     0.10000      Smpn (g/m^2/day) : Maximum potential sediment fluxes
!----------------------------------------------------------------------------!
! PHOSPHORUS constants                                                       !
!----------------------------------------------------------------------------!
! UPmax (mg P/mg Chla/day) : Maximum rate of phosphorus uptake               !
 0.20000E+00
 0.25000E+00
 0.20000E+00
 0.07500E+00
 0.20000E+00
 0.20000E+00
 0.15000E+00
! UPmax (mg P/mg C/day) : Maximum rate of phosphorus uptake                  !
 0.13000E-03
 0.10000E-03
 0.10000E-03
 0.10000E-03
! IPcon (mg P/mg Chla) : Phytoplankton constant internal phosphorus          !
     1.00000
! IPZcon (mg P/mg C) : Zooplankton constant internal phosphorus              !
     1.00000      IPZconF : Freshwater systems
     1.00000      IPZconM : Marine systems
     1.00000      IPZconE : Estuarine systems
   -99.00000      IPZcon  : If INZcon/=-99, then use the specified value
!----------------------------------------------------------------------------!
     0.02000   KOAP (/day)      : Anaerobic organic mineralisation rate
     0.01500   KOP  (/day)      : Aerobic organic mineralisation rate
     1.50000   kOPm (g/m^3)     : Half saturation for mineralisation
    -0.10E-5   Pset (m/s)       : Settling velocity for particulate P
     2.50000   tcp  (N/m^2)     : Critical shear stress
     0.00001   alpP (g/m^2/s)   : Resuspension rate constants
     0.05000   KTP  (g/m^2)     : Controls rate of resuspension
     0.00500   Smpp (g/m^2/day) : Maximum potential sediment fluxes
!----------------------------------------------------------------------------!
! IRON constants                                                             !
!----------------------------------------------------------------------------!
     1.08000   vFeR  (no units)  : Temperature multiplier for reduction
     0.10000   kFeR  (/day)      : Maximum reduction rate
     2.00000   K_FeR (mg/L)      : Half saturation for reduction
     1.08000   vFeO  (no units)  : Temperature multiplier for oxidation
     0.10000   kFeO  (/day)      : Maximum oxidation rate
     2.00000   K_FeO (mg/L)      : Half saturation for oxidation
     0.01000   SFe   (g/m^2/day) : Sediment release rate
     4.00000   KDOFe (mg/L)      : Oxygen sediment half saturation
     7.00000   KpHFe (no units)  : pH sediment half saturation
     0.00001   alpFe (g/m^2/s)   : Resuspension rate
     0.05000   tcFe  (N/m^2)     : Critical shear stress
     0.00000   Feset (m/s)       : Settling velocity of particulate iron
!----------------------------------------------------------------------------!
! MANGANESE constants                                                        !
!----------------------------------------------------------------------------!
     1.08000   vMnR  (no units)  : Temperature multiplier for reduction
```

```
     0.10000   kMnR  (/day)      : Maximum reduction rate
     2.00000   K_MnR (mg/L)      : Half saturation for reduction
     1.08000   vMnO  (no units)  : Temperature multiplier for oxidation
     0.10000   kMnO  (/day)      : Maximum oxidation rate
     2.00000   K_MnO (mg/L)      : Half saturation for oxidation
     0.01000   Smn   (g/m^2/day) : Sediment release rate
     4.00000   KDOMn (mg/L)      : Oxygen sediment half saturation
     7.00000   KpHMn (no units)  : pH sediment half saturation
     0.00001   alpMn (g/m^2/s)   : Resuspension rate
     0.05000   tcMn  (N/m^2)     : Critical shear stress
     0.00000   Mnset (m/s)       : Settling velocity of particulate Mn
!-------------------------------------------------------------------------------!
! ALUMINIUM constants                                                           !
!-------------------------------------------------------------------------------!
     1.08000   vAlR  (no units)  : Temperature multiplier for reduction
     0.10000   kAlR  (/day)      : Maximum reduction rate
     2.00000   K_AlR (mg/L)      : Half saturation for reduction
     1.08000   vAlO  (no units)  : Temperature multiplier for oxidation
     0.10000   kAlO  (/day)      : Maximum oxidation rate
     2.00000   K_AlO (mg/L)      : Half saturation for oxidation
     0.01000   S_AL  (g/m^2/day) : Sediment release rate
     4.00000   KDOAl (mg/L)      : Oxygen sediment half saturation
     7.00000   KpHAl (no units)  : pH sediment half saturation
     0.00001   alpAl (g/m^2/s)   : Resuspension rate
     0.05000   tcAl  (N/m^2)     : Critical shear stress
     0.00000   Alset (m/s)       : Settling velocity of particulate Al
```

Meteorological, inflow and withdrawal files are not included in this appendix because the number of lines for each files is 18263 lines (equivalent 240 pages).

# Appendix A.2 Files of water quality simulations of Cressbrook reservoir

### *Batch file|*

```
createDYref CressPWQ.stg CressPWQ.met CressPWQ.inf CressPWQ.wdr DYref.nc
createDYsim CressPWQ.pro CressPWQ.par CressPWQ.con DYsim.nc
extractDYinfo DYref.nc DYsim.nc CressPWQ.cfg
dycd>log.txt
```

### *Configuration file*

```
<#4>
! DYRESM-CAEDYM configuration file of Cressbrook
2004001                 # Simulation start day
18263                   # Simulation length (unit=days)
.TRUE.                  # Run CAEDYM (.TRUE. or .FALSE.)
7                       # Output Interval (in days, or -9999 for every time step)
0.35                    # Light extinction coefficient (m-1)
0.00                    # Benthic Boundary Thickness (m)
0.5                     # Min layer thickness (m)
5.0                     # Max layer thickness (m)
7200                    # Time Step (s)
10                      # Number of Output Selections
SALINITY TEMPTURE DENSITY DO NO3 TP TFE TMN CYANO PH  # List of Output Selections
.FALSE.                  # Activate destrat system (.TRUE. or .FALSE.)
.TRUE.                  # Activate non-neutral atmospheric stability (.TRUE. or
.FALSE.)
```

***Note:*** if the destratification system is activated in a simulation, the value is set to be .TRUE.

### *Initial physical file*

```
! Cooby Reservoir day 2003363
44       # number of layers
DEPTH TEMP    SAL
1      27.55  0.18
2      27.48  0.18
3      27.31  0.18
4      27     0.18
5.1    24.79  0.19
6      21.78  0.18
7      21.09  0.19
8      19.43  0.19
9      18.45  0.2
10     17.11  0.18
11     16.41  0.18
12     16.17  0.18
13     16.01  0.18
14     15.74  0.18
15     15.52  0.19
16     15.47  0.19
17     15.38  0.19
17.6   15.43  0.20
19     15.2   0.2
20     15.0   0.2
21     14.9   0.2
```

```
22     14.8   0.2
23     14.8   0.2
24     14.7   0.2
25     14.7   0.2
26     14.7   0.2
27     14.7   0.2
28     14.7   0.2
29     14.7   0.2
30     14.7   0.2
31     14.7   0.2
32     14.7   0.2
33     14.7   0.2
34     14.7   0.2
35     14.7   0.2
36     14.7   0.2
37     14.7   0.2
38     14.7   0.2
39     14.7   0.2
40     14.7   0.2
41     14.7   0.2
42     14.7   0.2
43     14.7   0.2
44.43  14.7   0.2
```

### *Initial water quality file*

```
3D DATA
CYANO
  IN_I
  8
  0.500 12.25 15.75 19.25 22.75 29.75 31.10 40.00
  1.16  1.27  1.78  0.60  0.12  0.09  0.02  0.995
  0.05
IC_CYA
  CO_I
  0.01
  0.0
DN_CYA
  CO_I
  996.0
  996.0
CHLOR
  CO_I
  -50.0
  0.0
IC_CHL
  CO_I
  -50
  0.0
FDIAT
  CO_I
  9.0
  0.0
IC_FDI
  CO_I
  -50
  0.0
SIZE1
  CO_I
  0.03
  0.000
SIZE2
  CO_I
  0.003
  0.000
DO
  IN_I
  25
```

```
  1.0  2.0    3.0    4.0    5.0    6.0    7.0    8.0    9.0    10.0   11.0   12.0
       13.0   14.0   17.6   18.7   19.2   20.1   21.1   22.1   23.0   24.0   25.0
       26.0   26.8
  5.1  5.1    5.1    5.2    3.6    0.5    0.1    0.1    0.1    0.1    0.1    0.1
       0.1    0.1    0.1    0.1    0.1    0.1    0.1    0.1    0.1    0.1    0.1
       0.1    0.1
  0.01
PO4
  CO_I
  0.01
  0.0
IP_CYA
  CO_I
  0.002
  0.002
TP
  IN_I
  8
  0.500 12.25 15.75 19.25 22.75 29.75 31.10 40.00
  0.05  0.05  0.05  0.10  0.10  0.10  0.10  0.10
  0.01
NO3
  IN_I
  8
  0.500 12.25 15.75 19.25 22.75 29.75 31.10 40.00
  1.00  1.10  0.50  0.05  0.30  0.05  0.05  0.05
  0.01
NH4
  CO_I
  0.05
  0.0
IN_CYA
  CO_I
  0.001
  0.5
TN
  IN_I
  8
  0.500 12.25 15.75 19.25 22.75 29.75 31.10 40.00
  1.50  1.60  0.75  0.1  0.40  0.10  0.10  0.10
  0.05
PH
  IN_I
  28
  1.0   2.0   3.0    4.0    5.0    6.0    7.0    8.0    9.0    10.0   11.0   12.0
       13.0   14.0   15.0   16.0   17.0   17.6   18.7   19.2   20.1   21.1   22.1
       23.0   24.0   25.0   26.0   26.8
 10.76 10.83  10.84  10.81  10.55  10.19  9.88   9.79   9.71   9.69   9.64   9.59
       9.56   9.54   9.52   9.5    9.49   9.32   9.00   9.00   9.00   9.00   9.00
       8.50   8.50   8.00   8.00   8.00
  0.01
SSOL1
  CO_I
  1.3
  4.0
SSOL2
  CO_I
  8.0
  0.0
FBOD
  CO_I
  2.0
  -10.0
SBOD
  CO_I
  0.0
  -10.0
SiO2
  CO_I
  0.5
  0.0
FE2
```

```
  CO_I
  0.001
  0.0
TFE
  IN_I
  8
  0.500 12.25 15.75 19.25 22.75 29.75 31.10 40.00
  0.010 0.010 0.010 0.110 0.210 0.970 1.100 0.270
  0.05
MN2
  CO_I
  0.001
  0.0
TMN
  IN_I
  8
  0.500 12.25 15.75 19.25 22.75 29.75 31.10 40.00
  0.020 0.040 0.020 0.460 0.780 0.890 0.950 0.170
  0.05
COL
  CO_I
  10.0
  0.0
2D DATA
EOF
```

### *Basic hydrodynamic file*

```
<#5>
Cressbrook Parameters File.
1.3E-3      # bulk aerodynamic mmt. transport coeff.
0.08        # mean albedo of water
0.96        # emissivity of a water surface          (Imberger & Patterson
[1981,p316])
3.00        # critical wind speed [m s^-1]
36000       # time of day for output (in seconds from midnight)
0.002       # entrainment coefficient constant
0.012       # bubbler entrainment coefficient         (Alexander 2000)
0.083       # buoyant plume entrainment coefficient   (Fischer et al. 1979)
0.080       # shear production efficiency
0.20        # potential energy mixing efficiency
0.06        # wind stirring efficiency (0.06)
1.0E+7      # effective surf. area coeff.
200         # vertical mix coeff.
================================================================================
```

### *Water quality configuration file*

```
^@
!-----------------------------------------------------------------------------!
! GENERAL constants                                                           !
!-----------------------------------------------------------------------------!
! Base extinction coefficient                                                 !
     0.2500
!-----------------------------------------------------------------------------!
! PHYTOPLANKTON constants                                                     !
!-----------------------------------------------------------------------------!
! Pmax (/day) : Maximum potential growth rate of phytoplankton                !
     0.50000            : dinoflagellatte growth rate
     0.37000            : cyanobacteria growth rate
     0.90000            : nodularia growth rate
     1.20000            : chlorophyte growth rate
     0.70000            : cyrptophyte growth rate
```

```
     1.90000            : marine diatom growth rate
     1.80000            : freshwater diatom growth rate
! Ycc (mg C/mg chla) : Average ratio of C to chlorophyll a                     !
    40.00000
    40.00000
    40.00000
    40.00000
    40.00000
    40.00000
    40.00000
!--------------------------------------------------------------------------!
! Light limitation (2=no photoinhibition, 3=photoinhibition)                 !
! algt (no units) : Type of light limitation algorithm                       !
           2
           3
           2
           3
           2
           2
           3
! IK (microE/m^2/s) : Parameter for initial slope of P_I curve               !
    60.00000
    95.00000
    95.00000
    80.00000
    60.00000
    90.00000
    100.0000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                 !
   200.00000
   200.00000
   200.00000
   200.00000
   200.00000
   400.00000
   140.00000
! Kep (ug chlaL^-1m^-1) : Specific attenuation coefficient                   !
     0.02000
     0.02000
     0.02000
     0.02000
     0.02000
     0.02000
     0.02000
!--------------------------------------------------------------------------!
! Nutrient limitation                                                        !
! KP (mg/L) : Half saturation constant for phosphorus                        !
     0.00500
     0.01000
     0.01000
     0.01000
     0.00500
     0.00500
     0.01000
! Po (mg/L) : Low concentrations of PO4 at which uptake ceases               !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! KN (mg/L) : Half saturation constant for nitrogen                          !
     0.02000
     0.00300
     0.00300
     0.07000
     0.02300
     0.01500
     0.03500
! No (mg/L) : Low concentrations of N at which uptake ceases                 !
     0.00000
```

```
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! Sicon : Constant internal Silica concentration                              !
     0.00000            dinoflagellates
     0.00000            f'water cyanobacteria
     0.00000            nodularia
     0.00000            chlorophytes
     0.00000            cryptophytes
     0.00000            marine diatoms
     0.00000            f'water diatoms
! KSi (mg/L) : Half saturation constant for silica                            !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.14000
     0.14000
! No (mg/L) : Low concentrations of Si at which uptake ceases                !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! KCa (mg/L) : Half saturation constant for carbon                            !
     2.00000
     2.00000
     2.00000
     2.00000
     2.00000
     2.00000
     2.00000
! INmin (mg N/mg Chla) : Minimum internal N concentration                     !
     2.80000
     2.50000
     2.50000
     3.50000
     2.50000
     2.50000
     3.50000
! INmax (mg N/mg Chla) : Maximum internal N concentration                     !
     6.50000
     5.00000
     6.00000
     6.00000
     6.00000
     6.00000
     6.00000
! IPmin (mg P/mg Chla) : Minimum internal P concentration                     !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! IPmax (mg P/mg Chla) : Maximum internal P concentration                     !
     2.00000
     2.00000
     2.00000
     2.00000
     2.00000
     2.00000
     2.00000
! ICmin (mg C/mg Chla) : Minimum internal C concentration                     !
    15.00000
```

```
    15.00000
    15.00000
    15.00000
    15.00000
    15.00000
    15.00000
! ICmax (mg C/mg Chla) : Maximum internal C concentration                      !
    80.00000
    80.00000
    80.00000
    80.00000
    80.00000
    80.00000
    80.00000
! UCmax (mg C/mg Chla/day) : Maximum rate of carbon uptake                      !
    50.00000
     1.50000
     1.50000
     1.50000
     1.50000
     1.50000
     1.50000
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
     1.08000
     1.09000
     1.08000
     1.05000
     1.08000
     1.08000
     1.04000
! Tsta (Deg C) : Standard temperature                                          !
    20.00000
    27.00000
    20.00000
    22.00000
    20.00000
    19.00000
    19.00000
! Topt (Deg C) : Optimum temperature                                           !
    33.00000
    33.00000
    33.00000
    28.00000
    33.00000
    27.00000
    22.00000
! Tmax (Deg C) : Maximum temperature                                           !
    39.00000
    39.00000
    39.00000
    36.00000
    39.00000
    32.00000
    34.00000
!------------------------------------------------------------------------------!
! Respiration, mortality, and excretion.                                       !
! kr (/day) : Respiration rate coefficient                                     !
     0.10000
     0.10000
     0.10000
     0.10000
     0.10000
     0.10000
     0.10000
! vR (no units) : Temperature multiplier (no units)                            !
     1.08000
     1.09000
     1.08000
     1.10000
     1.08000
```

```
     1.08000
     1.05000
!----------------------------------------------------------------------------!
! Salinity limitation                                                        !
! maxSP (psu) : Maximum potential salinity                                   !
    36.00000         dinoflagellates
    36.00000            f'water cyanobacteria
    36.00000            nodularia
    36.00000            chlorophytes
    36.00000            cryptophytes
    36.00000            marine diatoms
    36.00000            f'water diatoms
! phsal (no units) : Type of water environment (Angeline 23/08/2000)          !
    0
    0
    2
    0
    1
    1
    0
! Sop (psu) : Minimum bound of salinity tolerance                            !
    18.00000
     3.00000
    28.00000
    14.00000
    20.00000
    30.00000
     1.00000
! Bep (no units) : Salinity limitation value at S=0 and S=maxSP              !
     2.00000
     3.00000
     2.00000
     2.50000
     2.00000
     5.00000
     5.00000
! Aep (no units) : Salinity limitation value at S=Sop                        !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
!----------------------------------------------------------------------------!
! Vertical migration and settling  (0-stokes, 1-constant, 2-motile w/o
photoinhibition 3-motile w/ photoinhibition         !
! phvel (no units) : Type of vertical migration algorithm                    !
           4
           3
           0
           1
           1
           1
           1
! c1 (kgm^-3min^-1) : Rate coefficient for density decrease                  !
     0.90000            dinoflagellates
     0.90000            f'water cyanobacteria
     0.90000            nodularia
     0.20000            chlorophytes
     0.90000            cryptophytes
     0.90000            marine diatoms
     0.90000            f'water diatoms
! c3 (kgm^-3min^-1) : Minimum rate of density decrease with time             !
     0.04150            dinoflagellates
     0.04150            f'water cyanobacteria
     0.04150            nodularia
     0.040              chlorophytes
     0.04150            cryptophytes
     0.04150            marine diatoms
     0.04150            f'water diatoms
! c4 (mhr^-1) : Rate for light dependent migration velocity                  !
```

```
     2.50000         dinoflagellates
     0.85000            f'water cyanobacteria
     0.85000            nodularia
     0.800              chlorophytes
     0.85000            cryptophytes
     0.85000            marine diatoms
     0.85000            f'water diatoms
! c5 (mhr^-1) : Rate for nutrient dependent migration velocity                  !
     0.20000         dinoflagellates
     0.65000            f'water cyanobacteria
     0.65000            nodularia
     0.15000            chlorophytes
     0.65000            cryptophytes
     0.65000            marine diatoms
     0.65000            f'water diatoms
! IKm (uEm^-2s^-1) : Half saturation constant for density increase             !
    26.00000         dinoflagellates
    25.00000            f'water cyanobacteria
    25.00000            nodularia
    25.00000            chlorophytes
    25.00000            cryptophytes
    25.00000            marine diatoms
    25.00000            f'water diatoms
! min_pd (kg/m^3) : Minimum phytoplankton density
   980.00000         dinoflagellates
   980.00000            f'water cyanobacteria
   980.00000            nodularia
   980.00000            chlorophytes
   980.00000            cryptophytes
   980.00000            marine diatoms
   980.00000            f'water diatoms
! max_pd (kg/m^3) : Maximum phytoplankton density                              !
  1050.00000         dinoflagellates
  1050.00000            f'water cyanobacteria
  1050.00000            nodularia
  1030.00000            chlorophytes
  1050.00000            cryptophytes
  1050.00000            marine diatoms
  1050.00000            f'water diatoms
! pw20 (kgm^-3) : Density of water at 20 deg C                                  !
  1000.00000
! dia (m) : Diameter of phytoplankton                                           !
 0.10000E-04
 0.40000E-04            (range 0.25-0.60E-04m)
 0.50000E-04
 0.10000E-04
 0.10000E-04
 0.10000E-04
 0.20000E-04
! ws (ms^-1) : Constant settling velocity                                       !
 0.10000E-04
 0.69440E-04
 0.50000E-04
 -2.00000E-06
 0.10000E-04
 0.10000E-04
 -3.5000E-06
! oth (mg/l) dissolved oxgyen threshold for migration of motile phytoplankton  !
 0.0
 0.0
 0.0
 0.0
 0.0
 0.0
 0.0
!------------------------------------------------------------------------------!
! Resuspension                                                                  !
! tcpy (N/m^2) : Critical shear stress                                          !
     0.02000         dinoflagellates
     0.05000            f'water cyanobacteria
     0.05000            nodularia
     0.05000            chlorophytes
```

```
     0.05000            cryptophytes
     0.05000            marine diatoms
     0.05000            f'water diatoms
! alpPy (mg Chla/m^2/s) : Resuspension rate constant                           !
 0.23000E-03
! KTPy (mg Chla/m^2) : Controls rate of resuspension                           !
     1.00000         dinoflagellates
     2.00000            f'water cyanobacteria
     2.00000            nodularia
     2.00000            chlorophytes
     2.00000            cryptophytes
     2.00000            marine diatoms
     2.00000            f'water diatoms
! DTphy (days) : Phytoplankton sediment survival time                          !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! JELLYFISH constants                                                          !
!------------------------------------------------------------------------------!
! Jmax (/day) : Maximum potential growth rate of jellyfish                     !
     0.40000
! Ycj (mg C/mg medusae) : Carbon meduase ratio                                 !
     0.00400
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
     1.08000
! Tsta (Deg C) : Standard temperature                                          !
    20.00000
! Topt (Deg C) : Optimum temperature                                           !
    33.00000
! Tmax (Deg C) : Maximum temperature                                           !
    39.00000
!------------------------------------------------------------------------------!
! Salinity limitation                                                          !
! Sop (psu) : Minimum bound of salinity tolerance                              !
    25.00000
! Bep (no units) : Salinity limitation value at S=0 and S=maxSP                !
    27.00000
! Aep (no units) : Salinity limitation value at S=Sop                          !
     1.00000
!------------------------------------------------------------------------------!
! Light limitation.                                                            !
! algt (no units) : Type of light limitation algorithm                         !
           2
! IK (microE/m^2/s) : Parameter for initial slope of P-I curve                 !
    90.00000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                   !
    90.00000
!------------------------------------------------------------------------------!
! Nutrient limitation                                                          !
! KP (mg/L) : Half saturation constant for phosphorus                          !
     0.01000
! Po (mg/L) : Low concentrations of PO4 at which uptake ceases                 !
     0.00000
! KN (mg/L) : Half saturation constant for nitrogen                            !
     0.02500
! No (mg/L) : Low concentrations of N at which uptake ceases                   !
     0.00000
!------------------------------------------------------------------------------!
! Respiration mortality and excretion.                                         !
! krj (/day) : Respiration rate coefficient                                    !
     0.10000
! ke (/day) : Excretion rate coefficient                                       !
     0.10000
! KBODj (mg BOD/L) : Half saturation constant for organic nutrition            !
     2.00000
```

```
! vuk (m/s) : Upward swimming velocity constant                                !
     0.01000
! vdk (m/s) : Downward sinking velocity constant                               !
     0.00000
!------------------------------------------------------------------------------!
! ZOOPLANKTON constants                                                        !
!------------------------------------------------------------------------------!
! az (no units) : assimilation rate                                            !
     0.30000  : rotifers/small cladocerans
     0.30000  : large cladocerans/copepods
     0.30000
     0.30000
     0.30000
!------------------------------------------------------------------------------!
! Respiration mortality and excretion.                                         !
! fzz (no units) : Fraction of loss contributing to excretion only             !
     0.20000
! kz (/day) : Respiration rate coefficient                                     !
     0.10000
     0.05000
     0.05000
     0.05000
     0.05000
!------------------------------------------------------------------------------!
! Salinity limitation                                                          !
! Smxz (psu) : Maximum salinity, or optimum salinity for SIZE5                 !
    50.00000
    50.00000
    28.00000
    28.00000
    27.00000
! Smnz (psu) : Minimum salinity                                                !
     0.00000
     0.00000
     6.00000
     6.00000
     0.00000
! Bez (no units) : Salinity intercept (for S=0)                                !
     0.00000
     0.00000
     2.00000
     2.00000
     2.00000
!------------------------------------------------------------------------------!
! Dissolved oxygen limitation                                                  !
! DOmz (mg/L) : Minimum DO tolerance                                           !
     0.00000
     0.00000
     0.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier for growth NOTE SET TO 1.08 in
params.dat regardless of value HERE though this is the value used  !
     1.06000
     1.10000
     1.10000
     1.10000
     1.10000
! Tsta (Deg C) : Standard temperature                                          !
    20.00000
    20.00000
    20.00000
    20.00000
    20.00000
! Topt (Deg C) : Optimum temperature                                           !
    33.00000
    33.00000
    33.00000
    33.00000
    33.00000
```

```
! Tmax (Deg C) : Maximum temperature                                          !
    39.00000
    39.00000
    39.00000
    39.00000
    39.00000
!-----------------------------------------------------------------------------!
! Grazing                                                                     !
! ki (g phyto C/m^3)/(g zoo C/m^3)/day) : Grazing rate                        !
     1.00000            : SIZE1 grazing rate
     0.40000         : SIZE2 grazing rate
     0.72000
     0.20000
     0.20000
! vZ (no units) : Grazing/Respiration temperature dependence                  !
     1.12000
     1.06000
     1.07000
     1.07000
     1.07000
! Pij (no units) : Preference of zooplankton for phytoplankton                !
     0.00000    : SIZE1 on DINOF
     0.00000    : SIZE2 on DINOF
     0.00000    : SIZE3 on DINOF
     0.00000    : SIZE4 on DINOF
     0.00000    : SIZE5 on DINOF
     0.00000    : SIZE1 on CYANO
     0.00000    : SIZE2 on CYANO
     0.00000    : SIZE3 on CYANO
     0.00000    : SIZE4 on CYANO
     0.00000    : SIZE5 on CYANO
     0.00000    : SIZE1 on NODUL
     0.00000    : SIZE2 on NODUL
     0.00000    : SIZE3 on NODUL
     0.00000    : SIZE4 on NODUL
     0.00000    : SIZE5 on NODUL
     1.00000    : SIZE1 on CHLOR
     0.00000    : SIZE2 on CHLOR
     0.00000    : SIZE3 on CHLOR
     0.00000    : SIZE4 on CHLOR
     0.00000    : SIZE5 on CHLOR
     0.00000    : SIZE1 on CRYPT
     0.00000    : SIZE2 on CRYPT
     0.00000    : SIZE3 on CRYPT
     0.00000    : SIZE4 on CRYPT
     0.00000    : SIZE5 on CRYPT
     0.00000    : SIZE1 on MDIAT
     0.00000    : SIZE2 on MDIAT
     0.00000    : SIZE3 on MDIAT
     0.00000    : SIZE4 on MDIAT
     0.00000    : SIZE5 on MDIAT
     0.00000    : SIZE1 on FDIAT
     0.00000    : SIZE2 on FDIAT
     0.00000    : SIZE3 on FDIAT
     0.00000    : SIZE4 on FDIAT
     0.00000    : SIZE5 on FDIAT
! Pzij (no units) : Preference of zooplankton for zooplankton                 !
     0.00000    : SIZE1 prey of SIZE1
     0.00000    : SIZE1 prey of SIZE2
     0.00000    : SIZE1 prey of SIZE3
     0.00000    : SIZE1 prey of SIZE4
     0.00000    : SIZE1 prey of SIZE5
     0.00000    : SIZE2 prey of SIZE1
     0.00000    : SIZE2 prey of SIZE2
     0.00000    : SIZE2 prey of SIZE3
     0.00000    : SIZE2 prey of SIZE4
     0.00000    : SIZE2 prey of SIZE5
     0.00000    : SIZE3 prey of SIZE1
     0.00000    : SIZE3 prey of SIZE2
     0.00000    : SIZE3 prey of SIZE3
     0.00000    : SIZE3 prey of SIZE4
     0.00000    : SIZE3 prey of SIZE5
```

```
     0.00000    : SIZE4 prey of SIZE1
     0.00000    : SIZE4 prey of SIZE2
     0.00000    : SIZE4 prey of SIZE3
     0.00000    : SIZE4 prey of SIZE4
     0.00000    : SIZE4 prey of SIZE5
     0.00000    : SIZE5 prey of SIZE1
     0.00000    : SIZE5 prey of SIZE2
     0.00000    : SIZE5 prey of SIZE3
     0.00000    : SIZE5 prey of SIZE4
     0.00000    : SIZE5 prey of SIZE5
! Pbij (no units) : Preference of zooplankton for detritus                     !
     0.00000    : FBOD by SIZE1
     0.00000    : FBOD by SIZE2
     0.00000    : FBOD by SIZE3
     0.00000    : FBOD by SIZE4
     0.00000    : FBOD by SIZE5
     0.00000    : SBOD by SIZE1
     0.00000    : SBOD by SIZE2
     0.00000    : SBOD by SIZE3
     0.00000    : SBOD by SIZE4
     0.00000    : SBOD by SIZE5
! Kj (g C/m^3) : Half saturation constant for grazing                          !
     2.00000
     0.24000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! Predation                                                                    !
! kk (/day) : Grazing rate of fish on zooplankton                              !
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
! PFi (no units) : Preference of fish for zooplankton                          !
     0.20000
     0.20000
     0.20000
     0.20000
     0.20000
! KFk (g/m^3) : Half saturation constant for grazing                           !
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
!------------------------------------------------------------------------------!
! FISH constants                                                               !
!------------------------------------------------------------------------------!
! swin (m/s) : Swimming speed                                                  !
     0.02000
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
     0.00200
! mfl (/day) : Threshold of fish mortality                                     !
     0.30000
     0.30000
     0.30000
```

```
      0.30000
      0.30000
      0.30000
      0.30000
      0.30000
      0.30000
! mtol (%) : Mortality migration tolerance                                   !
      2.00000
      0.00000
      0.00000
      0.00000
      0.00000
      0.00000
      0.00000
      0.00000
      0.00000
!----------------------------------------------------------------------------!
! Temperature representation                                                 !
! vT (no units) : Temperature multiplier                                     !
      1.08000
      1.08000
      1.08000
      1.08000
      1.08000
      1.08000
      1.08000
      1.08000
      1.08000
! Tsta (Deg C) : Standard temperature                                        !
     20.00000
     20.00000
     20.00000
     20.00000
     20.00000
     20.00000
     20.00000
     20.00000
     20.00000
! Topt (Deg C) : Optimum temperature                                         !
     33.00000
     33.00000
     33.00000
     33.00000
     33.00000
     33.00000
     33.00000
     33.00000
     33.00000
! Tmax (Deg C) : Maximum temperature                                         !
     39.00000
     39.00000
     39.00000
     39.00000
     39.00000
     39.00000
     39.00000
     39.00000
     39.00000
!----------------------------------------------------------------------------!
! Salinity limitation                                                        !
! maxS (psu) : Maximum potential salinity                                    !
     45.00000
! SL (psu) : Optimal salinity growth for fish                                !
     10.00000
     10.00000
     10.00000
     10.00000
     10.00000
     10.00000
     10.00000
     10.00000
     10.00000
```

```
! SU (psu) : Salinity response for S>Slim (not including MULLT)              !
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
    30.00000
! cfs (no units) : Max. fractional salinity respiration increment            !
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
     5.00000
!----------------------------------------------------------------------------!
! Dissolved oxygen limitation.                                               !
! DOmin (mg/L) : Lower dissolved oxygen tolerance                            !
     0.00000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
     0.50000
! KDO (mg/L) : Dissolved oxygen response for DO>=DOmin (mg/L)                !
     0.40000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! ofl (no units) : Max. fractional oxygen respiration increment              !
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
    10.00000
!----------------------------------------------------------------------------!
! Predation response to light.                                               !
! dfs (no units) : Max. fractional light respiration increment               !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! Ikf (uE/m^2/s) : Half saturation constant for light                        !
   400.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
```

```
     1.00000
     1.00000
!--------------------------------------------------------------------------!
! Grazing constants                                                        !
! FZ (/day) : Grazing rate                                                 !
     0.14000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
     0.11000
! KFb (g C/m^2) : Half saturation constant for grazing on benthos          !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! PFij (no units) : Preference of fish grazing on invertabrates            !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
! PFij (no units) : Preference of fish grazing on detritus                 !
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
     0.00000
!--------------------------------------------------------------------------!
! Respiration, mortality and excretion                                     !
! kf (/day) : Respiration rate coefficient                                 !
     0.07000
     0.08000
     0.08000
     0.08000
     0.08000
     0.08000
     0.08000
```

```
     0.08000
     0.08000
! vF (no units) : Temperature multiplier for respiration                       !
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
     1.08000
!------------------------------------------------------------------------------!
! Biomass size distribution                                                    !
! Ft1 (mg C change/mg fish C/day) : Threshold biomass for adults               !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
! Ft2 (mg C change/mg fish C/day) : Threshold biomass for juveniles            !
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! SEAGRASS constants                                                           !
!------------------------------------------------------------------------------!
! Yes (no units) : Ration of epiphyte C to seagrass C                          !
     1.00000
! Vmax (/day) : Maximum growth rate                                            !
     0.12500
!------------------------------------------------------------------------------!
! Light limitation                                                             !
! IK (microE/m^2/s) : Parameter for initial slope of P-I curve                 !
   120.00000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                   !
    90.00000
!------------------------------------------------------------------------------!
! Respiration                                                                  !
! kb (/day) : Respiration rate coefficient                                     !
     0.01250
! vB (no units) : Temperature multiplier                                       !
     1.08000
!------------------------------------------------------------------------------!
! Salinity limitation                                                          !
! Sop (psu) : Minimum bound of salinity tolerance                              !
    26.00000
! Bep (no units) : Salinity limitation value at S=0 and S=2 x Sop              !
     5.11600
! Aep (no units) : Salinity limitation value at S=Sop                          !
     0.58200
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
     1.08000
! Tsta (Deg C) : Standard temperature                                          !
    20.00000
! Topt (Deg C) : Optimum temperature                                           !
    25.00000
! Tmax (Deg C) : Maximum temperature                                           !
    30.00000
!------------------------------------------------------------------------------!
```

```
! MACROALGAE constants                                                         !
!------------------------------------------------------------------------------!
! Vmax (/day) : Maximum growth rates                                           !
     0.35000
     0.30000
     0.30000
     0.30000
! Ycc (mg C/mg chla) : Average ratio of C to chlorophyll a                     !
    50.00000
    50.00000
    50.00000
    50.00000
!------------------------------------------------------------------------------!
! Light limitation.                                                            !
! algt (no units) : Type of light limitation algorithm                         !
          2
          2
          2
          2
! IK (microE/m^2/s) : Parameter for initial slope of P-I curve                 !
    90.00000
    90.00000
    90.00000
    90.00000
! ISt (uEm^-2s^-1) : Light saturation for maximum production                   !
    90.00000
    90.00000
    90.00000
    90.00000
! Hmac (m/(gm^2)) : Conversion macroalgae biomass to height                    !
     0.01000
     0.01000
     0.01000
     0.01000
! Kmac (g C/m^2/m) : Specific light attenuation coefficients                   !
     1.00000
     3.00000
     3.00000
     3.00000
!------------------------------------------------------------------------------!
! Nutrient limitation                                                          !
! KP (mg/L) : Half saturation constant for phosphorus                          !
     0.01000
     0.01000
     0.01000
     0.01000
! Po (mg/L) : Low concentrations of PO4 at which uptake ceases                 !
     0.00000
     0.00000
     0.00000
     0.00000
! KN (mg/L) : Half saturation constant for nitrogen                            !
     0.05000
     0.05000
     0.05000
     0.05000
! No (mg/L) : Low concentrations of N at which uptake ceases                   !
     0.00000
     0.00000
     0.00000
     0.00000
! INmin (mg N/mg Chla) : Minimum internal N concentration                      !
     0.00500
     0.00500
     0.00500
     0.00500
! INmax (mg N/mg Chla) : Maximum internal N concentration                      !
     0.02000
     0.02000
     0.02000
     0.02000
! IPmin (mg P/mg Chla) : Minimum internal P concentration                      !
```

```
     0.00100
     0.00100
     0.00100
     0.00100
! IPmax (mg P/mg Chla) : Maximum internal P concentration                      !
     0.00000
     0.00000
     0.00000
     0.00000
!------------------------------------------------------------------------------!
! Temperature representation                                                   !
! vT (no units) : Temperature multiplier                                       !
     1.08000
     1.08000
     1.08000
     1.08000
! Tsta (Deg C) : Standard temperature                                          !
    20.00000
    20.00000
    20.00000
    20.00000
! Topt (Deg C) : Optimum temperature                                           !
    33.00000
    33.00000
    33.00000
    33.00000
! Tmax (Deg C) : Maximum temperature                                           !
    39.00000
    39.00000
    39.00000
    39.00000
!------------------------------------------------------------------------------!
! Salinity limitation                                                          !
! Sop (psu) : Minimum bound of salinity tolerance                              !
    25.00000
    25.00000
    25.00000
    25.00000
! Bep (no units) : Salinity limitation value at S=0 and S=2 x Sop              !
     2.00000
     2.00000
     2.00000
     2.00000
! Aep (no units) : Salinity limitation value at S=Sop                          !
     1.00000
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! Respiration                                                                  !
! kb (/day) Respiration rate coefficient                                       !
     0.07000
     0.07000
     0.07000
     0.07000
! vB (no units) : Temperature multiplier for respiration                       !
     1.08000
     1.08000
     1.08000
     1.08000
!------------------------------------------------------------------------------!
! Grazing                                                                      !
! PCm (no units) : Preference of crustaceans grazing on macroalgae             !
     0.20000
     0.20000
     0.20000
     0.20000
!------------------------------------------------------------------------------!
! INVERTABRATE constants                                                       !
!------------------------------------------------------------------------------!
! IZ (g C consumed/(g invert. C)/day) : Maximum consumption rate               !
     0.00000
```

```
     0.00000
     0.00000
! KIZ (g C/m^3) : Half saturation constant for grazing                         !
     0.00000
     0.00000
     0.00000
! KDOI (mg/L) : Half saturation for dissolved oxygen limitation                !
     0.00000
     0.00000
     0.00000
! BDOi (no units) : Basal respiration increase from DO limitation              !
     0.00000
     0.00000
     0.00000
!------------------------------------------------------------------------------!
! Salinity limitation                                                          !
! Minimum salinity tolerance for bivalves                                      !
     8.00000
! Maximum salinity tolerance for bivalves                                      !
    35.00000
! Sop (psu) : Minimum bound of salinity tolerance                              !
     8.00000
     8.00000
    25.00000
! Bep (no units) : Salinity limitation value at S=0 and S=2 x Sop              !
     2.00000
     2.00000
     2.00000
! Aep (no units) : Salinity limitation value at S=Sop                          !
     1.00000
     1.00000
     1.00000
!------------------------------------------------------------------------------!
! Respiration                                                                  !
! kb (/day) : Respiration rate coefficient                                     !
     0.10000
     0.10000
     0.08000
! vB (no units) : Temperature multiplier                                       !
     1.08000
     1.08000
     1.08000
!------------------------------------------------------------------------------!
! SUSPENDED SOLID constants                                                    !
!------------------------------------------------------------------------------!
! denSS (g/m^3) : Mean density of suspended solid in the sediment              !
 0.25000E+07      : SSOL1 sediment density
 0.25000E+07      : SSOL2 sediment density
! des (kg/m^3) : Density of suspended solid particles                          !
 0.11500E+04      : SSOL1 particle density
 0.12500E+04      : SSOL2 particle density
! diaSS (m) : Diameter of suspended solids groups                              !
 0.10000E-04      : SSOL1 particle diameter
 0.10000E-04      : SSOL2 particle diameter
! KeSS (mg^L-1m^-1) : Specific attenuation coefficient                         !
 0.05000E+00      : SSOL1 particle specific attenuation
 0.05000E+00      : SSOL2 particle specific attenuation
!------------------------------------------------------------------------------!
! Resuspension constants                                                       !
! tcs (N/m^2) : Critical shear stress                                          !
 0.50000E-01
 0.50000E-01
! alpS (g/m^2/s) : Resuspension rate constants                                 !
 0.30000E-03
 0.30000E-03
! KTS (g/m^2) : Controls rate of resuspension                                  !
 0.40000E+00
 0.40000E+00
!------------------------------------------------------------------------------!
! pH constants                                                                 !
!------------------------------------------------------------------------------!
     0.0000      kpho (m^3/g O)  : Photosynthetic / respiration pH constant
```

```
     0.0000      kphp (m^3/g O)  : BOD pH constant
     1.00000      KDOS (g/m^3)    : Controls release of sediment nutrients via O
     7.00000      KpHS (no units) : Controls release of sediment nutrient via pH
!-------------------------------------------------------------------------------!
! Colour / tracer constants                                                     !
!-------------------------------------------------------------------------------!
     0.00000      decr (/day) : Decay rate for colour/tracer
!-------------------------------------------------------------------------------!
! DISSOLVED OXYGEN constants                                                    !
!-------------------------------------------------------------------------------!
     1.08000   vOP    (no units) : Temperature multiplier for phytoplankton
     1.08000   vON    (no units) : Temperature multiplier for nitrification
     1.60000   KSO    (mg_O/L) : Half saturation cons. for sediment BOD uptake
    50.00000   PCmax  (g/m^2) : Maximum limit of polychaete biomass
     2.66667   YOC    (mg C/mg O) : Respiration stoichiometric ratio of C to
oxygen
     1.00000   YOZ    (mg zooC/mg O) Stoichiometric factor, zooplankton C : DO
     0.10000   fox    (no units) : Fraction of net DO allocated to seagrass roots
     2.66667   YSG    (mg seagC/mg O) : Stoichiometric factor, seagrass C : DO
     2.66667   YOJ    (mg jelC/mg O) : Stoichiometric factor, jellyfish C : DO
     0.05000   koNH   (/day) : Nitrification rate coefficient
     3.42857   YNH    (mg N/mg O) : Ratio for O2 to N during nitrification
     1.50000   KOn    (mg O/L) : Half saturation constant for nitrification
     1.60000   DOs    (cm^2/day) : Molecular diffusion of the sediments
    24.80000   DOb    (cm^2/day) : Diffusivity due to bioturbation
     0.00500   doxmin (m) : Minimum depth of the oxic layer
     0.30000   doxmax (m) : Sediment depth=max depth of the oxic layer
     0.03000   oxmin  (mg/L) : Minimum DO in the bottom layer (mg/L)
     0.10000   rSOs   (g/m^2/day) : Static sediment exchange rate
     2.00000   KSOs   (mg O/L) : 1/2 sat constant for static DO sediment flux
     0.14000   prc    (no units) : Photo-respiration phytoplankton DO loss
! Fraction of P respiration relative to total loss rate                         !
 0.70000E+00
 0.70000E+00
 0.70000E+00
 0.80000E+00
 0.70000E+00
 0.70000E+00
 0.70000E+00
 0.80000E+00
 0.80000E+00
 0.80000E+00
 0.80000E+00
 0.80000E+00
!-------------------------------------------------------------------------------!
! BOD Cconstants                                                                !
!-------------------------------------------------------------------------------!
 0.12000E+07   denB (g/m^3)    : Mean density of BOD in the sediment
     1.08000   vOB  (no units) : Temperature multiplier for BOD
! dib (m) : Diameter of BOD particles                                           !
 0.1000E-04                : SBOD diameter
 0.1000E-04                : FBOD diameter
! deb (kg/m^3) : Density of BOD particles                                       !
 0.11000E+04               : SBOD density
 0.10500E+04               : FBOD density
! tc (N/m^2) : Critical shear stress                                            !
     0.05000               : SBOD shear streass
     0.05000               : FBOD shear stress
! Kmass (g/m^2) : Controls rate of resuspension                                 !
     0.10000               : SBOD control on rate of resuspension
     0.10000               : FBOD control on rate of resuspension
! alp (g/m^2/s) : Resuspension rate                                             !
 0.12500E-03               : SBOD resuspension rate
 0.12500E-03               : FBOD resuspension rate
! tref (N/m^2) : Reference shear stress                                         !
     1.00000
! koB (/day) : Water column  mineralisation rate                                !
     0.01000               : SBOD mineralization rate
     0.10000               : FBOD mineralization rate
! KBOD (mg BOD/L) : Half saturation constant for mineralisation                 !
     5.0000
! kan (no units) : Anerobic relative to aerobic decomposition                   !
```

```
     0.30000
! kdB (/day) : Sediment decay rate                                              !
     0.00010                : SBOD sediment decay rate
     0.01000                       : FBOD sediment decay rate
! KeBOD (m^2/g) : Specific attenuation coefficient                              !
     0.01000                : SBOD specific attenuation
     0.01000                : FBOD specific attenuation
!-------------------------------------------------------------------------------!
     2.66667   YCBOD  (mg C/mg BOD)    : BOD to C ratio
     2.66667   YBODZ  (mg BOD/mg zooC) : Zooplankton C to BOD ratio
     2.66667   YBODJ  (mg BOD/mg jelC) : Jellyfish C to BOD ratio
     2.66667   YBODPC (mg BOD/mg polC) : Polychaete C to BOD ratio
     2.66667   YBODBV (mg BOD/mg bivC) : Bivalve C to BOD ratio
     2.66667   YBODMB (mg BOD/mg macC) : Macroalgae C to BOD ratio
     0.90000   mabw   (no units)       : Macroalgae beach wrack constant
!-------------------------------------------------------------------------------!
! NITROGEN constants                                                            !
!-------------------------------------------------------------------------------!
! UNmax (mg N/mg Chla/day) : Maximum rate of nitrogen uptake                    !
 0.15000E+01            : uptake rate for dinoflagellates
 0.25000E+01            : uptake rate for cyanobacteria
 0.15000E+01            : uptake rate for nodularia
 0.20000E+01            : uptake rate for chlorophytes
 0.15000E+01            : uptake rate for crptophytes
 0.15000E+01            : uptake rate for marine diatoms
 0.20000E+01            : uptake rate for freshwater diatoms
! UNmax (mg N/mg C/day) : Maximum rate of nitrogen uptake                       !
 0.20000E-02
 0.20000E-02
 0.20000E-02
 0.20000E-02
! INcon (mg N/mg Chla) : Phytoplankton constant internal nitrogen               !
     3.00000
! INZcon (mg N/mg C) : Zooplankton constant internal nitrogen                   !
     7.00000      INZconF : Freshwater systems
     7.00000      INZconM : Marine systems
     7.00000      INZconE : Estuarine systems
   -99.00000      INZcon  : If INZcon/=-99, then use the specified value
!-------------------------------------------------------------------------------!
     1.08000      vN2  (no units)  : Temperature multiplier for denitrification
     0.05000      koN2 (/day)      : Denitrification rate coefficient
     0.20000      KN2  (mg/L)      : Half saturation const for denitrification
     0.0100       KMAN (/day)      : Anaerobic organic mineralisation rate
     0.0200       KMN  (/day)      : Aerobic organic mineralisation rate
     1.08000      vM   (no units)  : Temp. multiplier for mineralisation
     1.50000      kONm (mg O/L)    : Half saturation for mineralisation
    -0.10E-5      Nset (m/s)       : Settling velocity for particulate N
     2.50000      tcn  (N/m^2)     : Critical shear stress
     0.00005      alpN (g/m^2/s)   : Resuspension rate constants
     0.50000      KTNr (g/m^2)     : Controls rate of resuspension
     0.10000      Smpn (g/m^2/day) : Maximum potential sediment fluxes
!-------------------------------------------------------------------------------!
! PHOSPHORUS constants                                                          !
!-------------------------------------------------------------------------------!
! UPmax (mg P/mg Chla/day) : Maximum rate of phosphorus uptake                  !
 0.20000E+00
 0.25000E+00
 0.20000E+00
 0.07500E+00
 0.20000E+00
 0.20000E+00
 0.15000E+00
! UPmax (mg P/mg C/day) : Maximum rate of phosphorus uptake                     !
 0.13000E-03
 0.10000E-03
 0.10000E-03
 0.10000E-03
! IPcon (mg P/mg Chla) : Phytoplankton constant internal phosphorus             !
     1.00000
! IPZcon (mg P/mg C) : Zooplankton constant internal phosphorus                 !
     1.00000      IPZconF : Freshwater systems
     1.00000      IPZconM : Marine systems
```

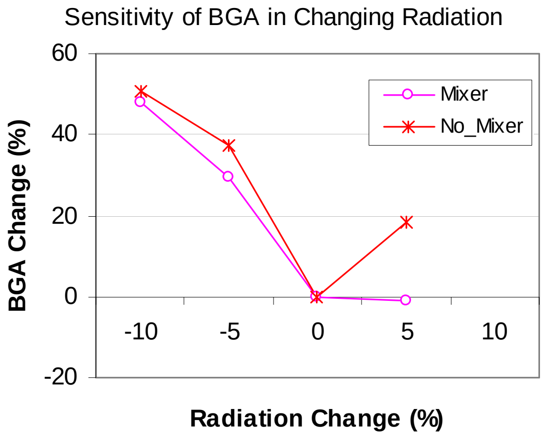
```
    1.00000      IPZconE : Estuarine systems
  -99.00000      IPZcon  : If INZcon/=-99, then use the specified value
!-------------------------------------------------------------------------------!
    0.02000   KOAP (/day)      : Anaerobic organic mineralisation rate
    0.01500   KOP  (/day)      : Aerobic organic mineralisation rate
    1.50000   kOPm (g/m^3)     : Half saturation for mineralisation
   -0.10E-5   Pset (m/s)       : Settling velocity for particulate P
    2.50000   tcp  (N/m^2)     : Critical shear stress
    0.00001   alpP (g/m^2/s)   : Resuspension rate constants
    0.05000   KTP  (g/m^2)     : Controls rate of resuspension
    0.00500   Smpp (g/m^2/day) : Maximum potential sediment fluxes
!-------------------------------------------------------------------------------!
! IRON constants                                                                !
!-------------------------------------------------------------------------------!
    1.08000   vFeR  (no units)  : Temperature multiplier for reduction
    0.10000   kFeR  (/day)      : Maximum reduction rate
    2.00000   K_FeR (mg/L)      : Half saturation for reduction
    1.08000   vFeO  (no units)  : Temperature multiplier for oxidation
    0.10000   kFeO  (/day)      : Maximum oxidation rate
    2.00000   K_FeO (mg/L)      : Half saturation for oxidation
    0.01000   SFe   (g/m^2/day) : Sediment release rate
    4.00000   KDOFe (mg/L)      : Oxygen sediment half saturation
    7.00000   KpHFe (no units)  : pH sediment half saturation
    0.00001   alpFe (g/m^2/s)   : Resuspension rate
    0.05000   tcFe  (N/m^2)     : Critical shear stress
    0.00000   Feset (m/s)       : Settling velocity of particulate iron
!-------------------------------------------------------------------------------!
! MANGANESE constants                                                           !
!-------------------------------------------------------------------------------!
    1.08000   vMnR  (no units)  : Temperature multiplier for reduction
    0.10000   kMnR  (/day)      : Maximum reduction rate
    2.00000   K_MnR (mg/L)      : Half saturation for reduction
    1.08000   vMnO  (no units)  : Temperature multiplier for oxidation
    0.10000   kMnO  (/day)      : Maximum oxidation rate
    2.00000   K_MnO (mg/L)      : Half saturation for oxidation
    0.01000   Smn   (g/m^2/day) : Sediment release rate
    4.00000   KDOMn (mg/L)      : Oxygen sediment half saturation
    7.00000   KpHMn (no units)  : pH sediment half saturation
    0.00001   alpMn (g/m^2/s)   : Resuspension rate
    0.05000   tcMn  (N/m^2)     : Critical shear stress
    0.00000   Mnset (m/s)       : Settling velocity of particulate Mn
!-------------------------------------------------------------------------------!
! ALUMINIUM constants                                                           !
!-------------------------------------------------------------------------------!
    1.08000   vAlR  (no units)  : Temperature multiplier for reduction
    0.10000   kAlR  (/day)      : Maximum reduction rate
    2.00000   K_AlR (mg/L)      : Half saturation for reduction
    1.08000   vAlO  (no units)  : Temperature multiplier for oxidation
    0.10000   kAlO  (/day)      : Maximum oxidation rate
    2.00000   K_AlO (mg/L)      : Half saturation for oxidation
    0.01000   S_AL  (g/m^2/day) : Sediment release rate
    4.00000   KDOAl (mg/L)      : Oxygen sediment half saturation
    7.00000   KpHAl (no units)  : pH sediment half saturation
    0.00001   alpAl (g/m^2/s)   : Resuspension rate
    0.05000   tcAl  (N/m^2)     : Critical shear stress
    0.00000   Alset (m/s)       : Settling velocity of particulate Al
```

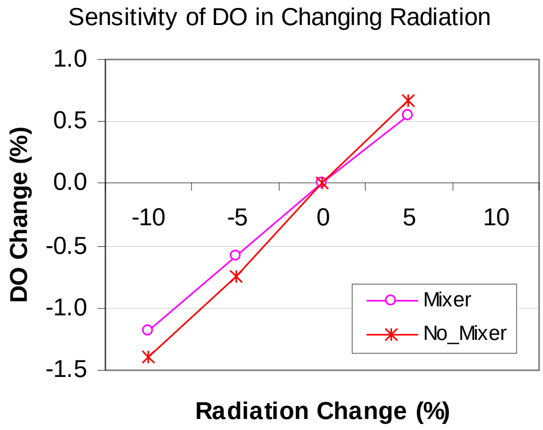
Meteorological, inflow and withdrawal files are not included in this appendix because the number of lines for each files is 18263 lines which require 240 pages.

# Appendix B.1 Sensitivity of water quality simulations of Cooby reservoir

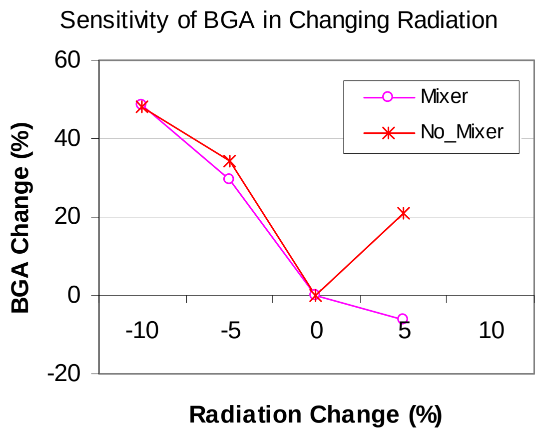
## A. Sensitivity of radiation to Cyanobacteria and dissolved oxygen

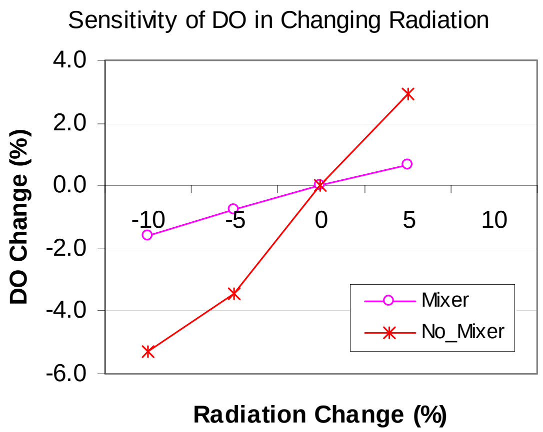
### *Surface Layer*



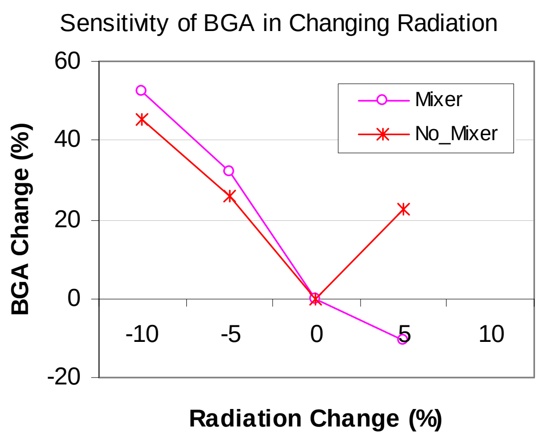



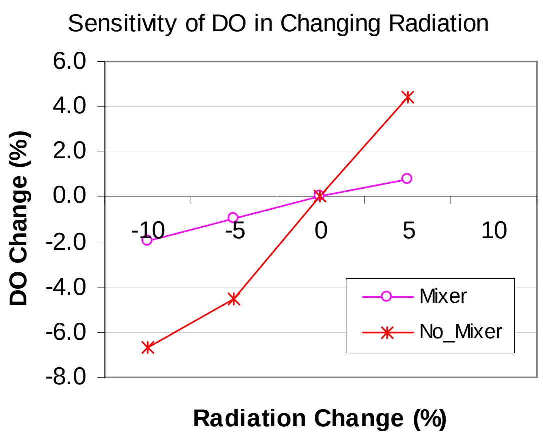

### *Layer 9.14 m depth*



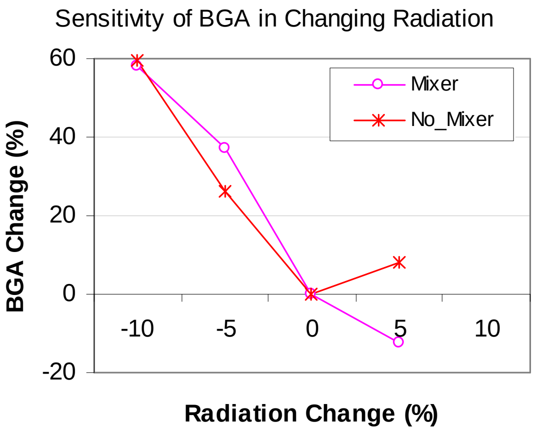



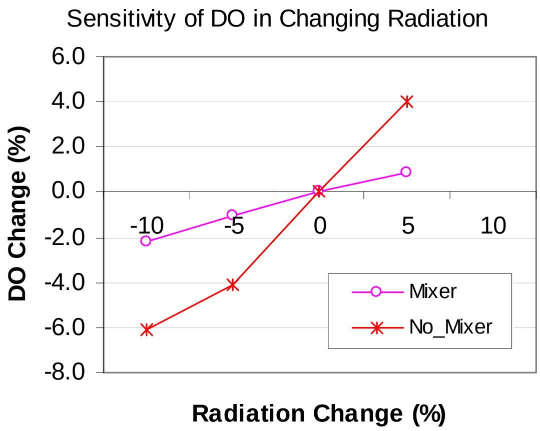

### *Layer 16.46 m depth*



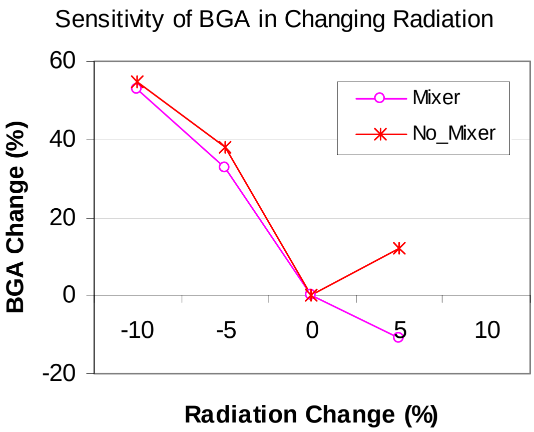



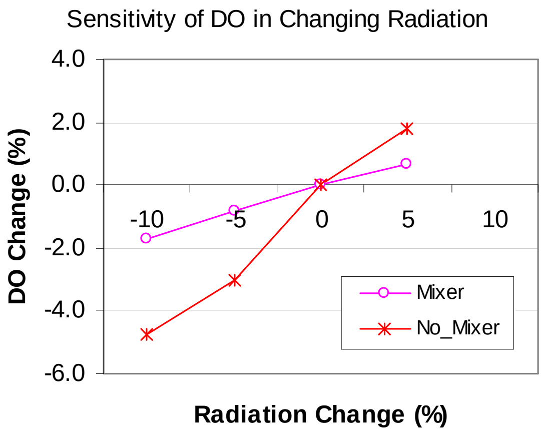
### *Bottom Layer*



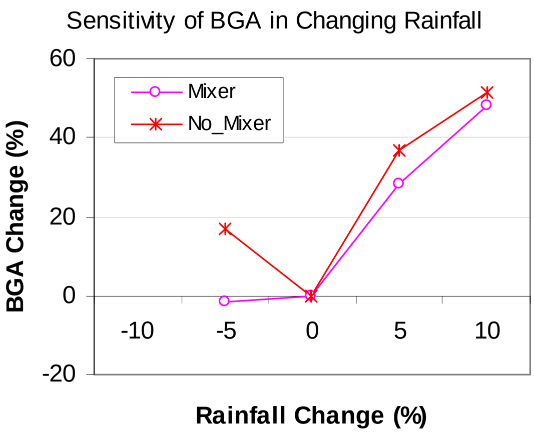

### *Pumping Layer*

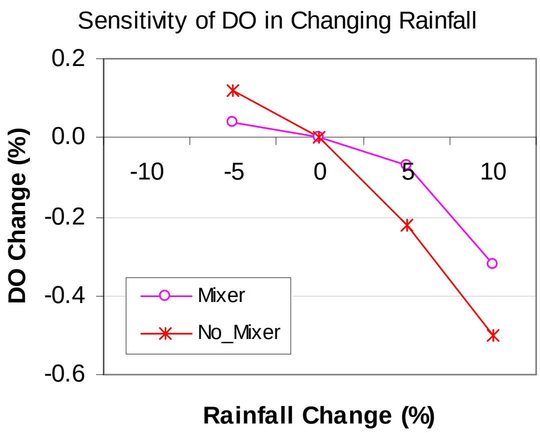


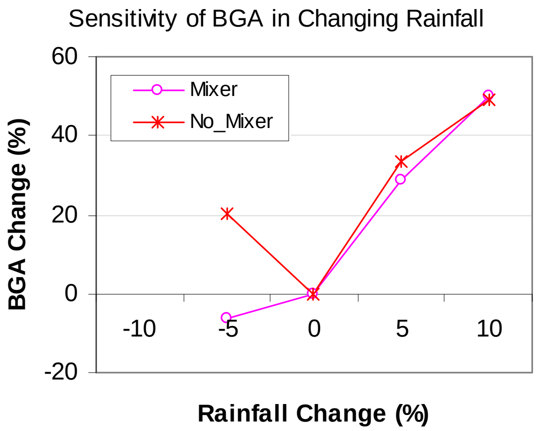

## B. Sensitivity of rainfall to Cyanobacteria and dissolved oxygen

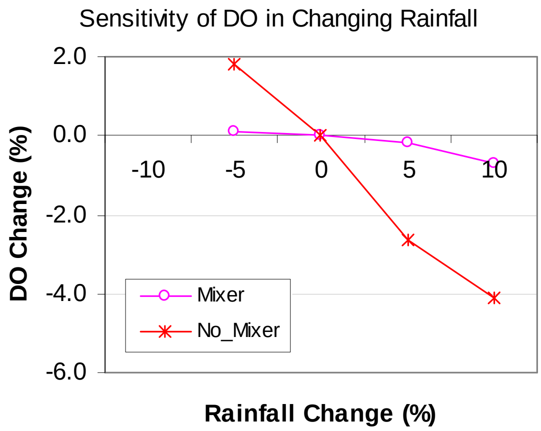
### *Surface Layer*



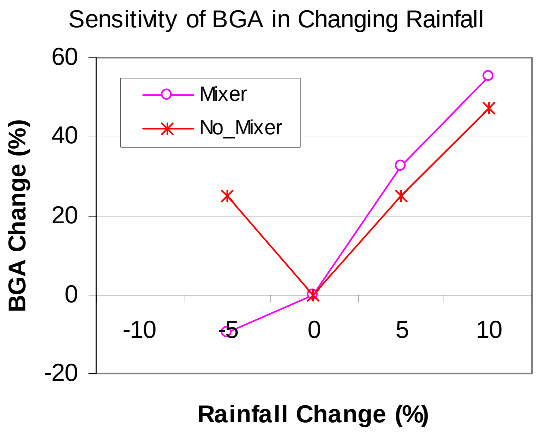



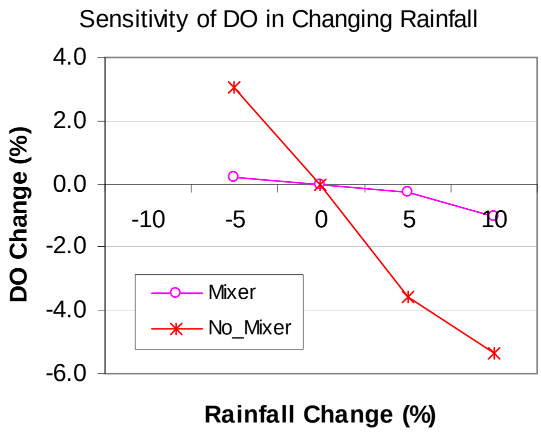
*Layer 9.14 m depth*



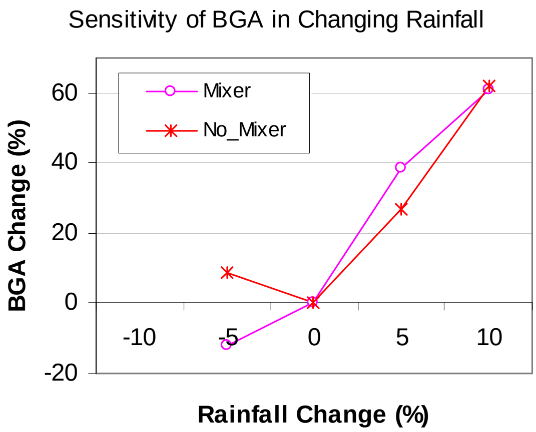



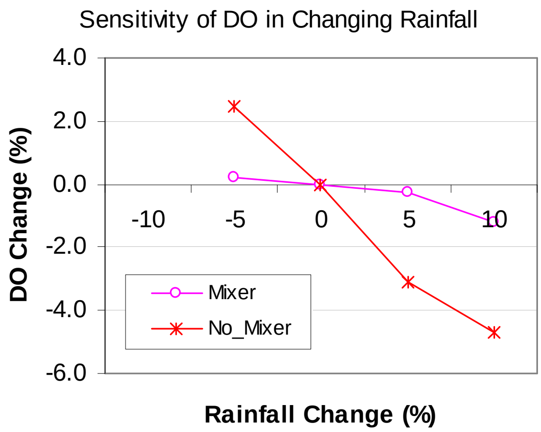

*Layer 16.46 m depth*



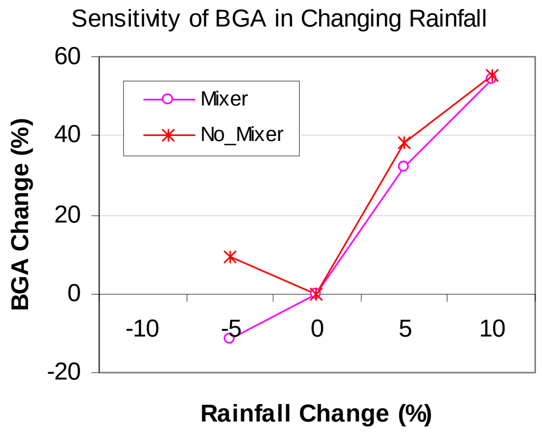



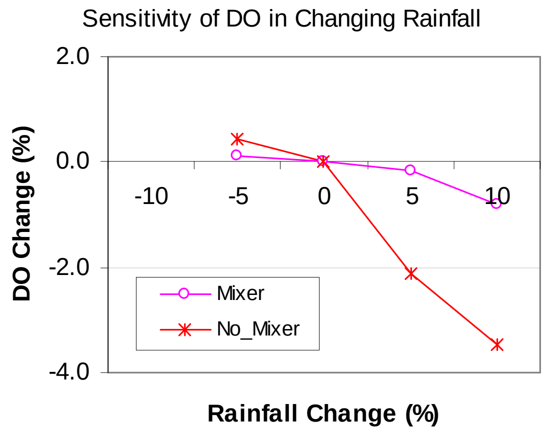

*Bottom Layer*



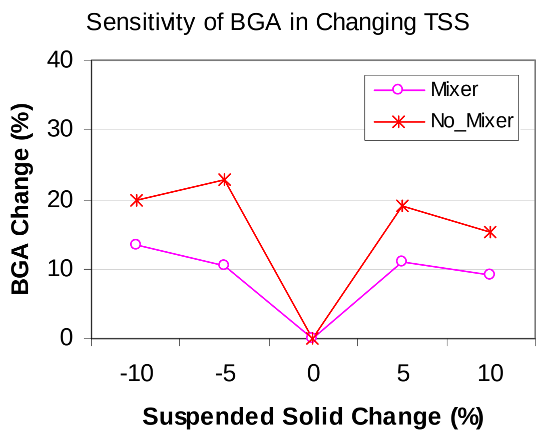
### *Pumping Layer*

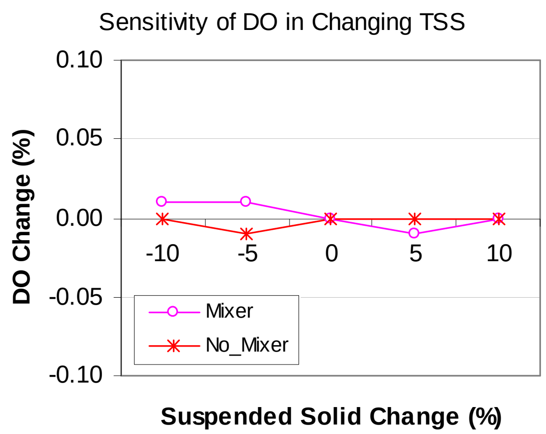


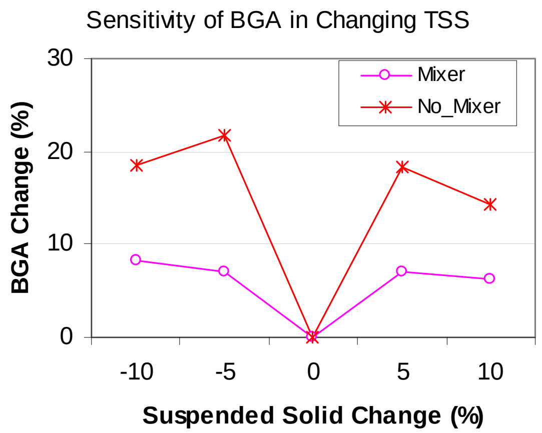

## C. Sensitivity of suspended solid to Cyanobacteria and dissolved oxygen

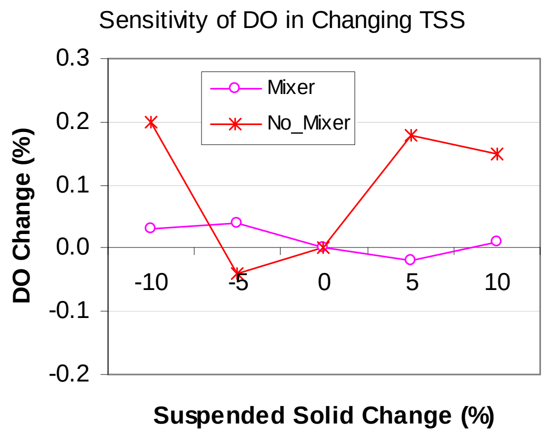
### *Surface Layer*



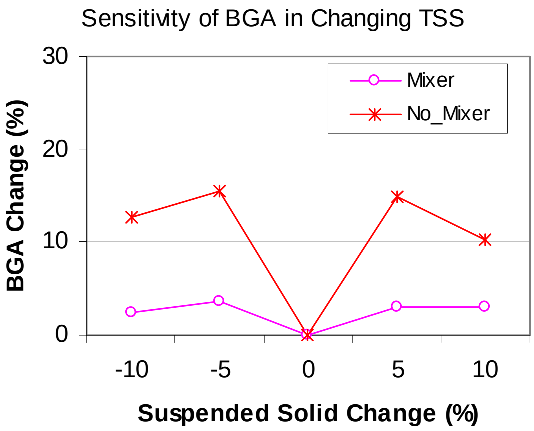



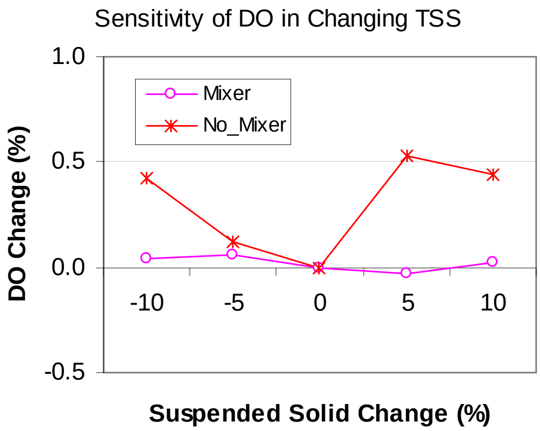

### *Layer 9.14 m depth*



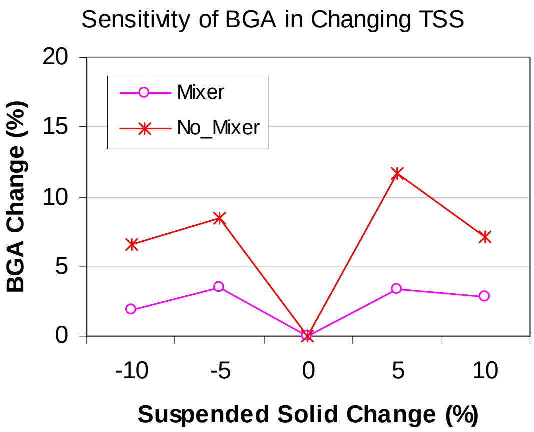



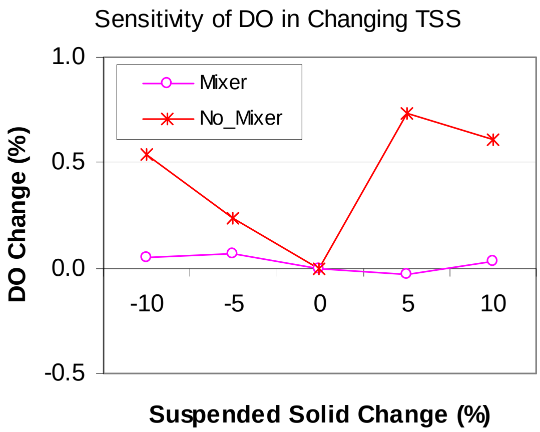
*Layer 16.46 m depth*



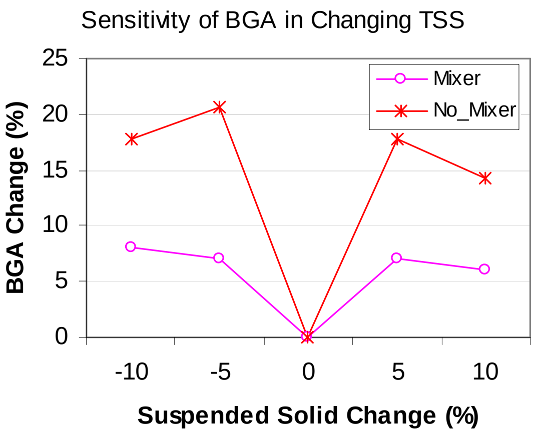



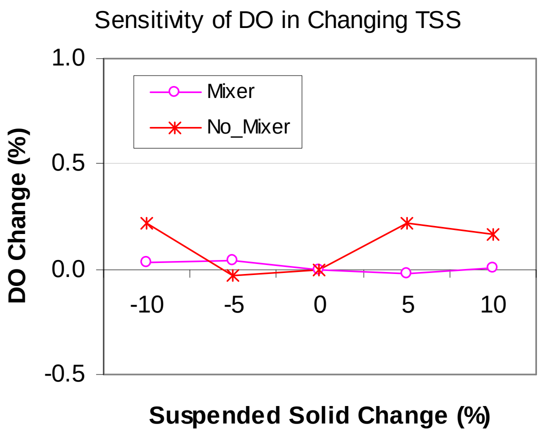

*Bottom Layer*



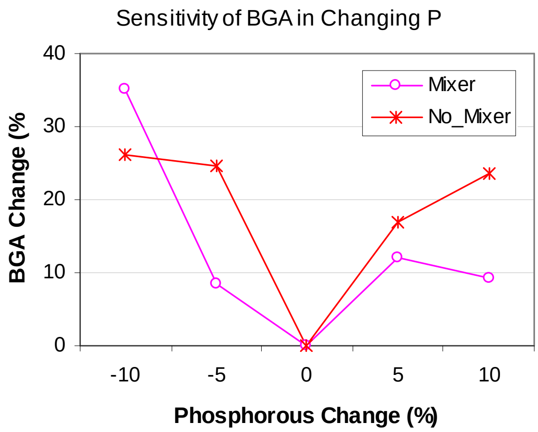

*Pumping Layer*

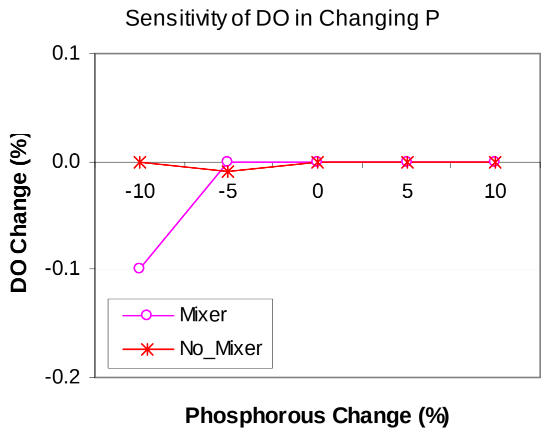


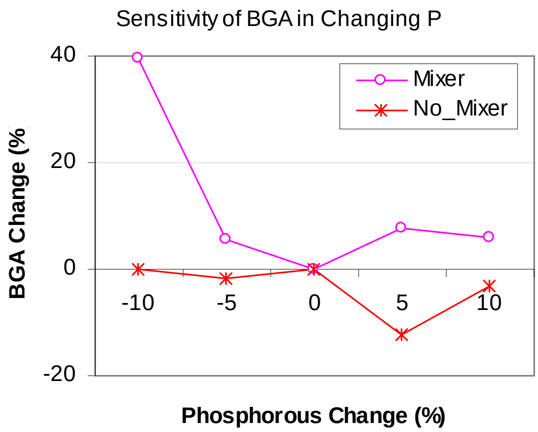
## D. Sensitivity of phosphorus to Cyanobacteria and dissolved oxygen

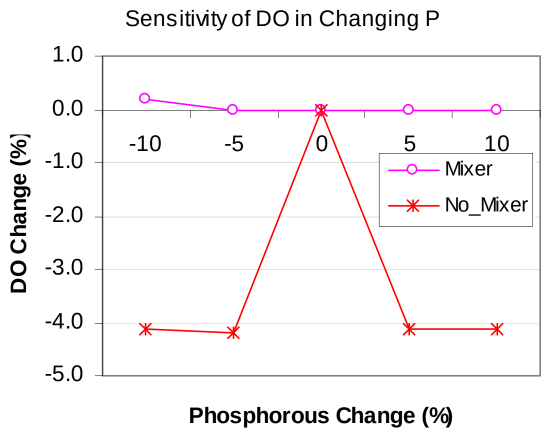
### *Surface Layer*



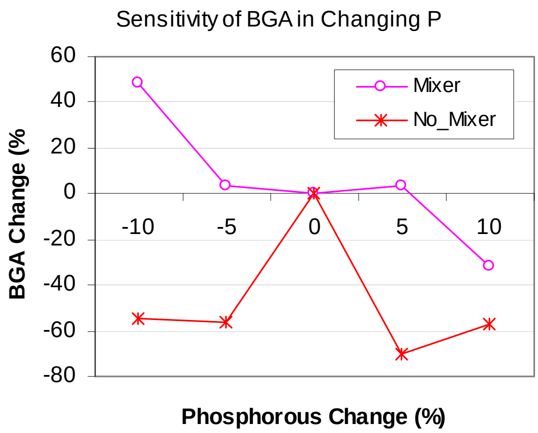



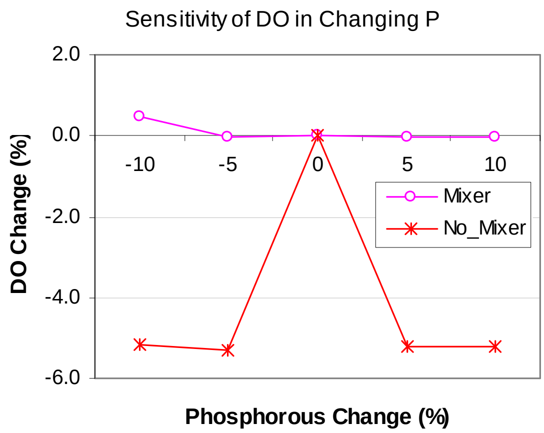

### *Layer 9.14 m depth*



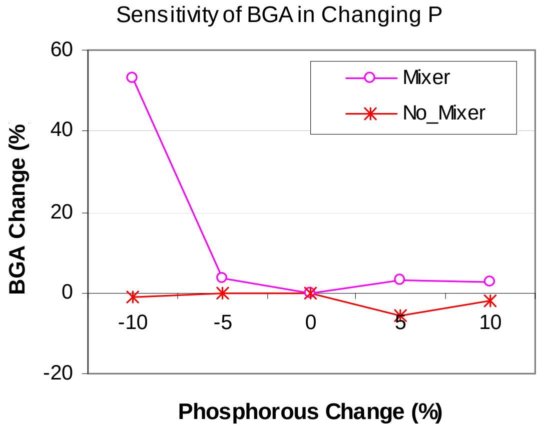



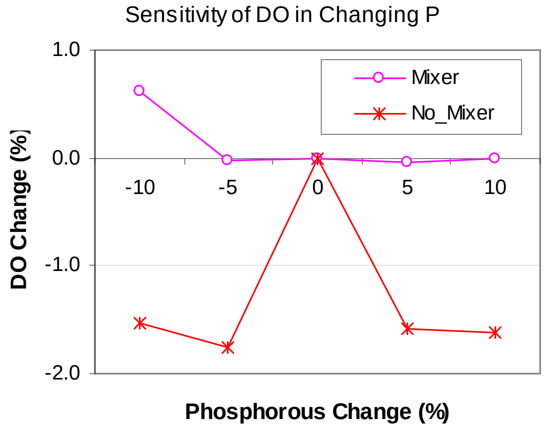

### *Layer 16.46 m depth*



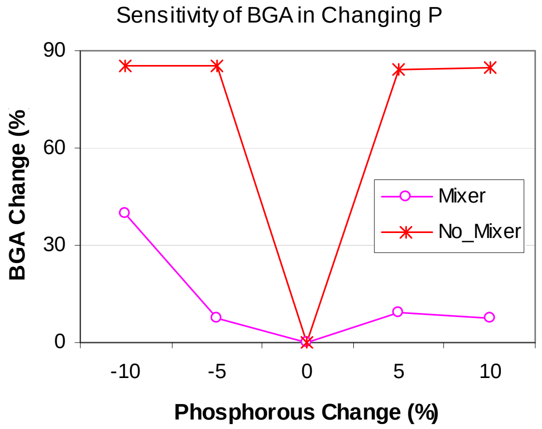



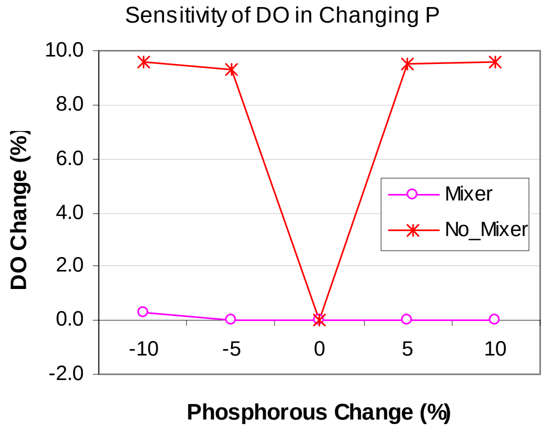
## *Bottom Layer*



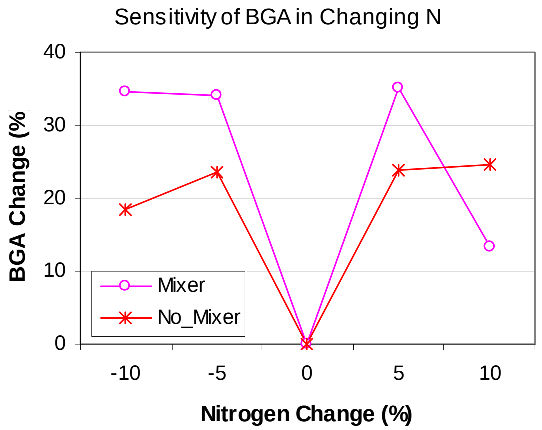

## *Pumping Layer*

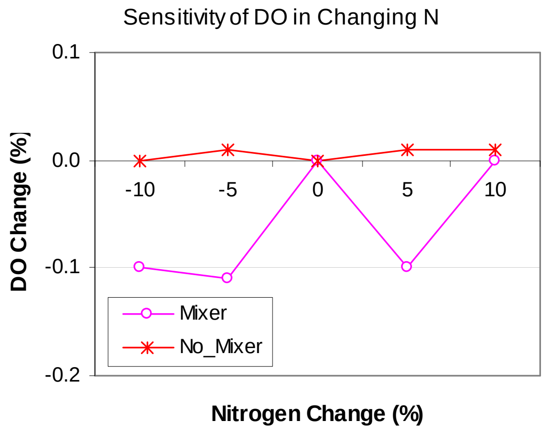


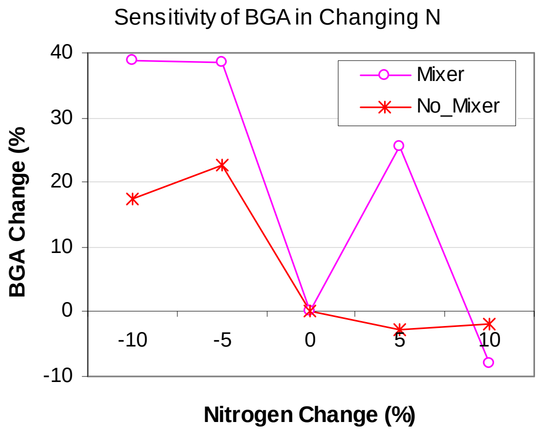

# E. Sensitivity of nitrate to Cyanobacteria and dissolved oxygen

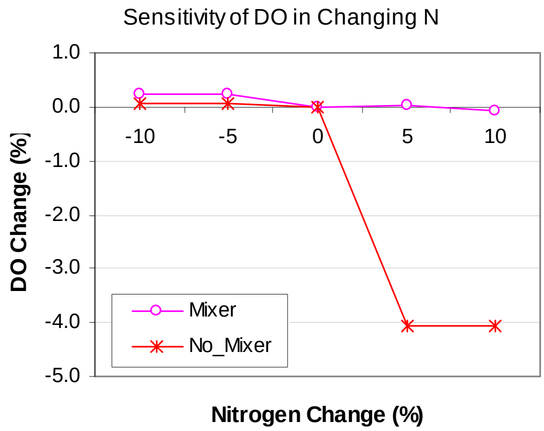
## *Surface Layer*



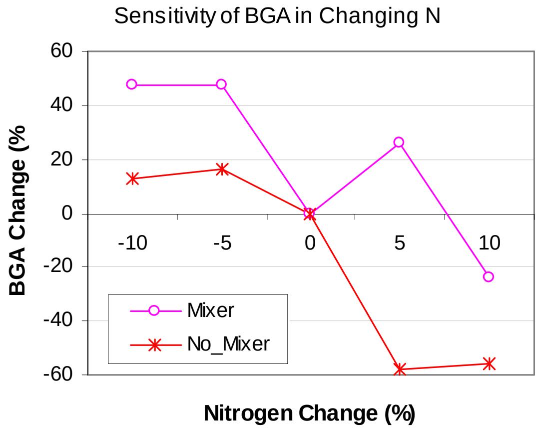



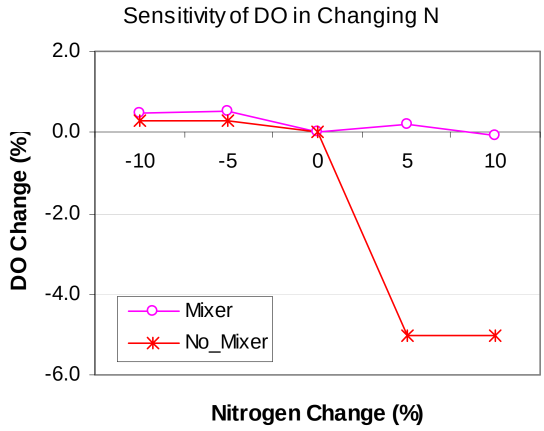
## *Layer 9.14 m depth*



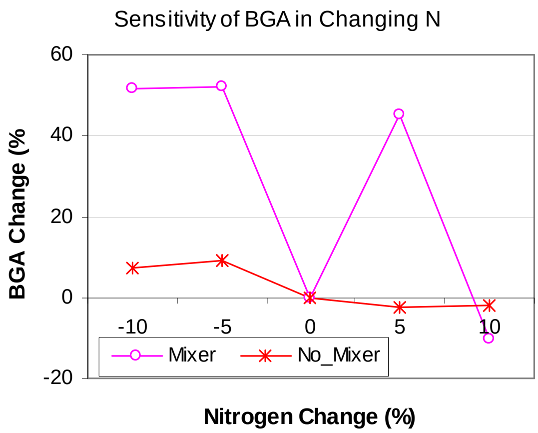



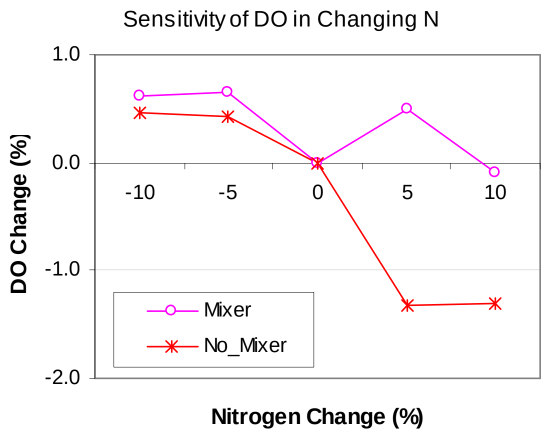

## *Layer 16.46 m depth*



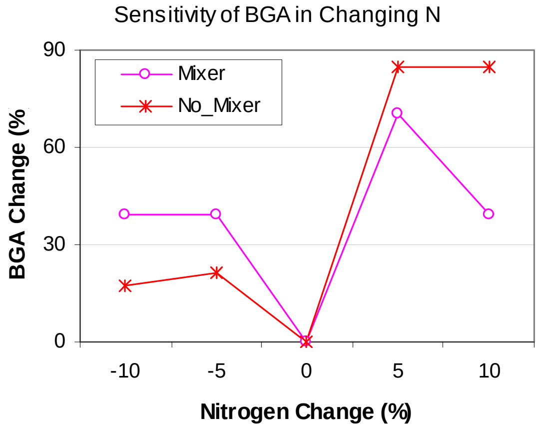



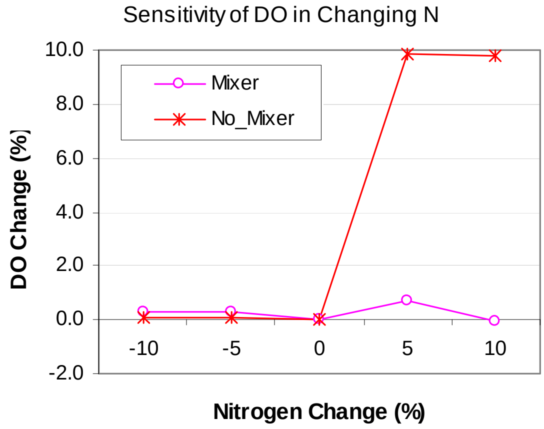

## *Bottom Layer*



### *Pumping Layer*

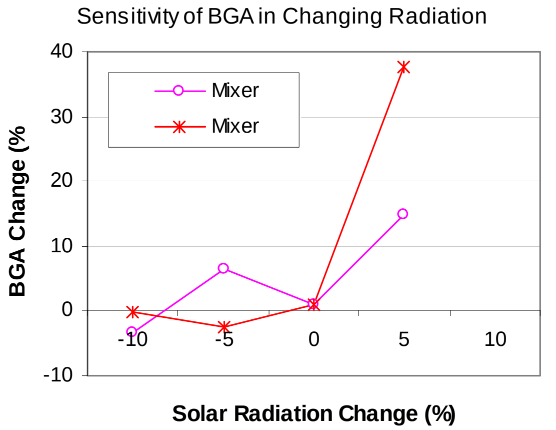


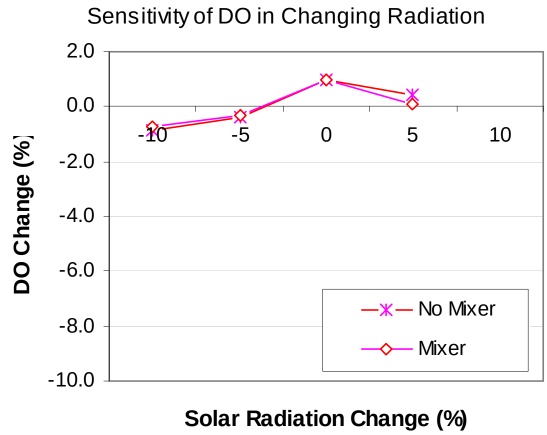



# Appendix B.2 Sensitivity of water quality simulations of Cressbrook reservoir

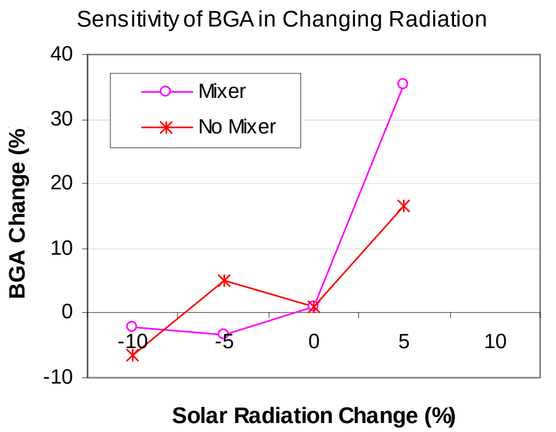
## A. Sensitivity of radiation to Cyanobacteria and dissolved oxygen

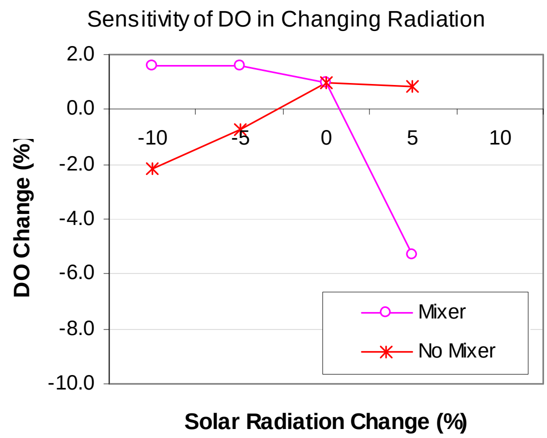
### *Surface Layer*



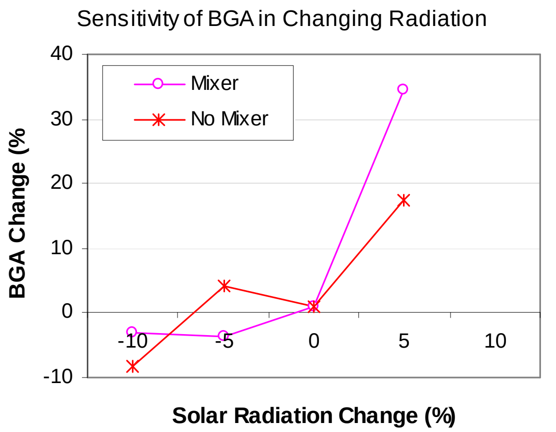



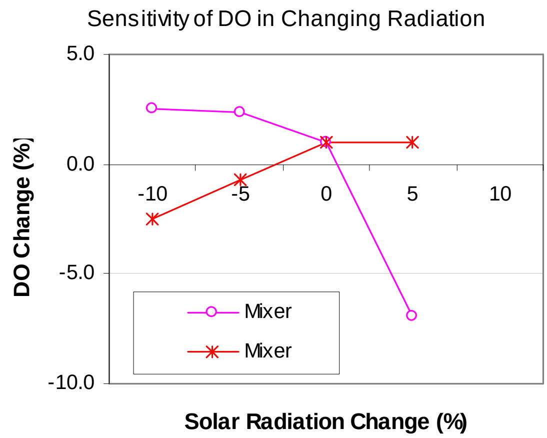

### *Layer 9.30 m depth*



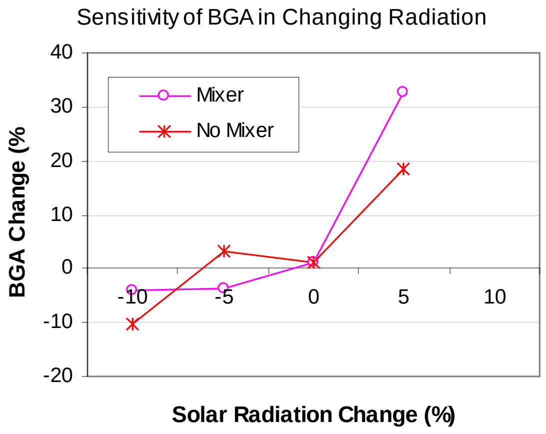



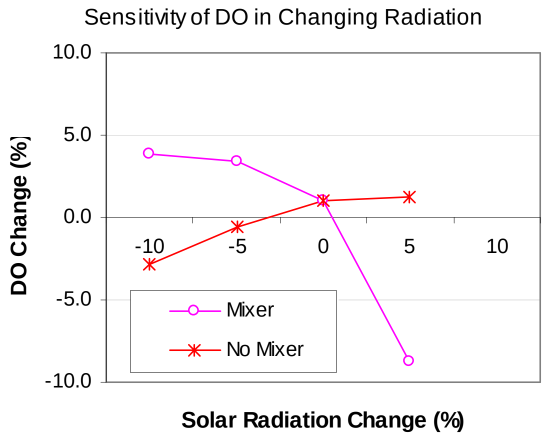

### *Layer 12.25 m depth*



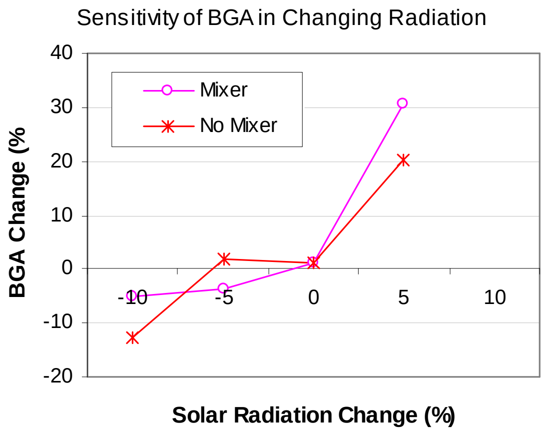



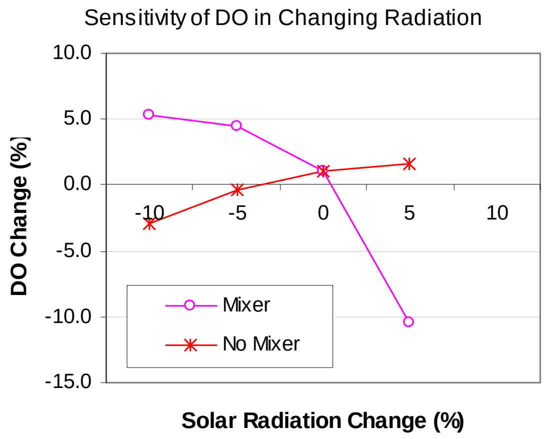
## *Layer 15.75 m depth*



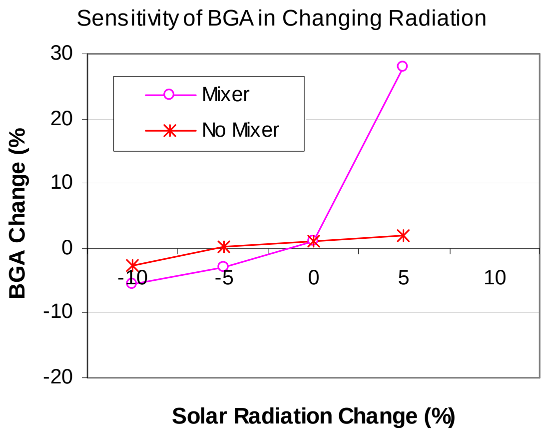



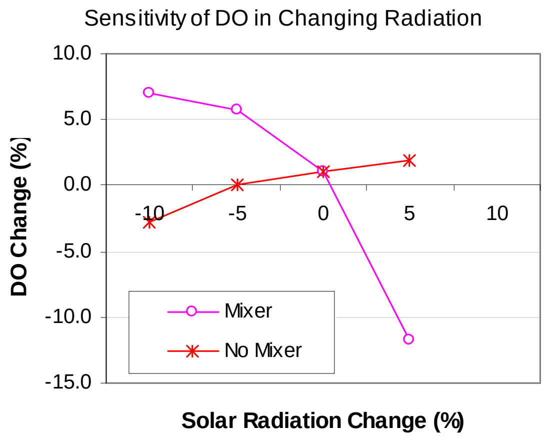

## *Layer 19.25 m depth*



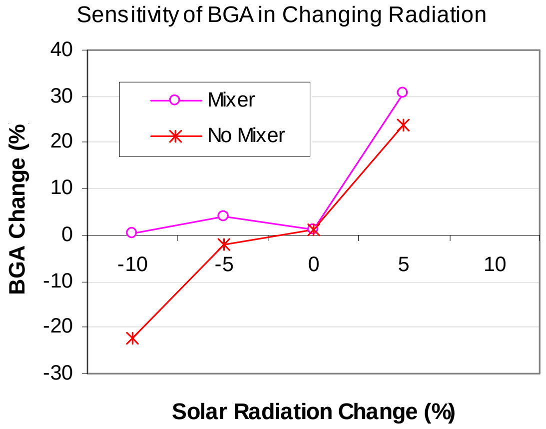



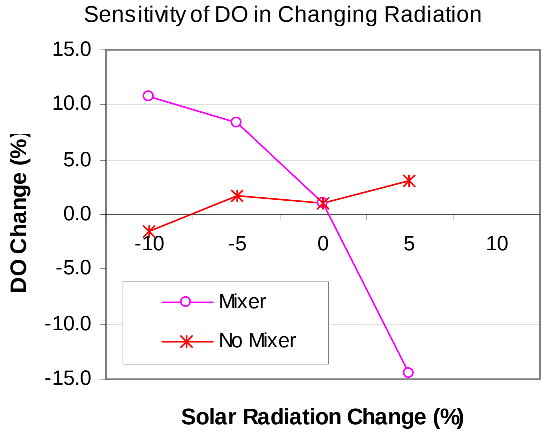

## *Layer 22.75 m depth*



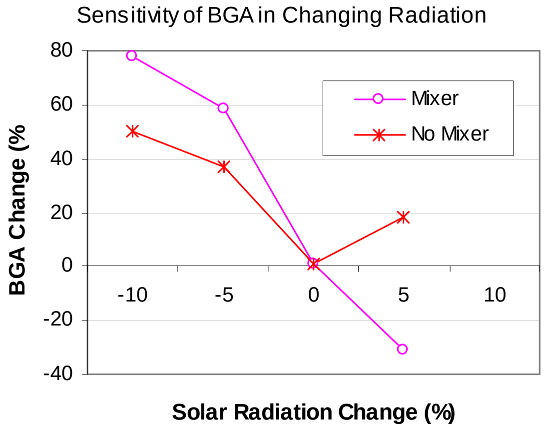



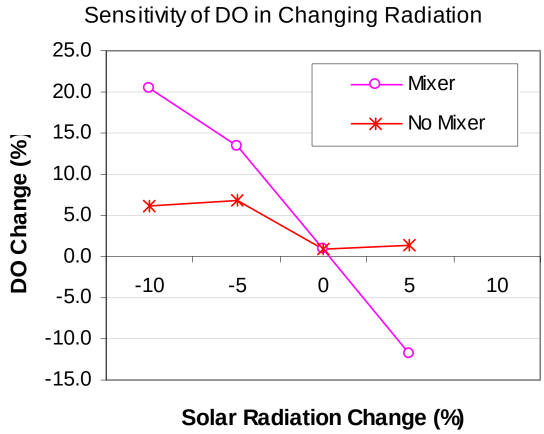
### *Layer 29.75 m depth*



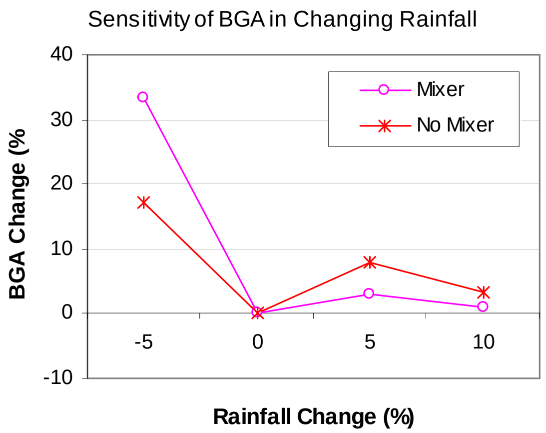

### *Bottom Layer*

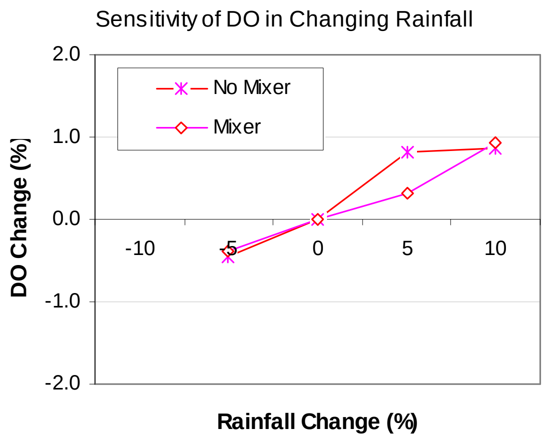


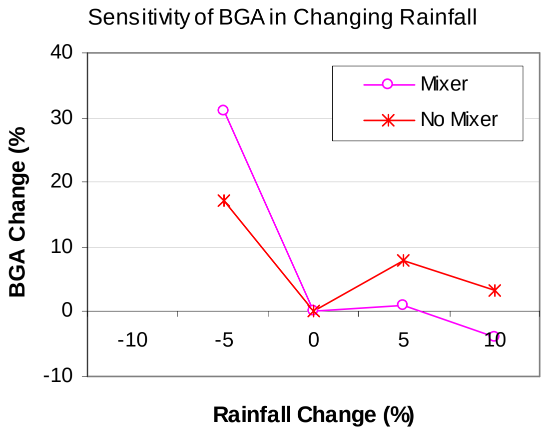

## B. Sensitivity of rainfall to Cyanobacteria and dissolved oxygen

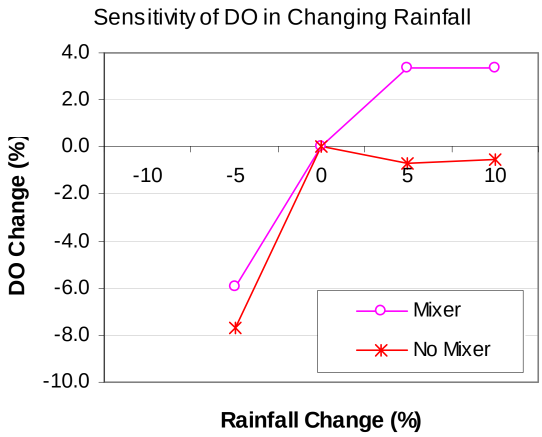
### *Surface Layer*



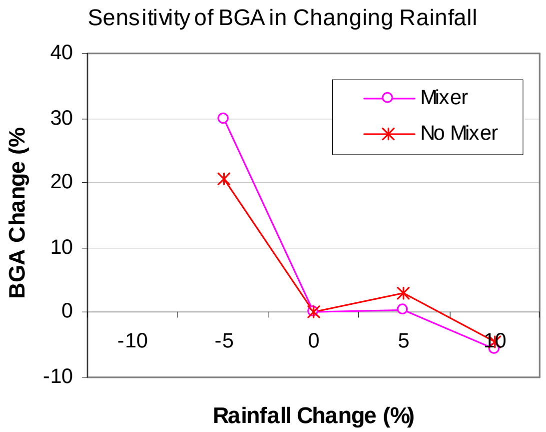



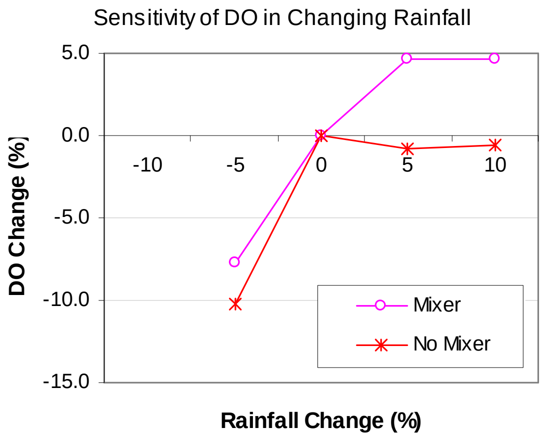
## *Layer 9.30 m depth*



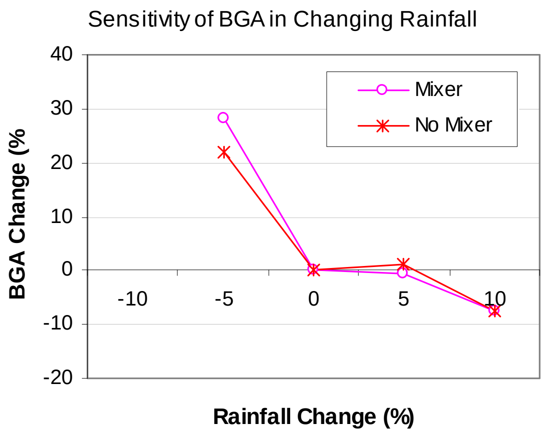



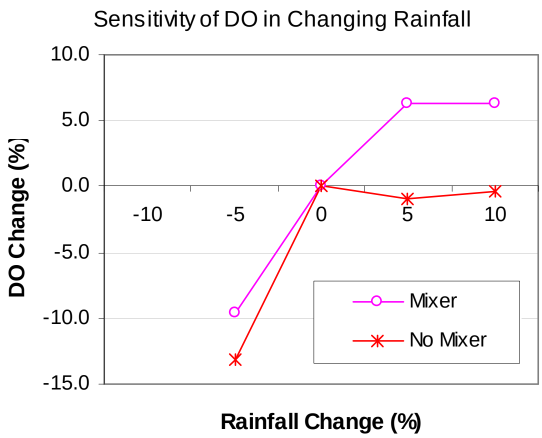

## *Layer 12.25 m depth*



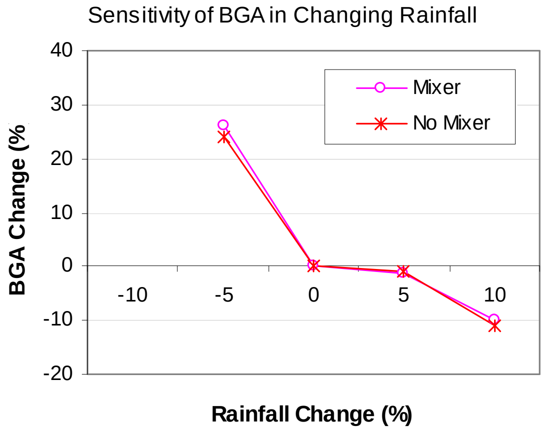



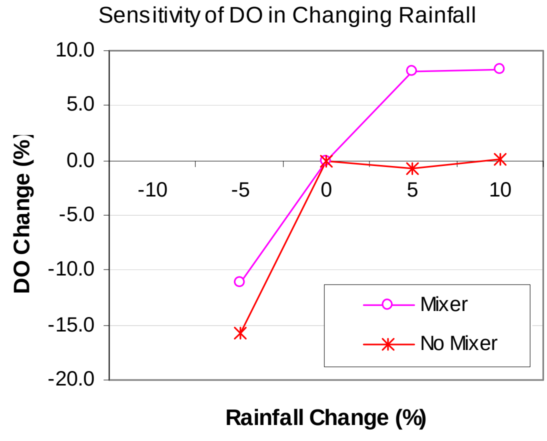

## *Layer 15.75 m depth*



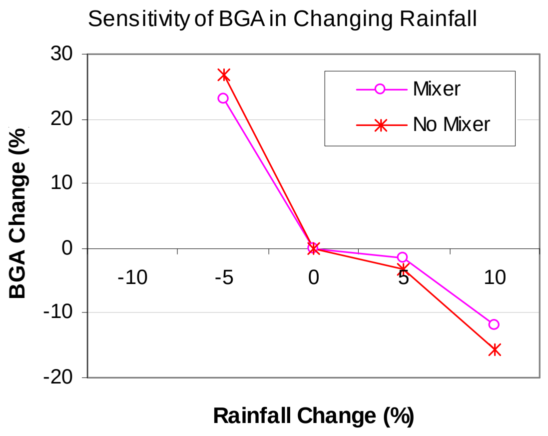



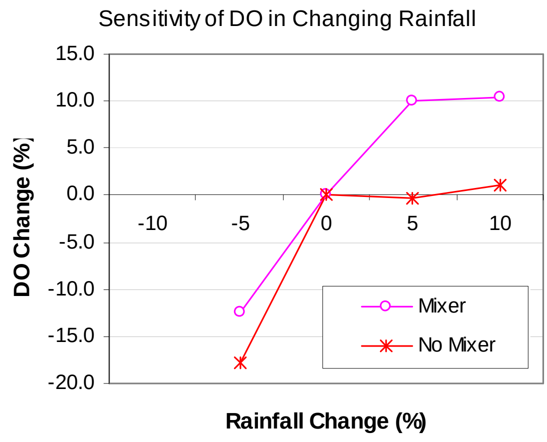
## *Layer 19.25 m depth*



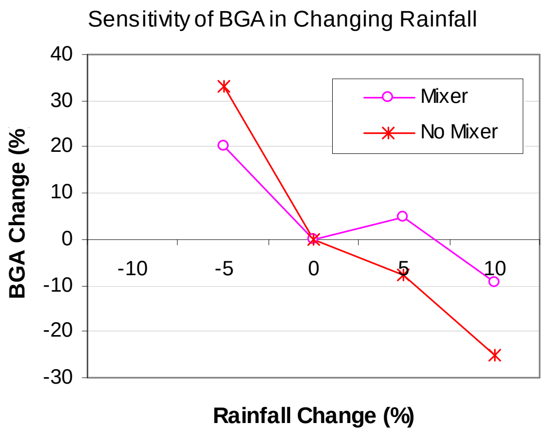



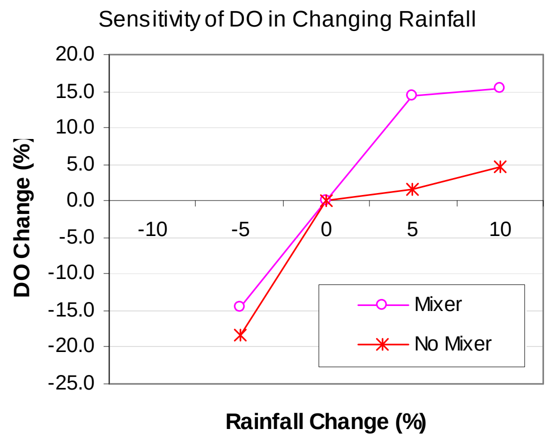

## *Layer 22.75 m depth*



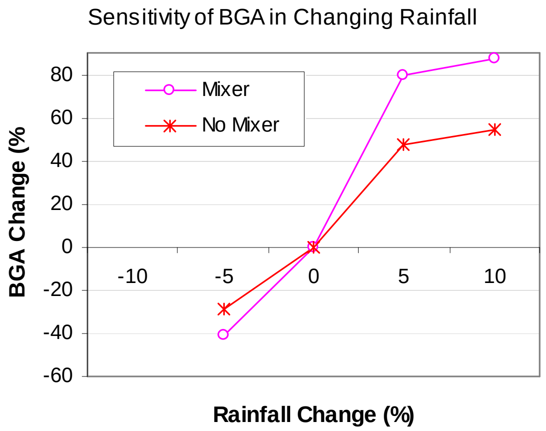



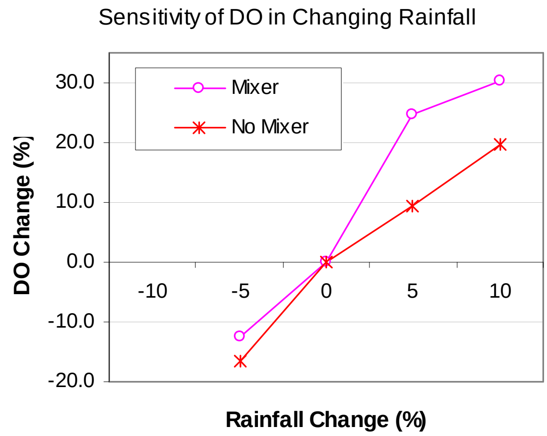

## *Layer 29.75 m depth*



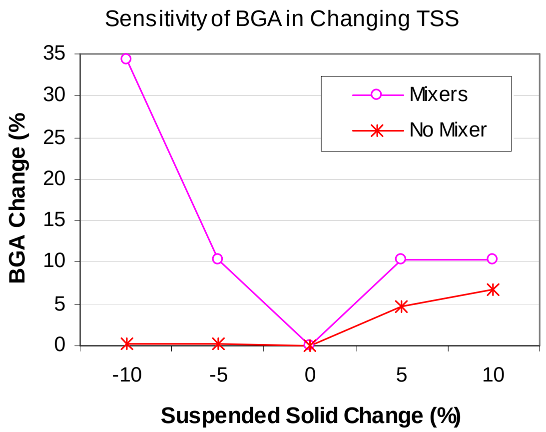
## *Bottom Layer*

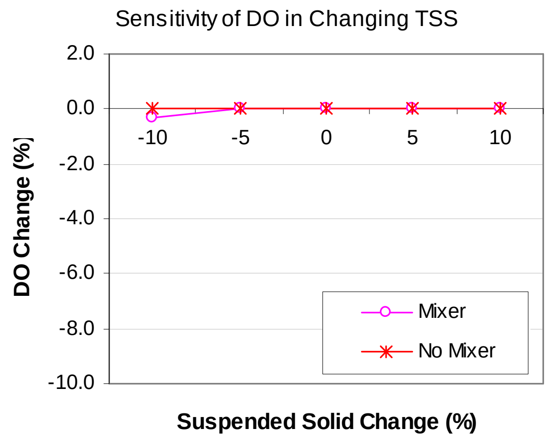


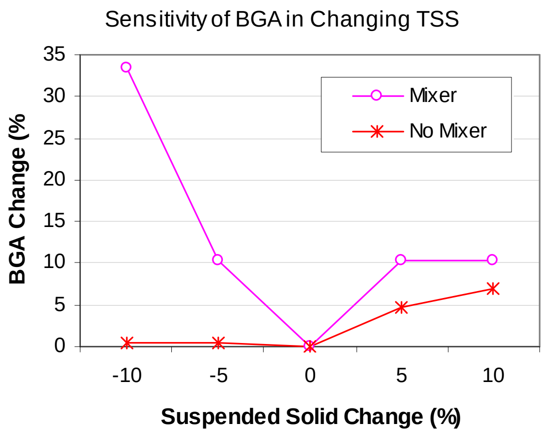

## C. Sensitivity of suspended solid to Cyanobacteria and dissolved oxygen

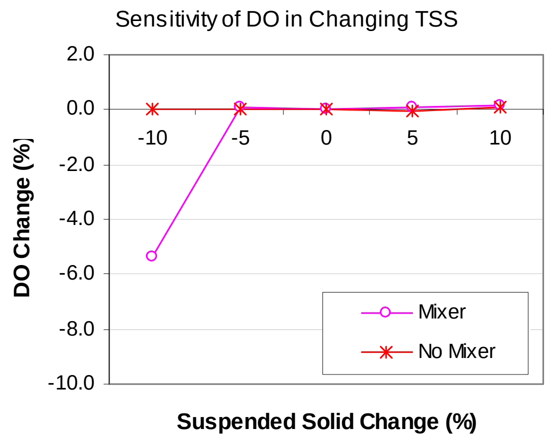
### *Surface Layer*



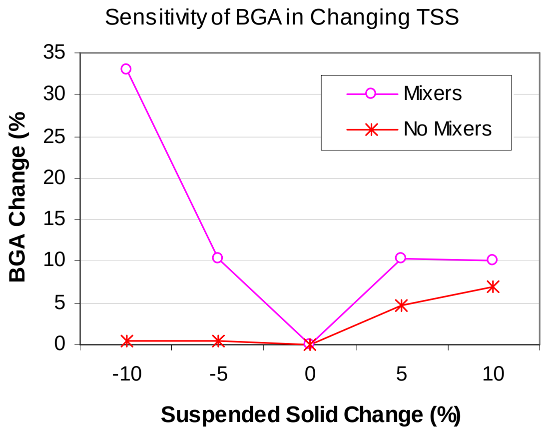



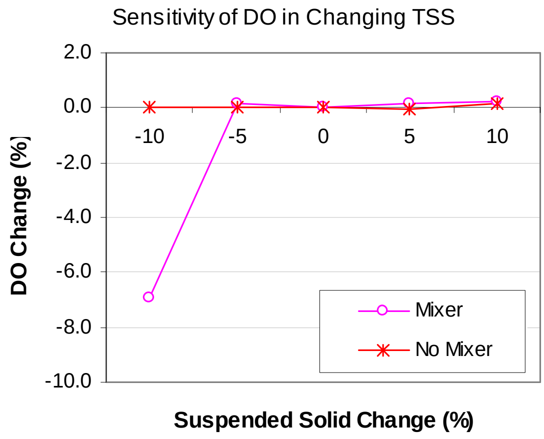

### *Layer 9.30 m depth*



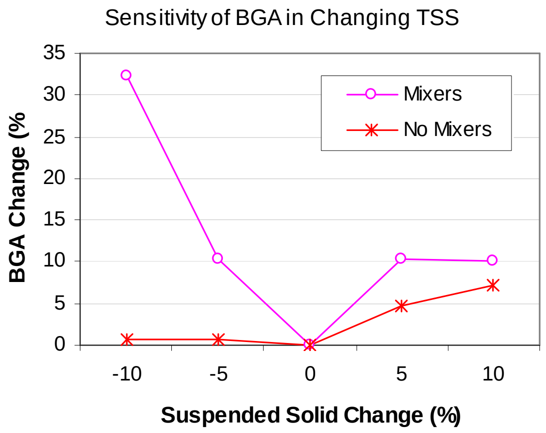



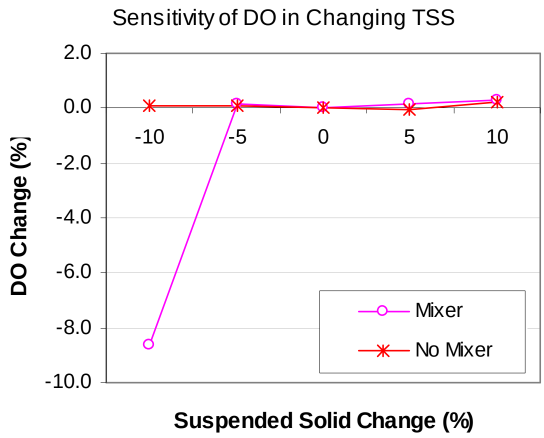
## *Layer 12.25 m depth*



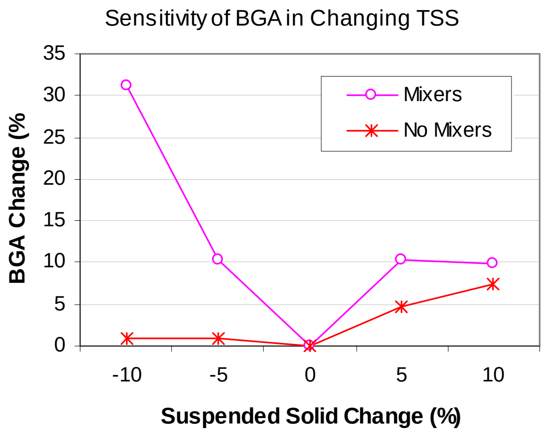



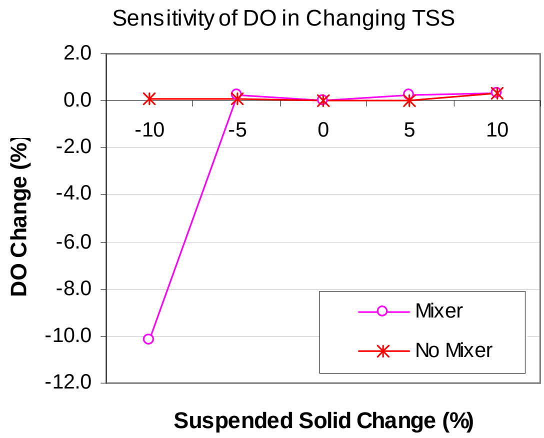

## *Layer 15.75 m depth*



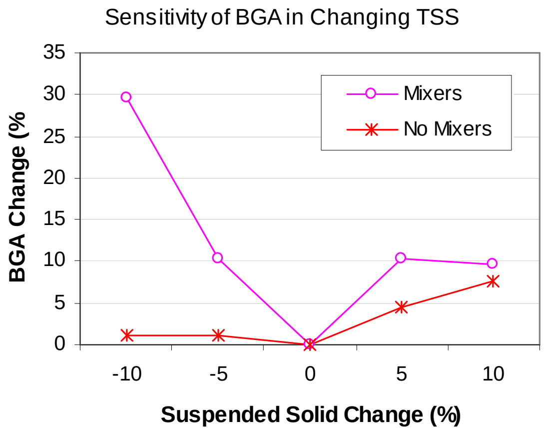



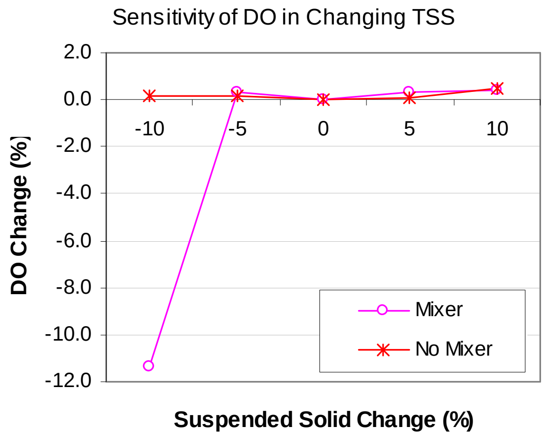

## *Layer 19.25 m depth*



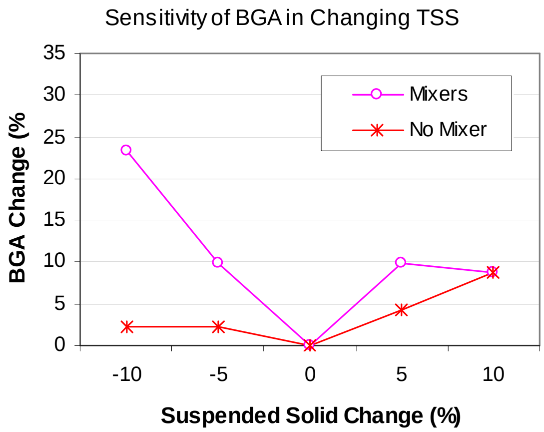



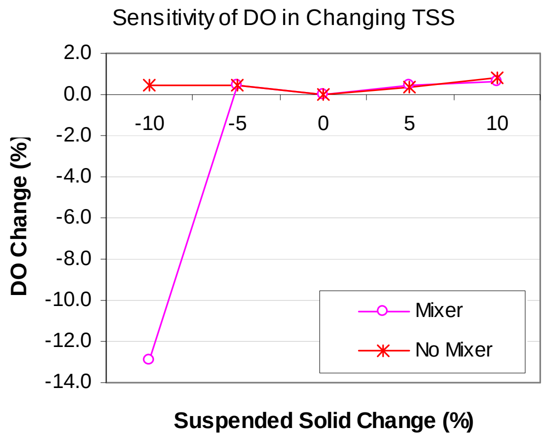
## *Layer 22.75 m depth*



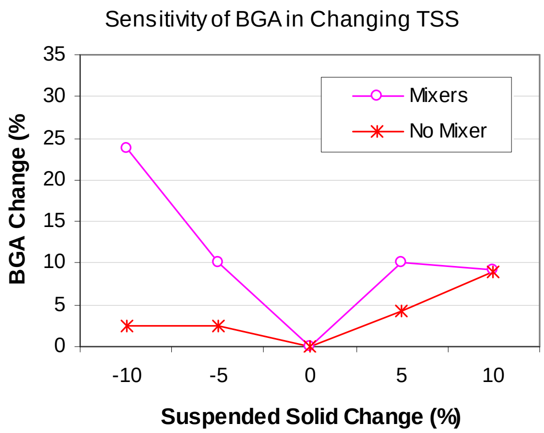



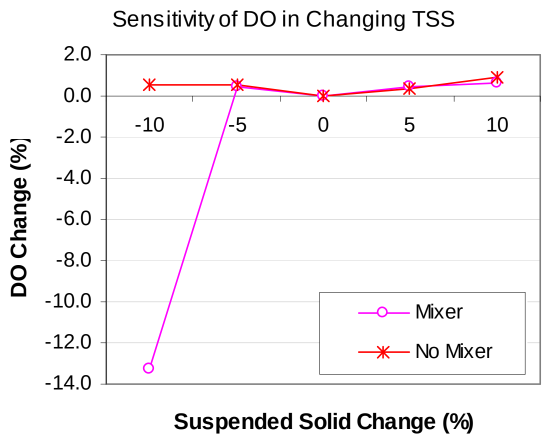

## *Layer 29.75 m depth*



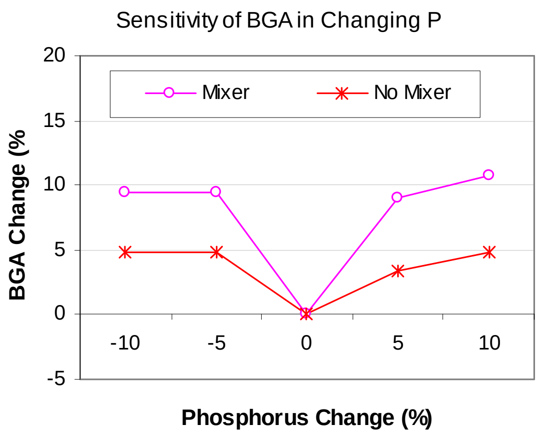

## *Bottom Layer*

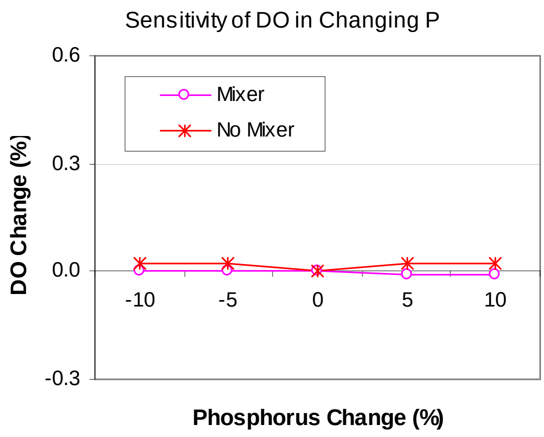


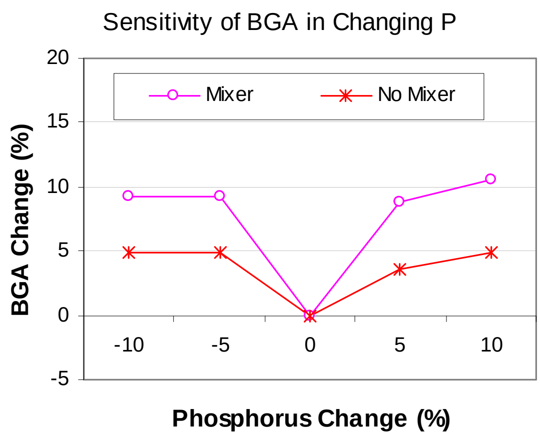
## D. Sensitivity of phosphorus to Cyanobacteria and dissolved oxygen

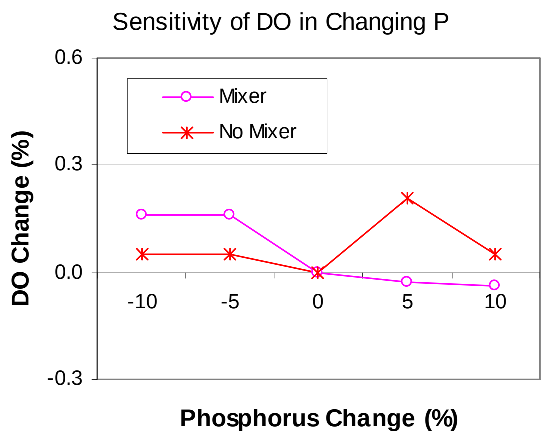
### *Surface Layer*



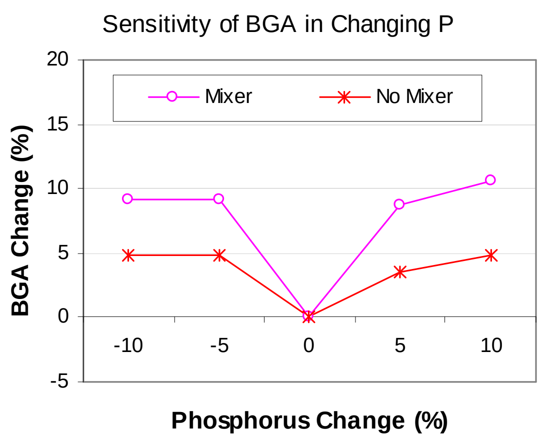



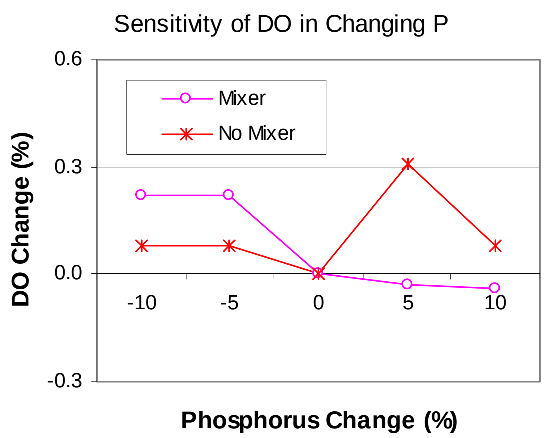

### *Layer 9.30 m depth*



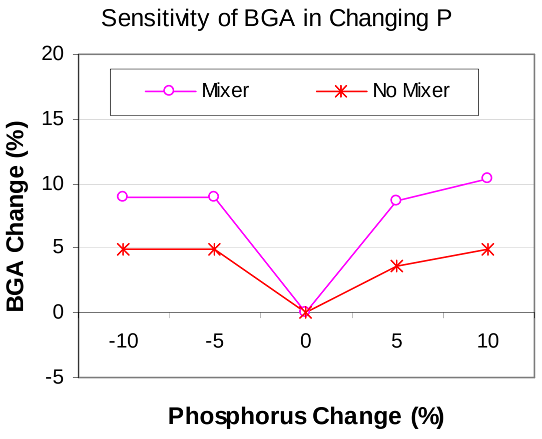



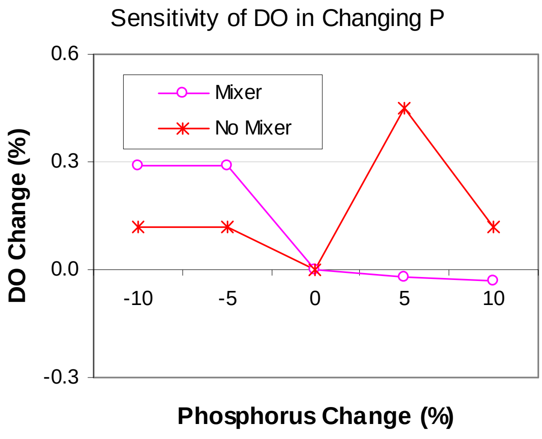

### *Layer 12.25 m depth*



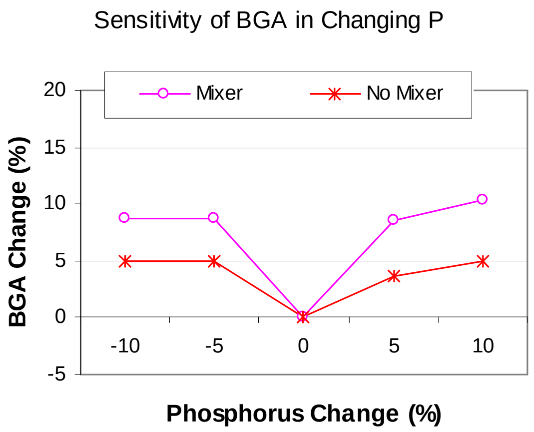



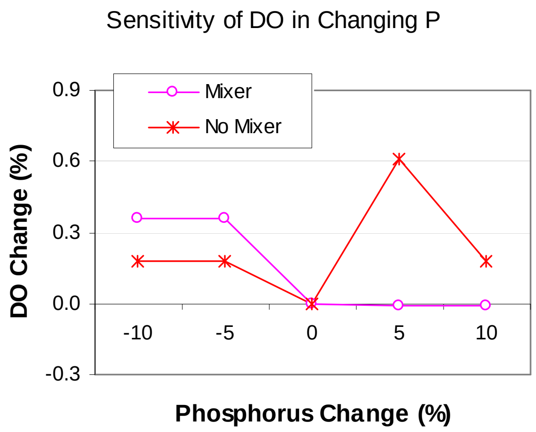
***Layer 15.75 m depth***



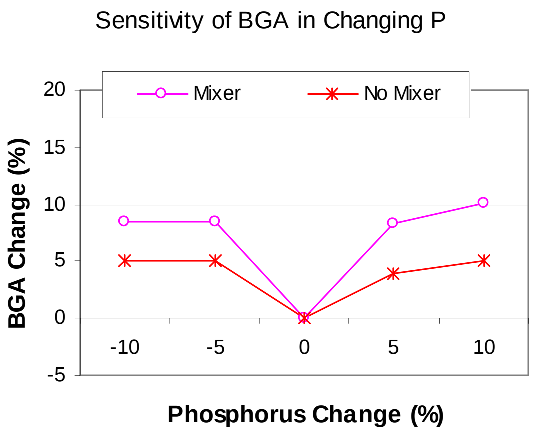



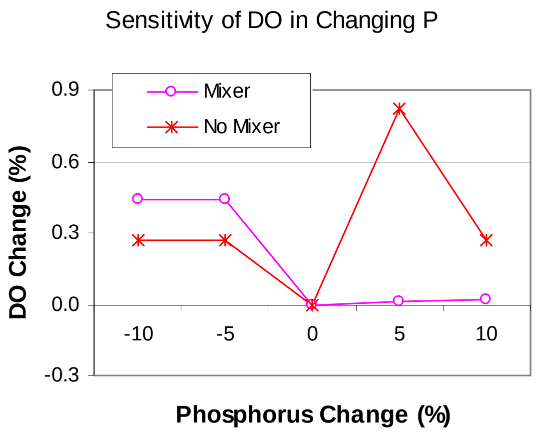

***Layer 19.25 m depth***



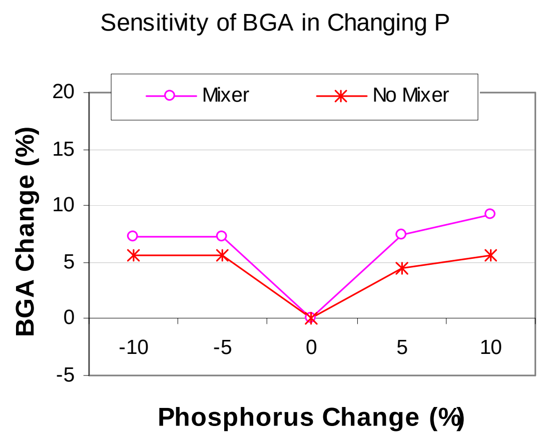



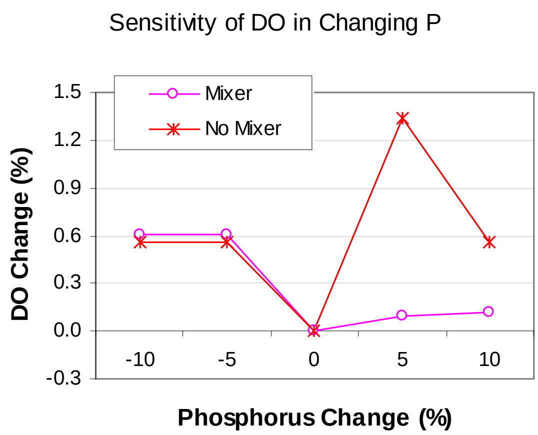

***Layer 22.75 m depth***



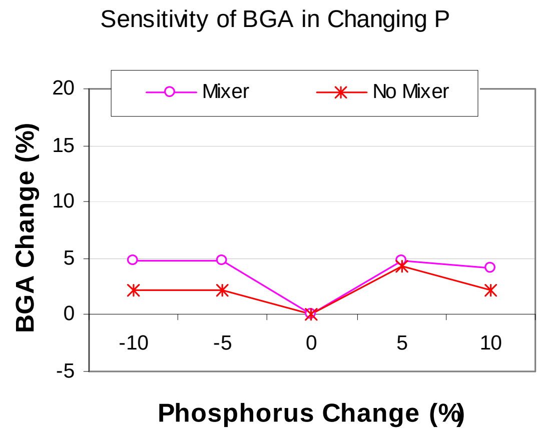



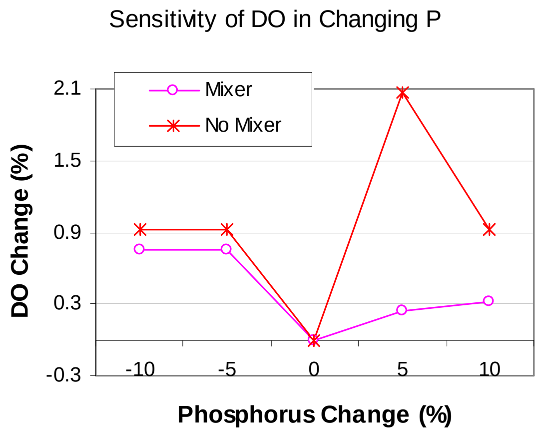
### *Layer 29.75 m depth*



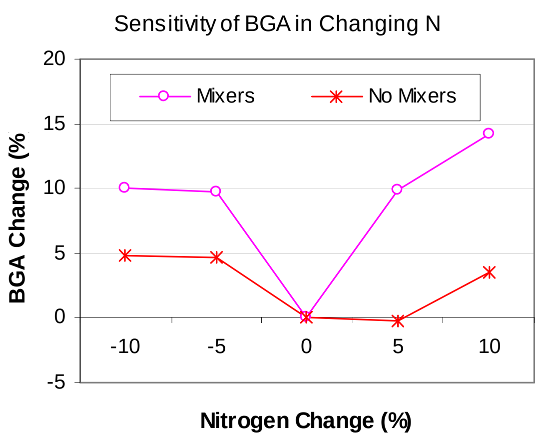

### *Bottom Layer*

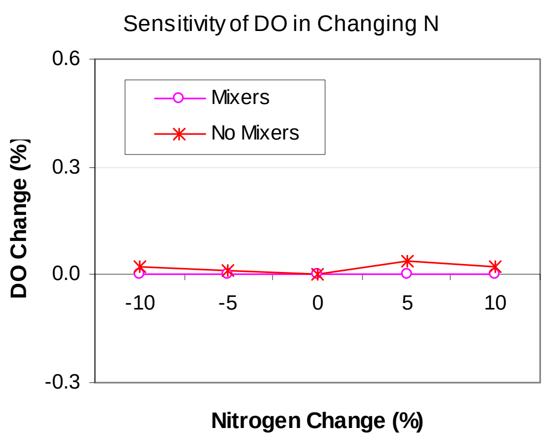


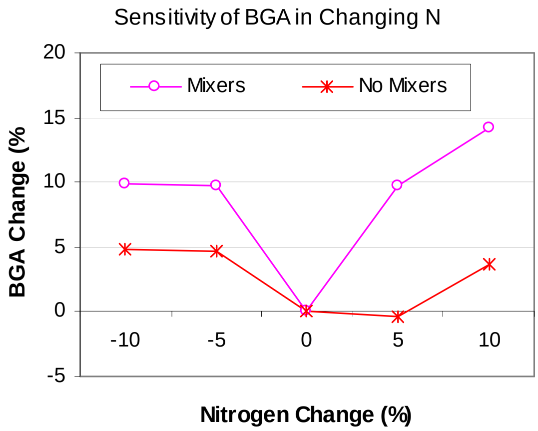

## E. Sensitivity of nitrate to Cyanobacteria and dissolved oxygen

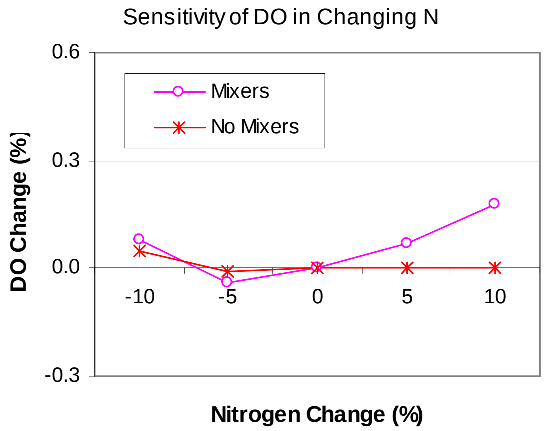
### *Surface Layer*



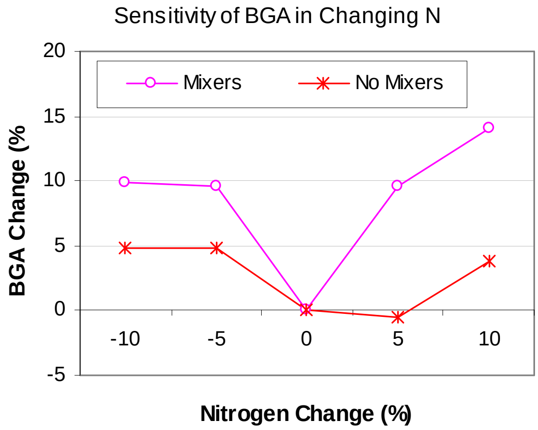



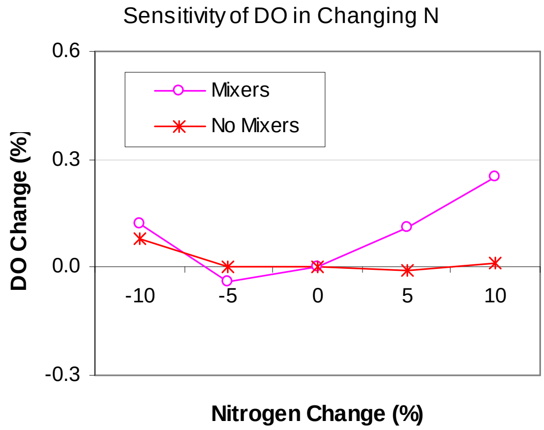
### *Layer 9.30 m depth*



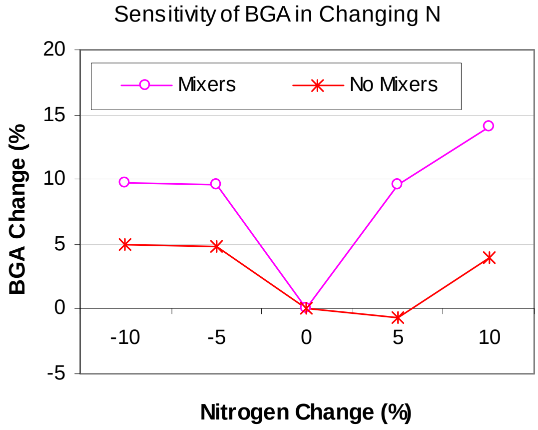



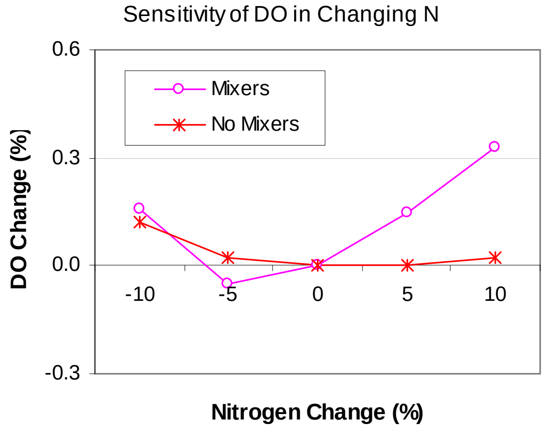

### *Layer 12.25 m depth*



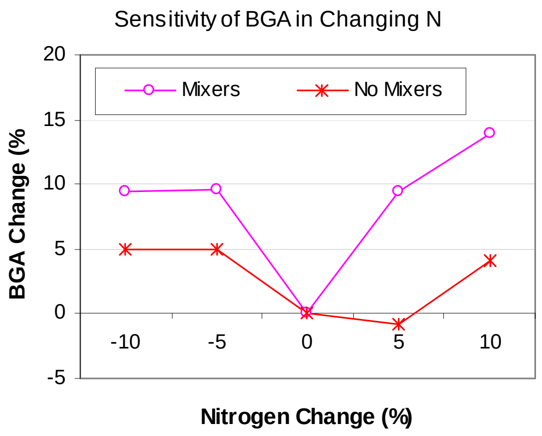



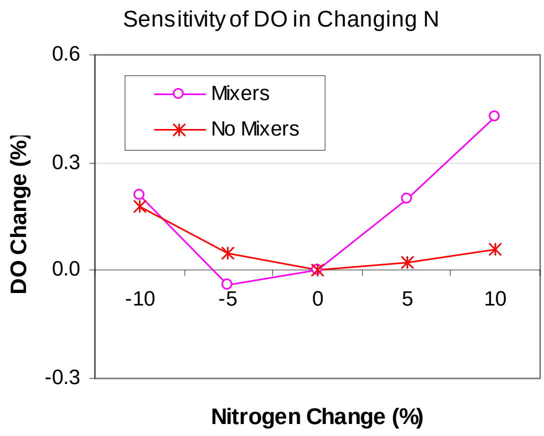

### *Layer 15.75 m depth*



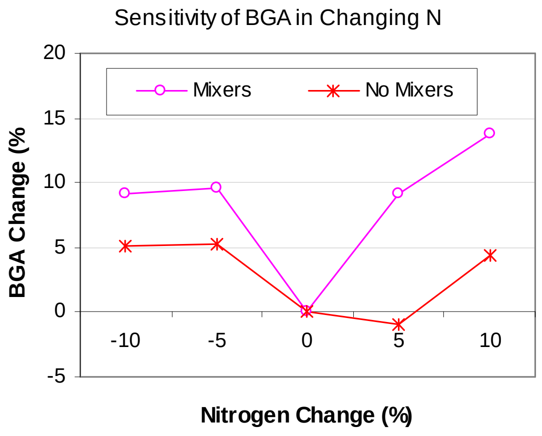



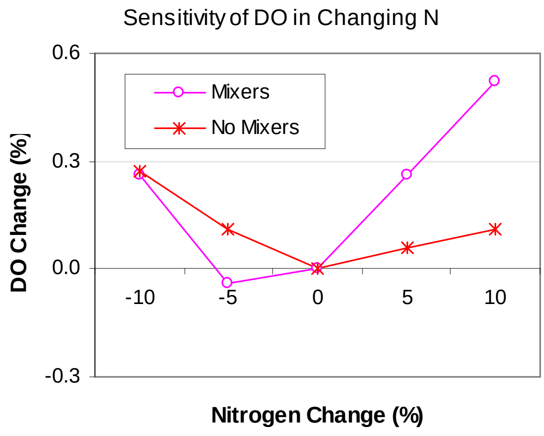
*Layer 19.25 m depth*



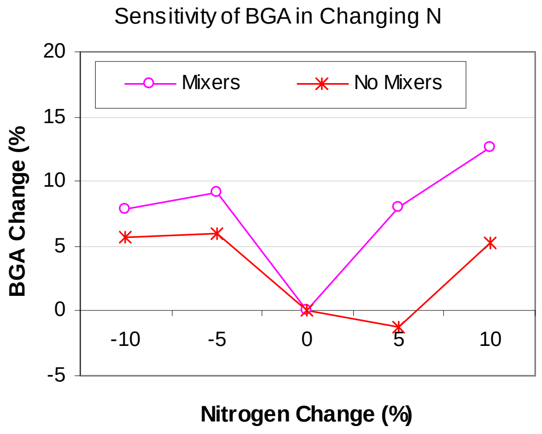



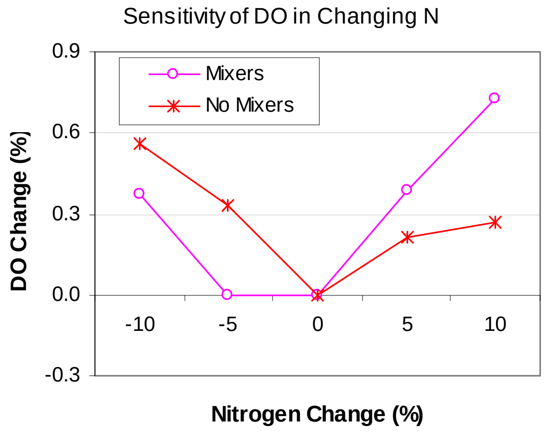

*Layer 22.75 m depth*



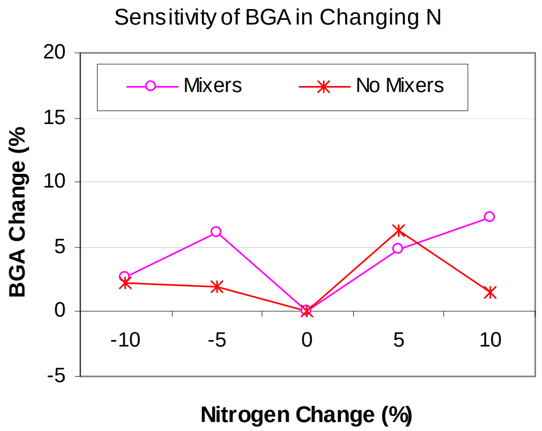



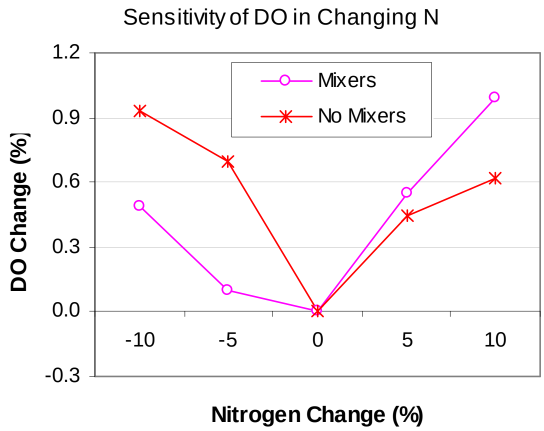

*Layer 29.75 m depth*



### *Bottom Layer*



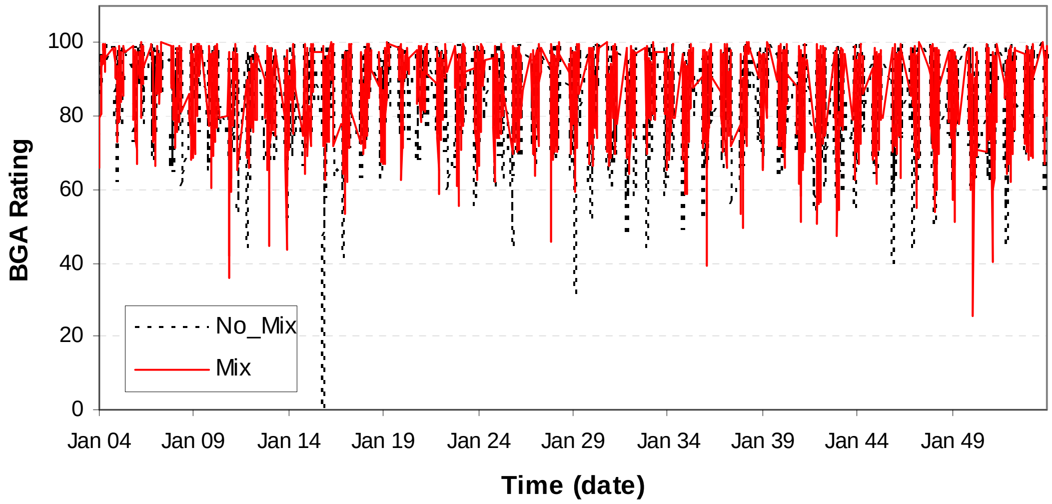



# Appendix C Individual water quality rating

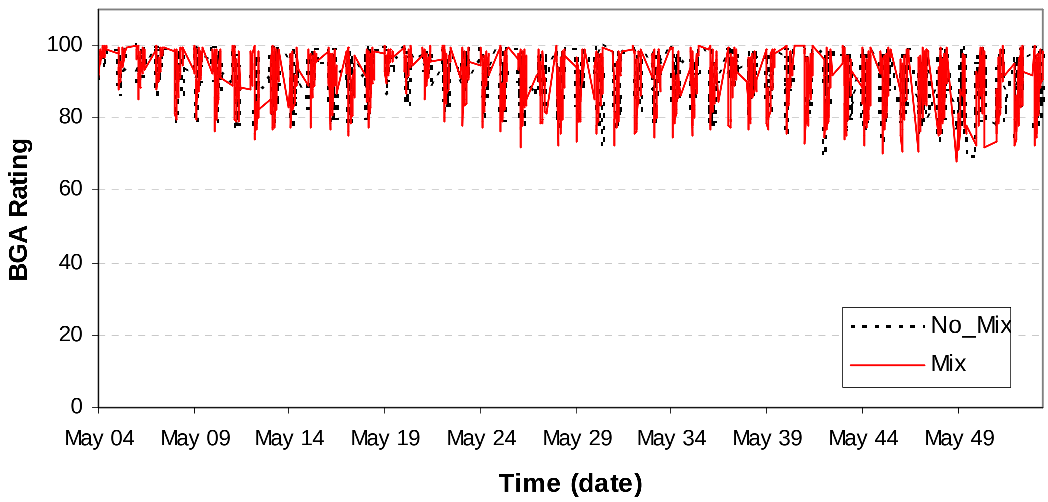
## A. Ratings of water quality indicators for Cooby storage

### *Cyanobacteria*

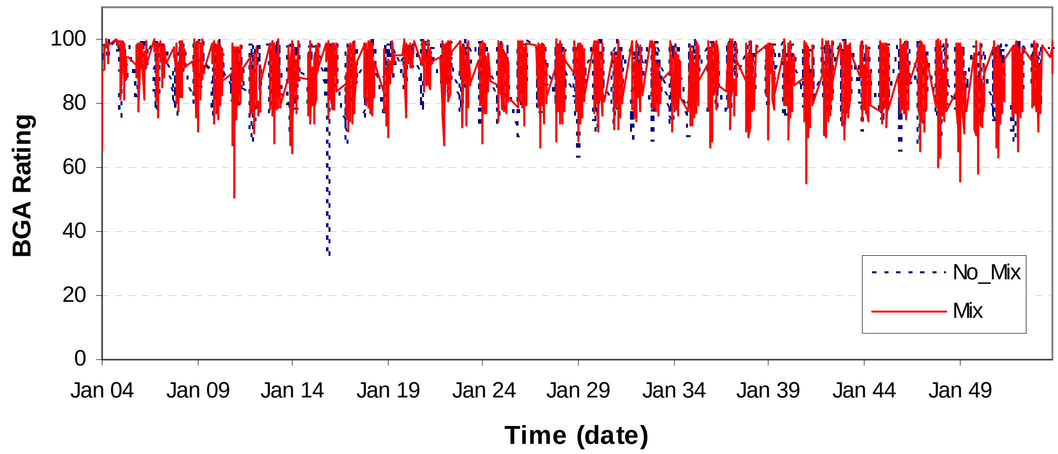
- Surface layer during warm period



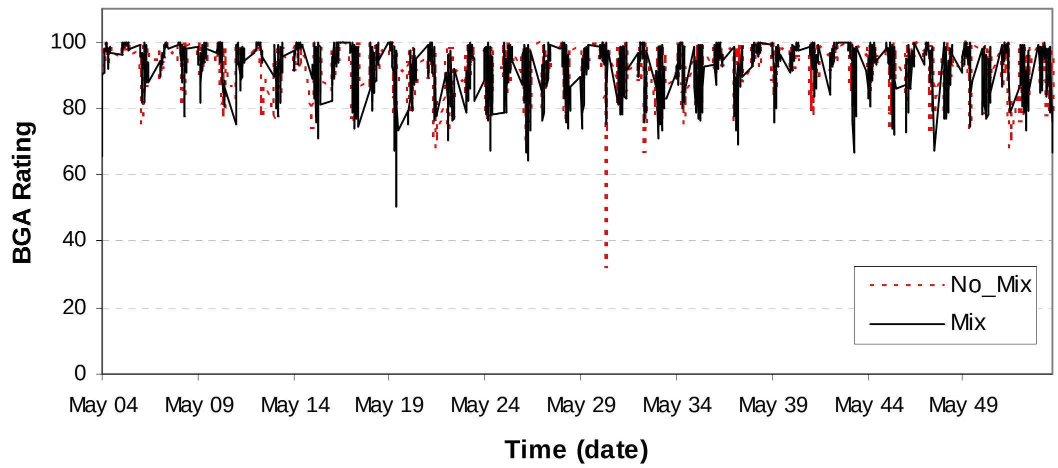

- Surface layer during cold period



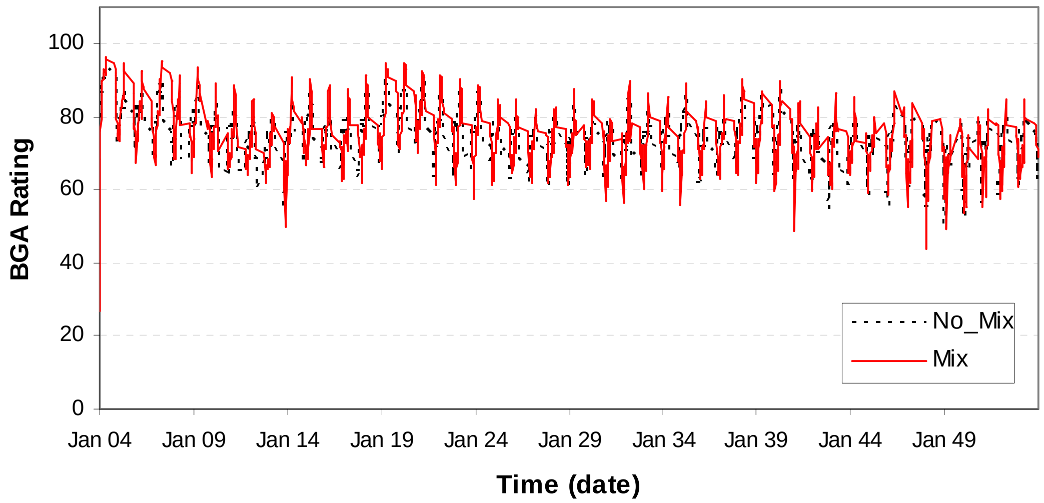
- Pumping layer during warm period



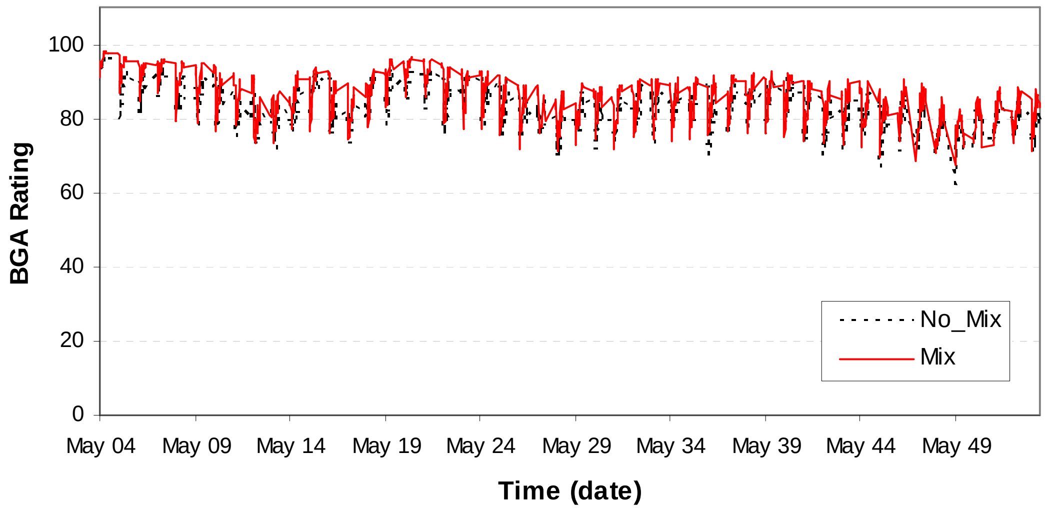

- Pumping layer during cold period




- Average of all layers during warm period

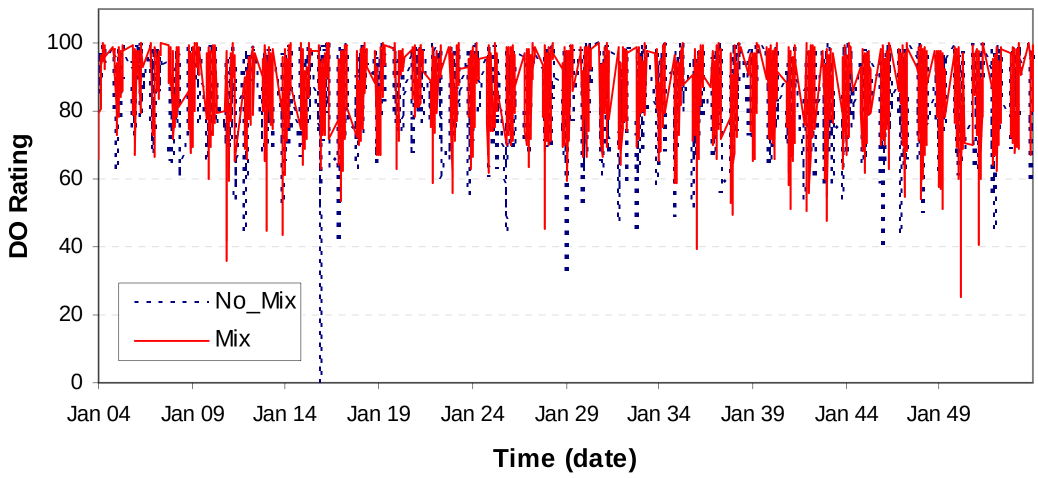


- Average of all layers during cold period

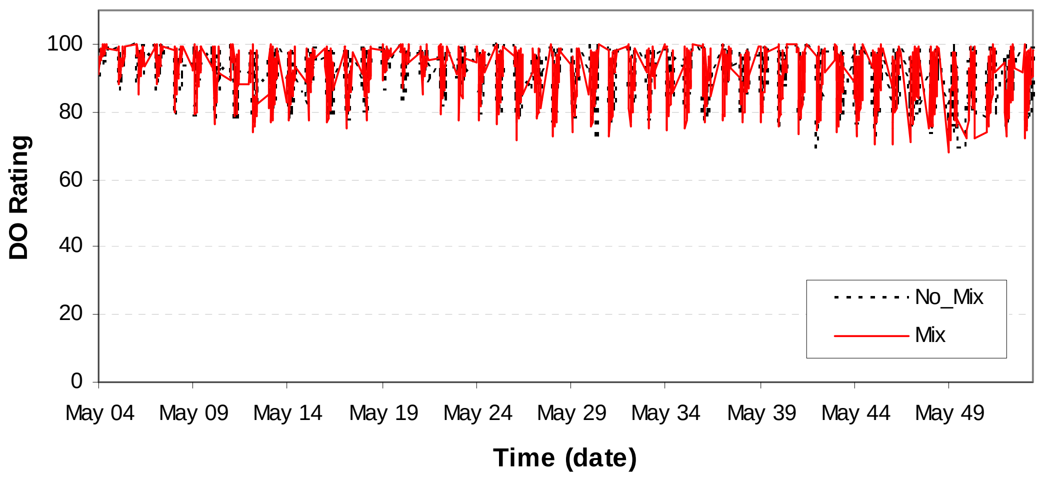



***Dissolved oxygen***

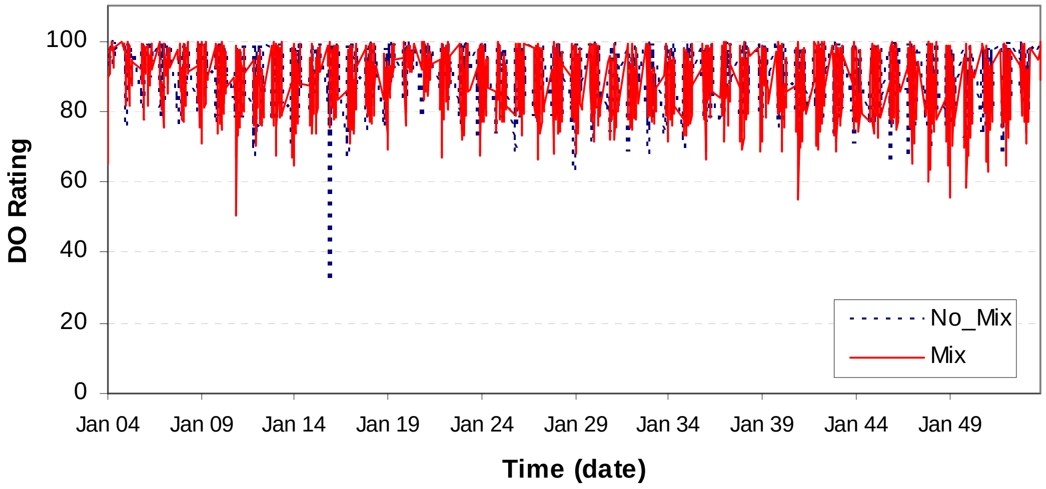
- Surface layer during warm period



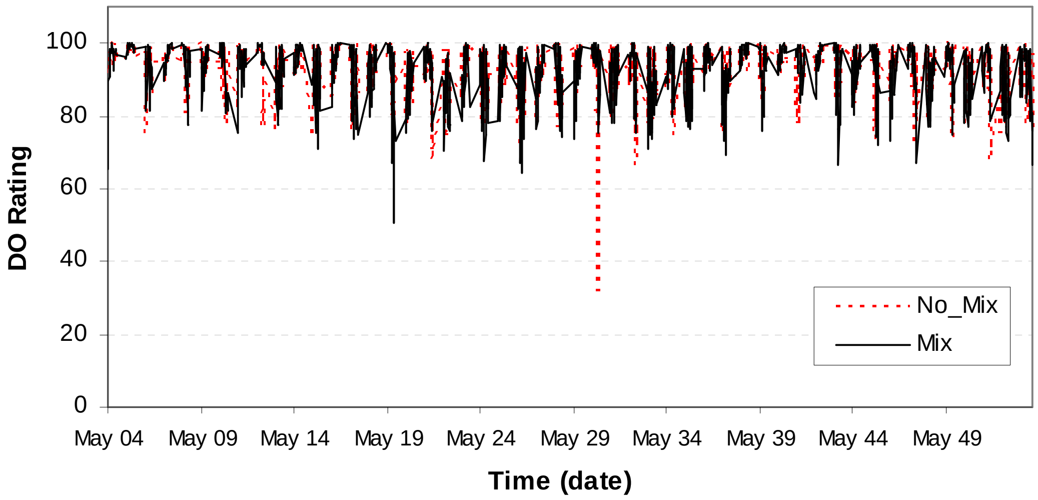

- Surface layer during cold period



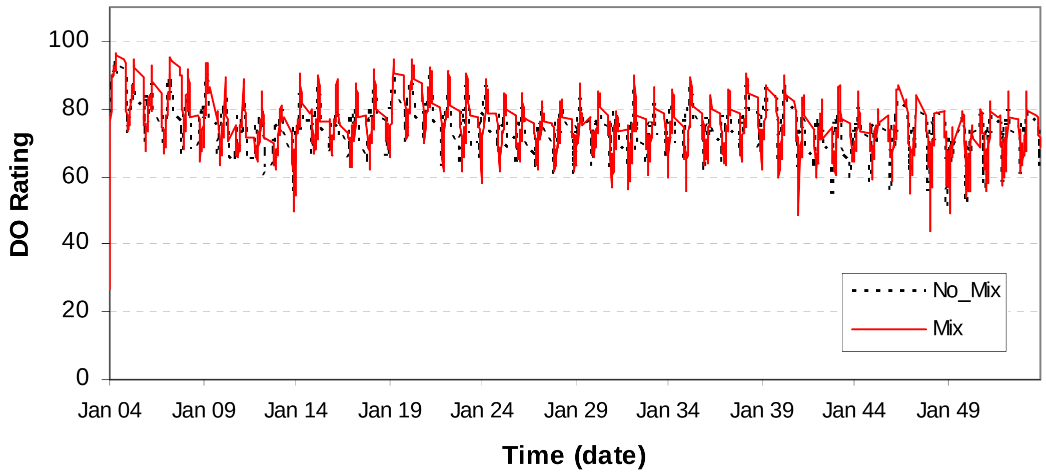
- Pumping layer during warm period



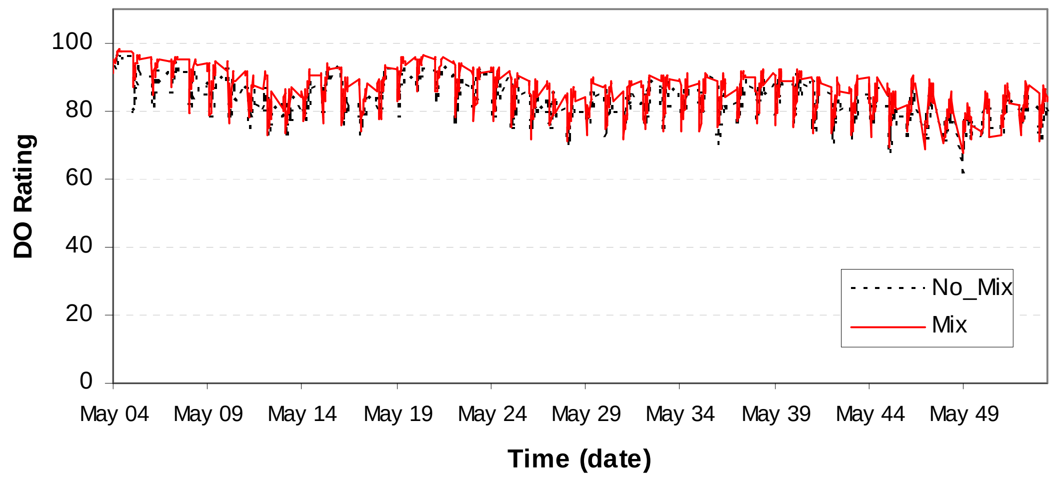

- Pumping layer during cold period




- Average of all layers during warm period

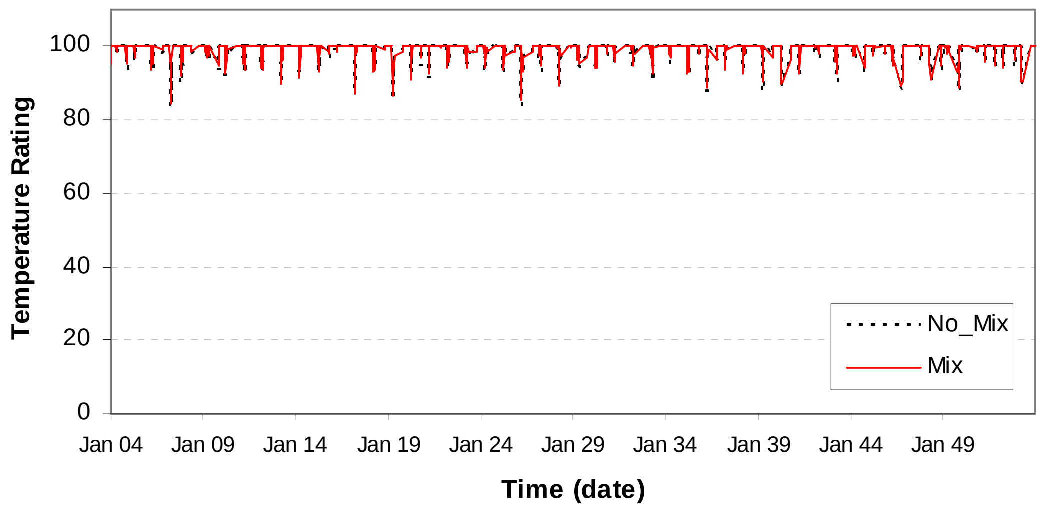


- Average of all layers during cold period

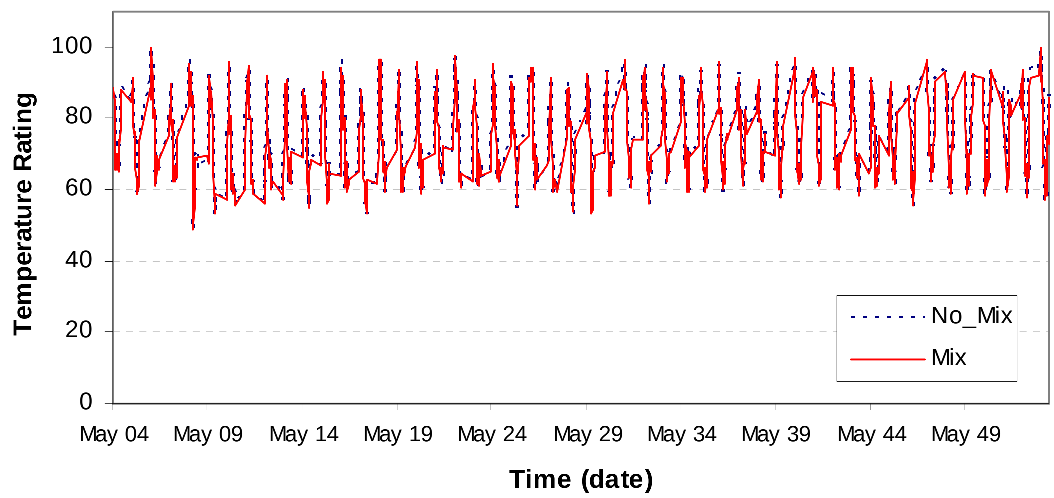



***Water temperature***

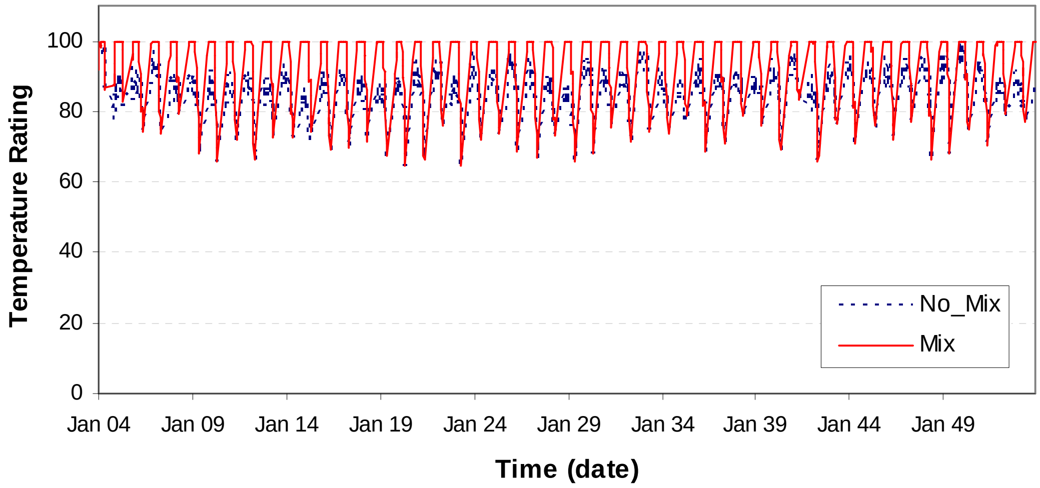
- Surface layer during warm period



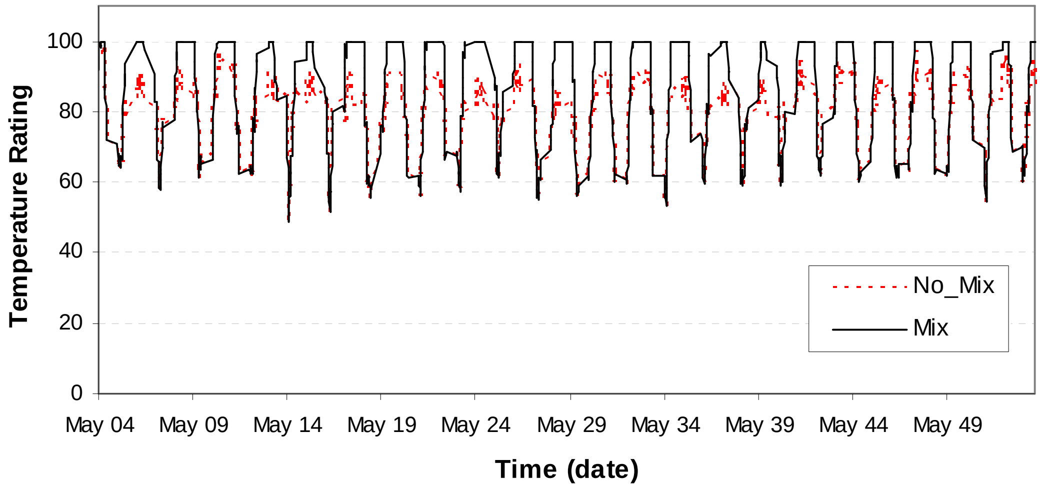

- Surface layer during cold period



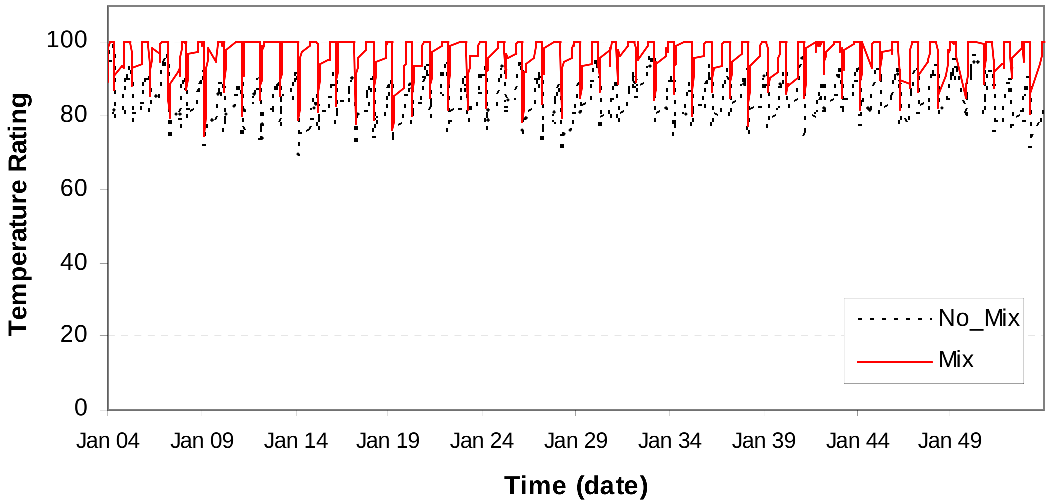
- Pumping layer during warm period



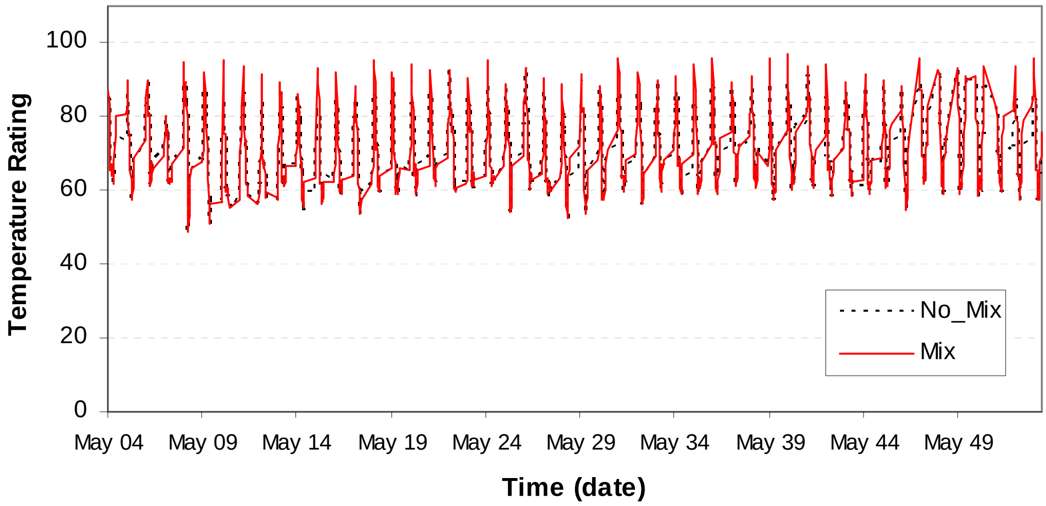

- Pumping layer during cold period




- Average of all layers during warm period

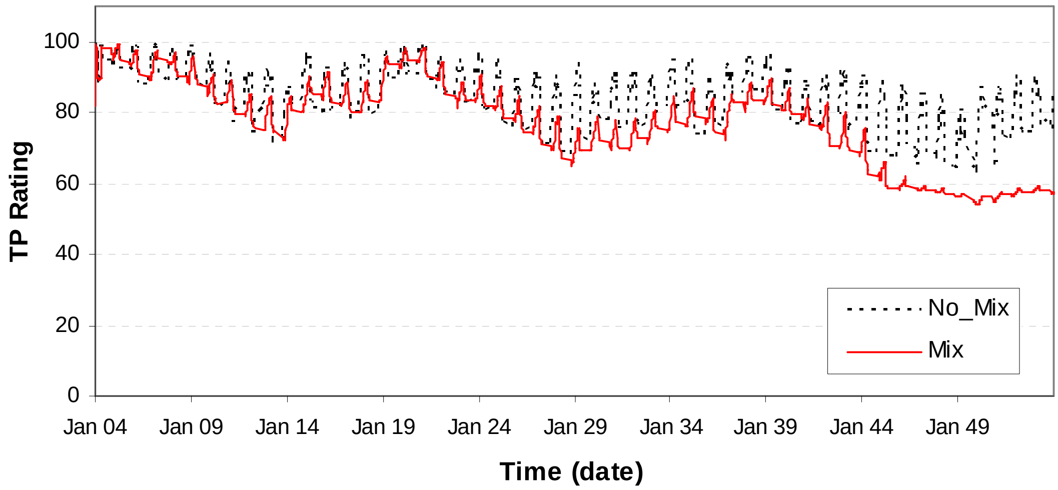


- Average of all layers during cold period

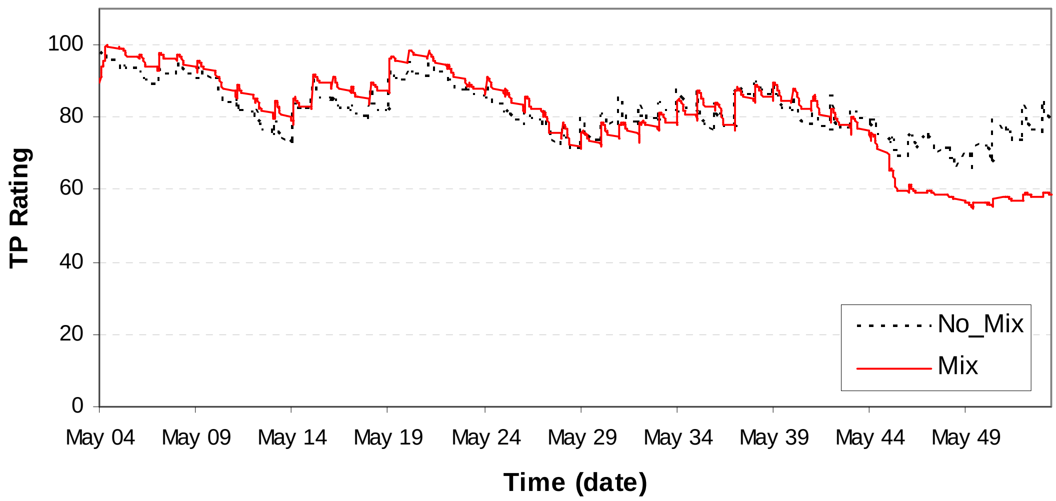



***Total phosphorus***

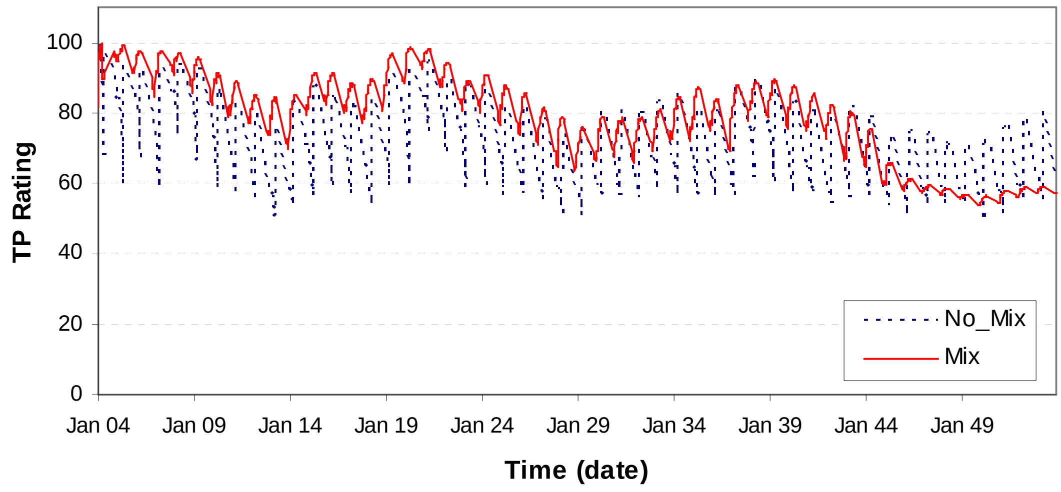
- Surface layer during warm period



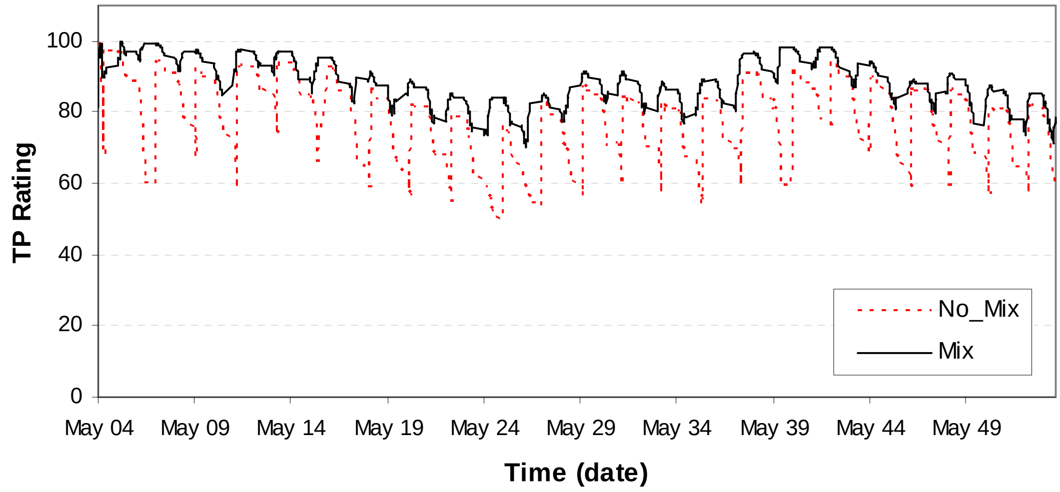

- Surface layer during cold period



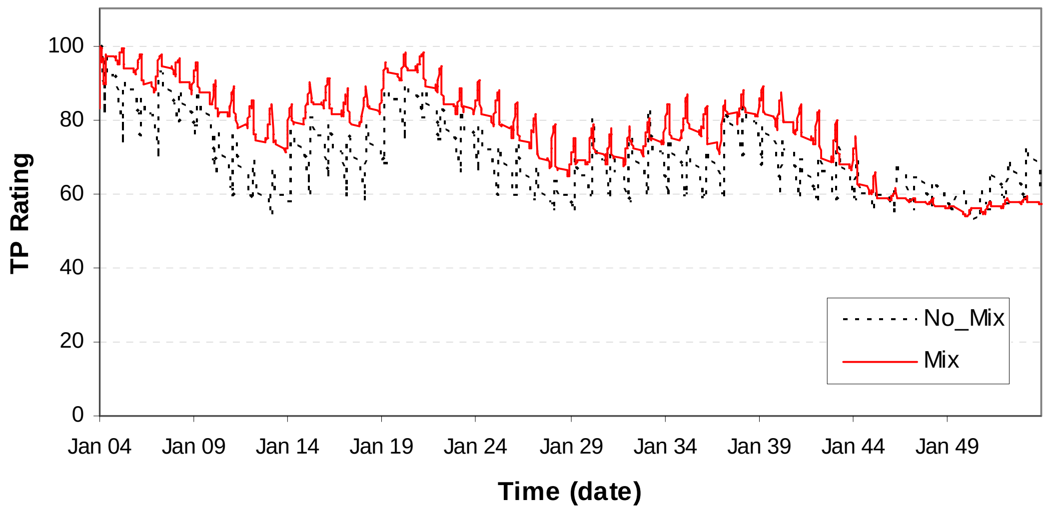
- Pumping layer during warm period



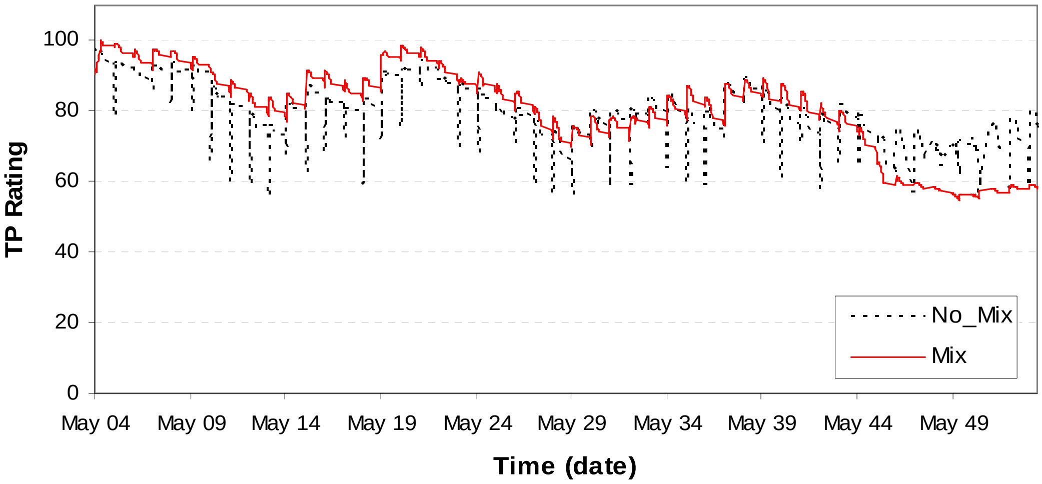

- Pumping layer during cold period




- Average of all layers during warm period

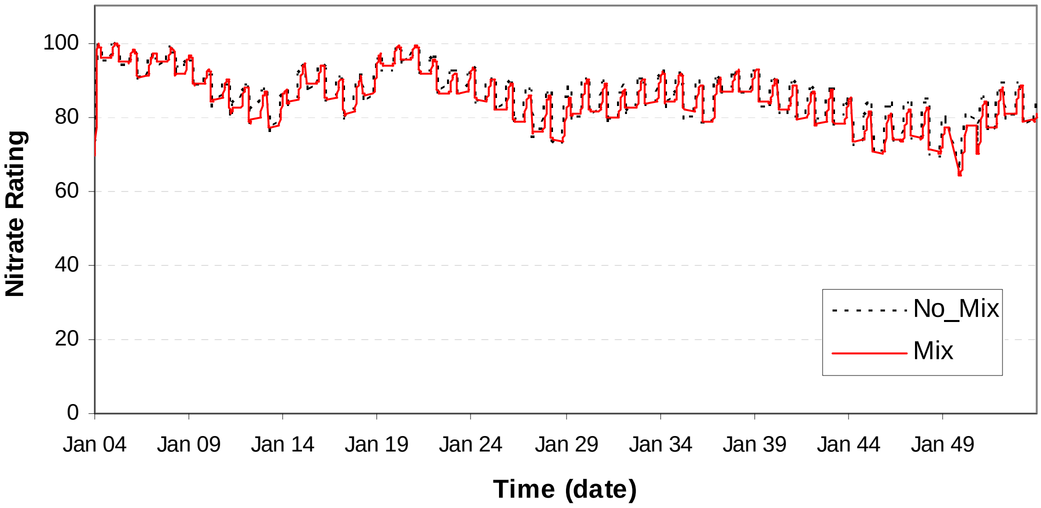


- Average of all layers during cold period

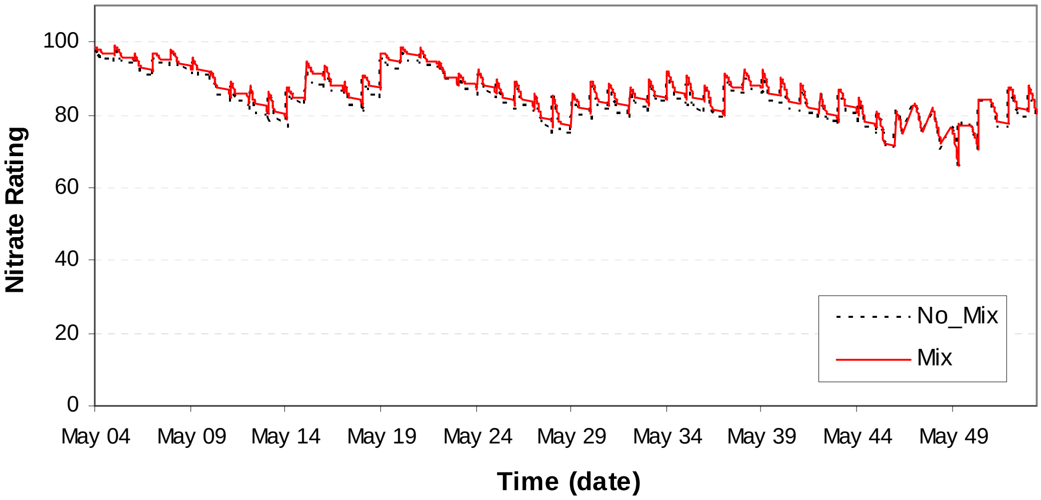



## *Nitrate*

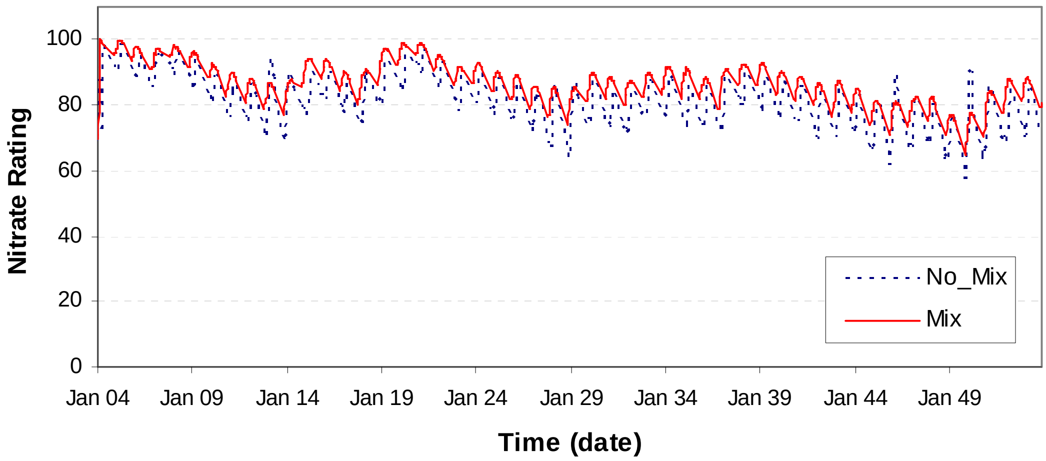
- Surface layer during warm period



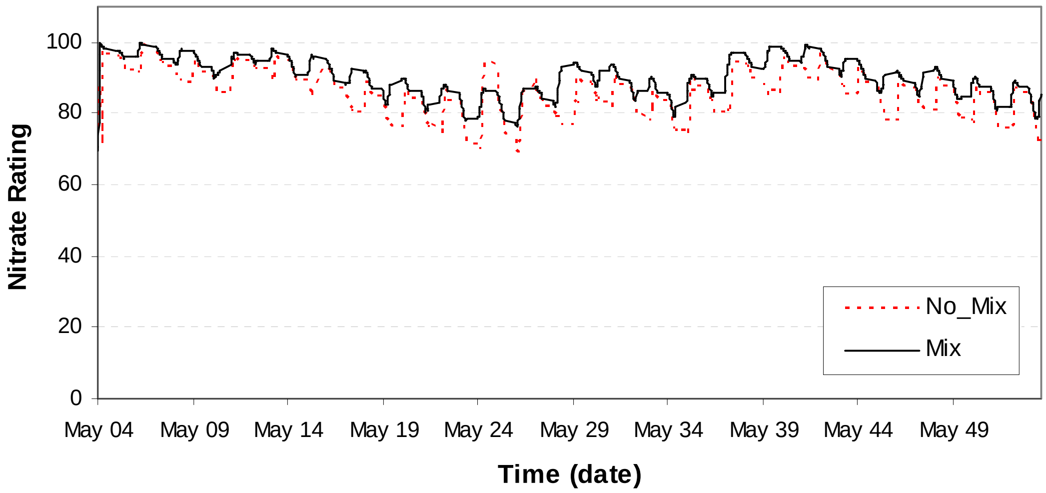

- Surface layer during cold period



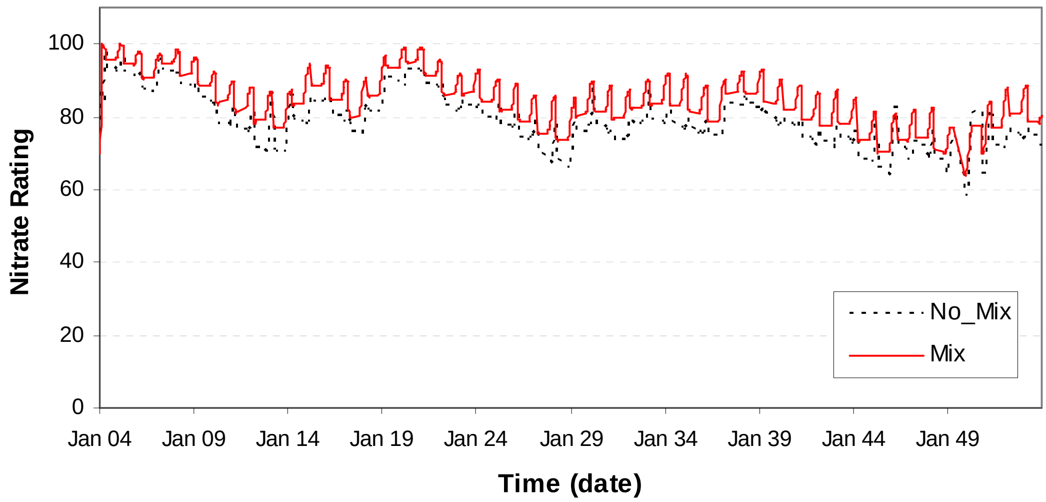
- Pumping layer during warm period



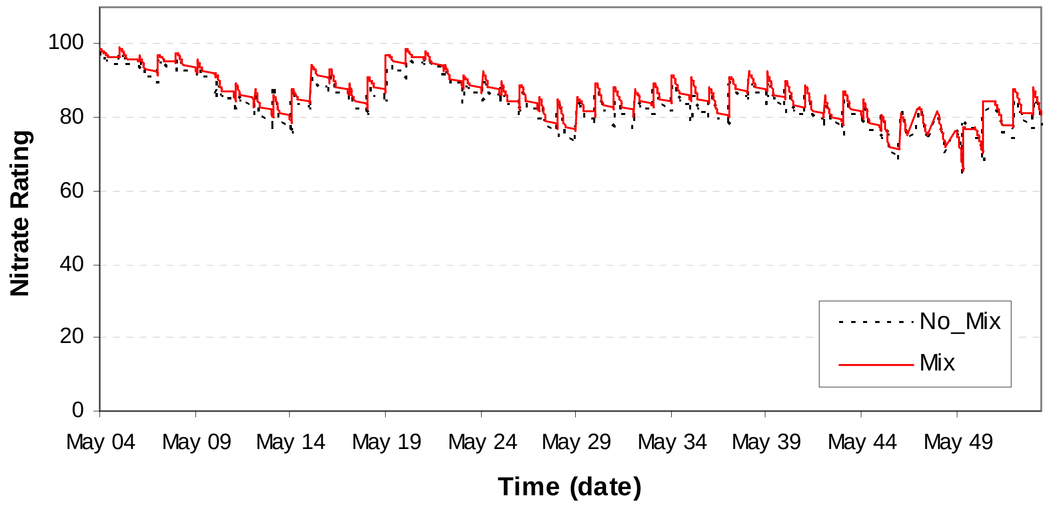

- Pumping layer during cold period




- Average of all layers during warm period

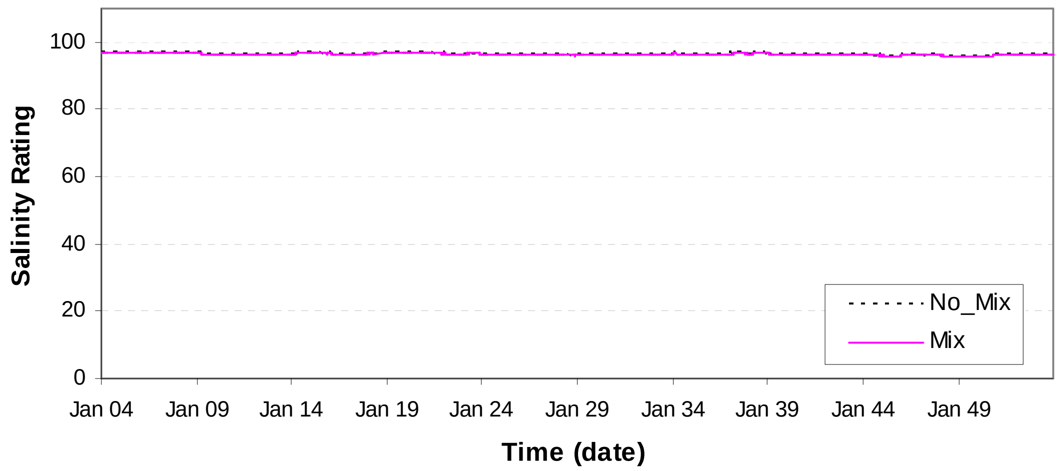


- Average of all layers during cold period

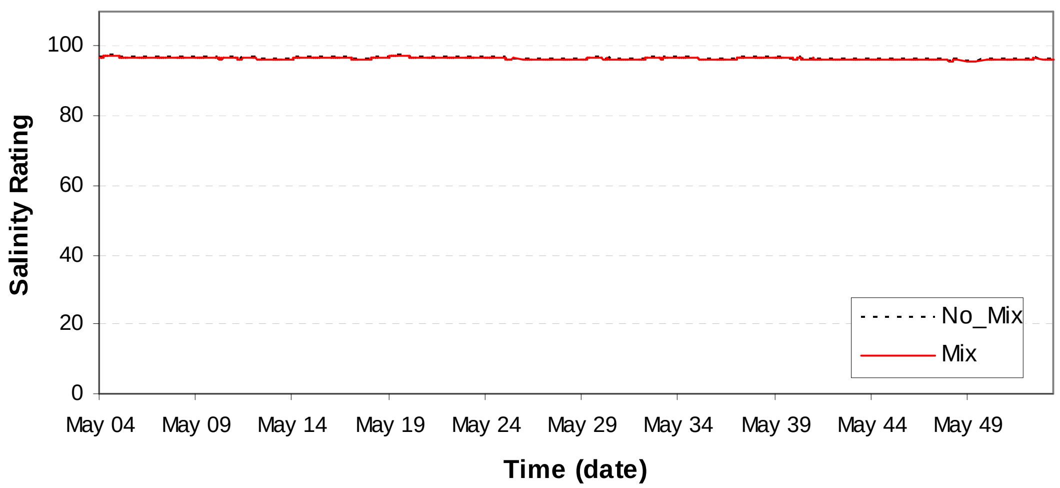



***Salinity***

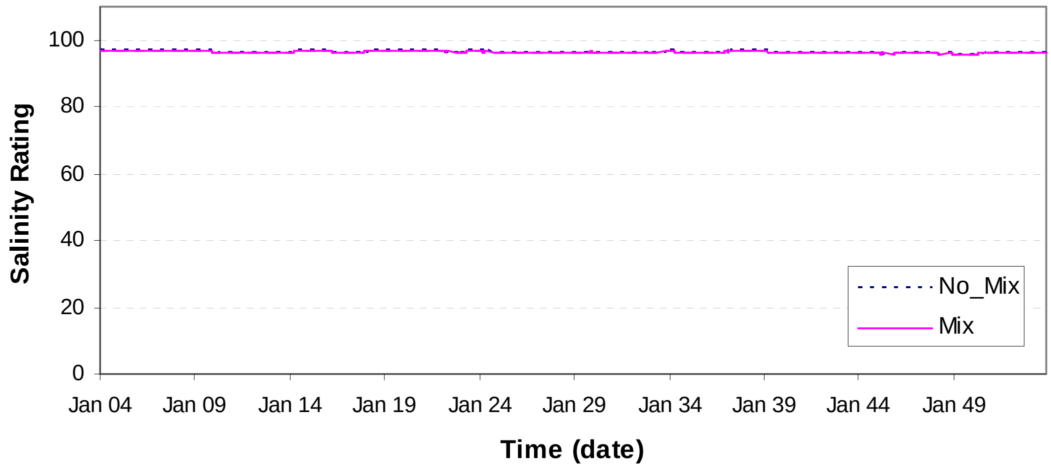
- Surface layer during warm period



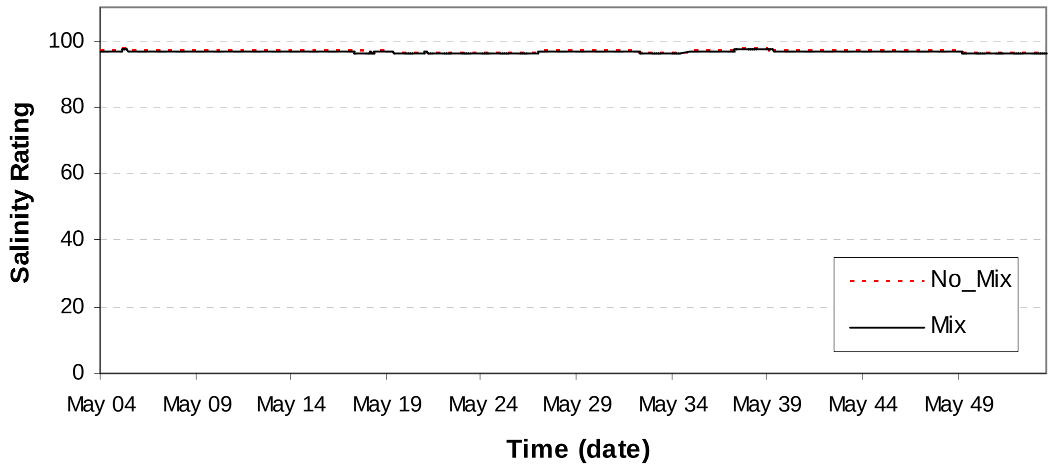

- Surface layer during cold period



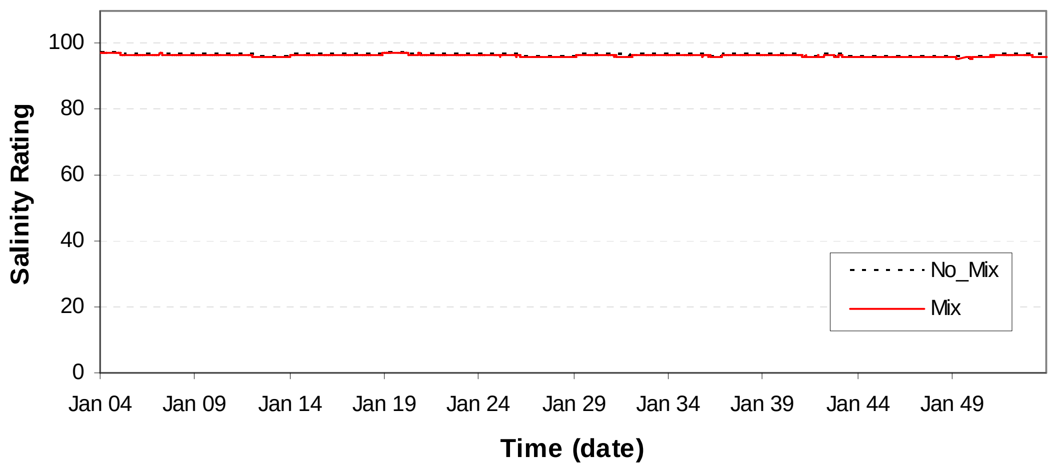
- Pumping layer during warm period



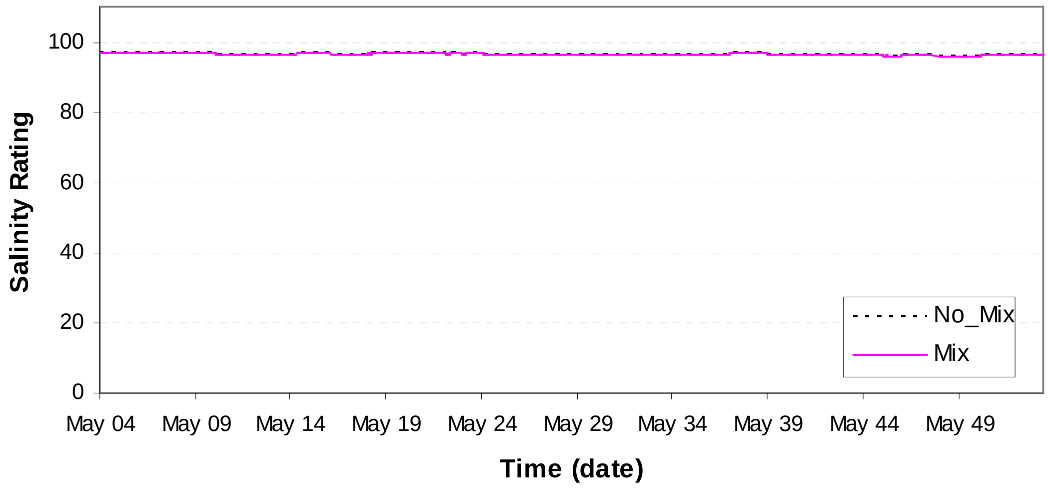

- Pumping layer during cold period




- Average of all layers during warm period

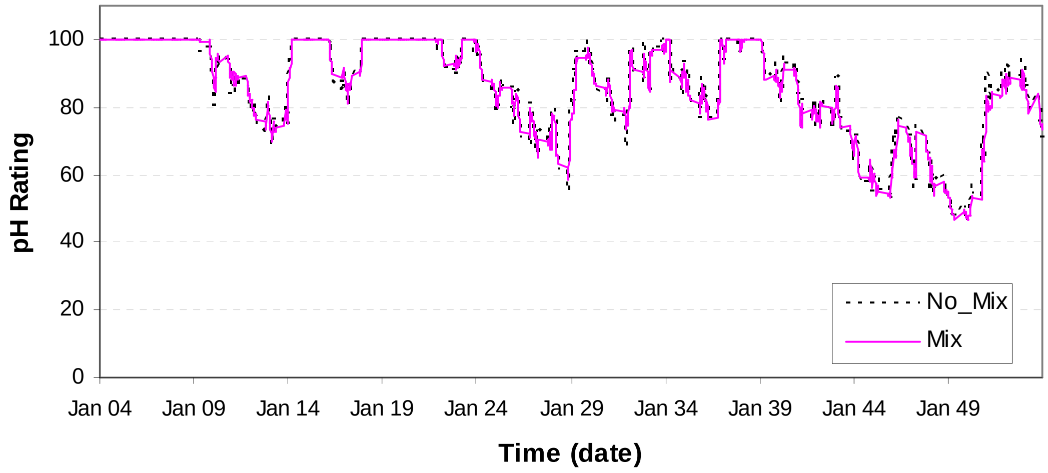


- Average of all layers during cold period

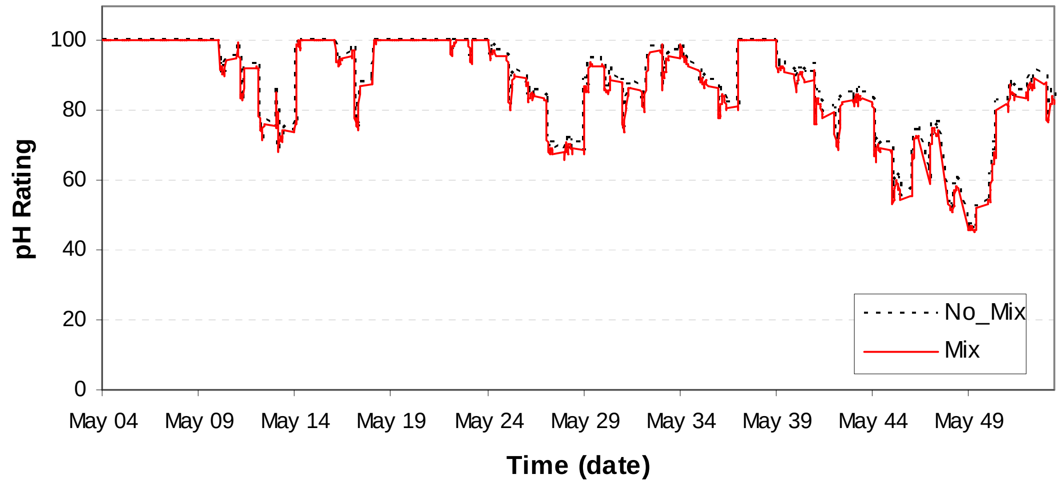



***pH***

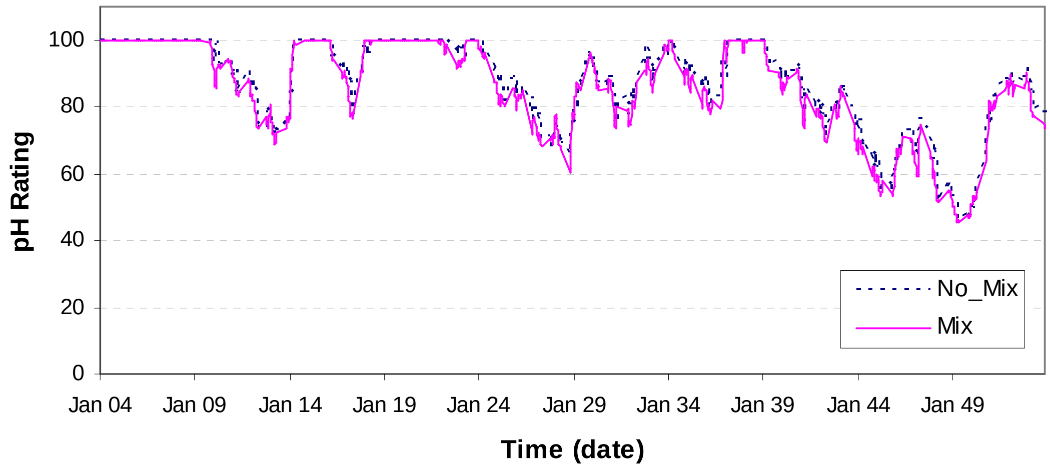
- Surface layer during warm period



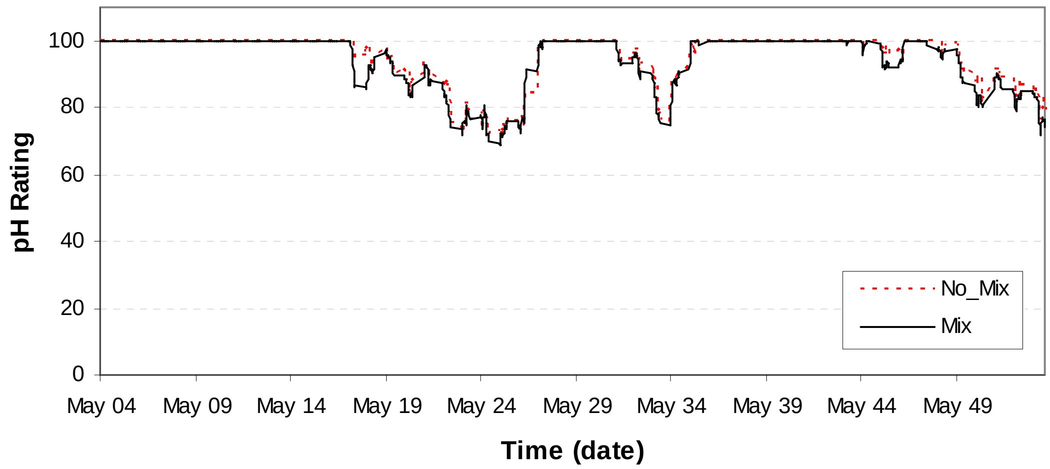

- Surface layer during cold period



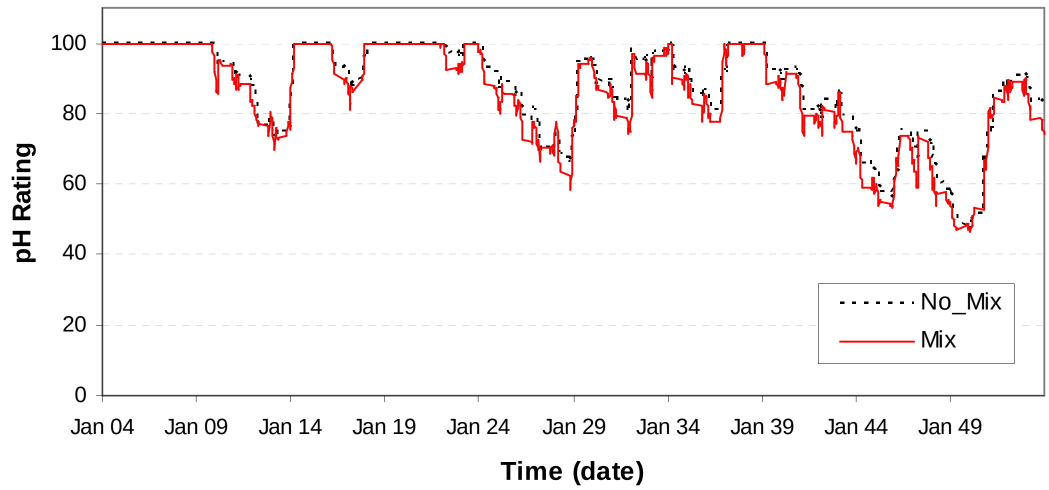
- Pumping layer during warm period



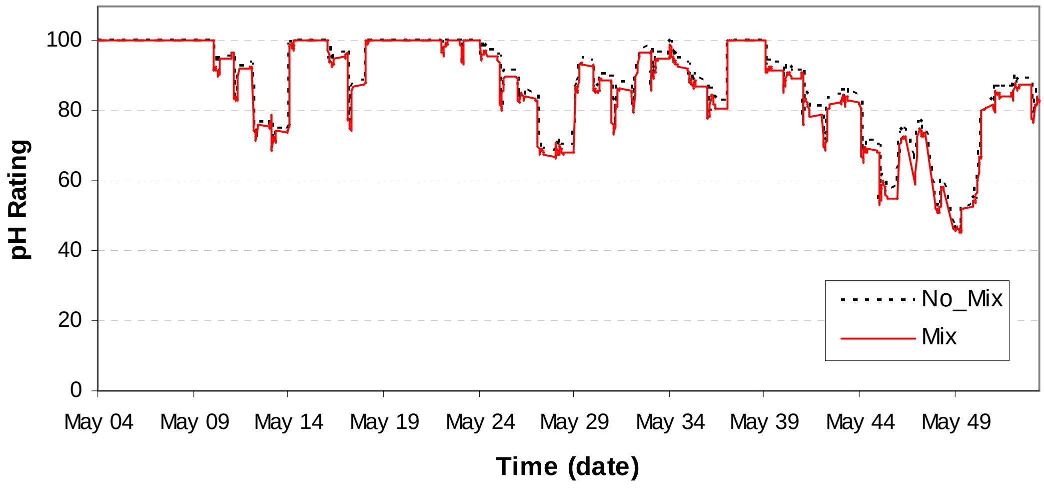

- Pumping layer during cold period




- Average of all layers during warm period

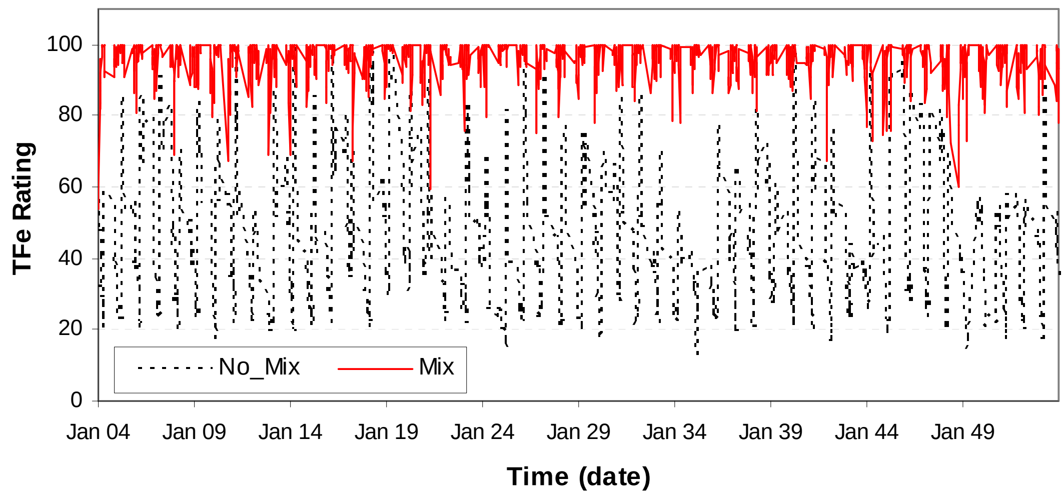


- Average of all layers during cold period

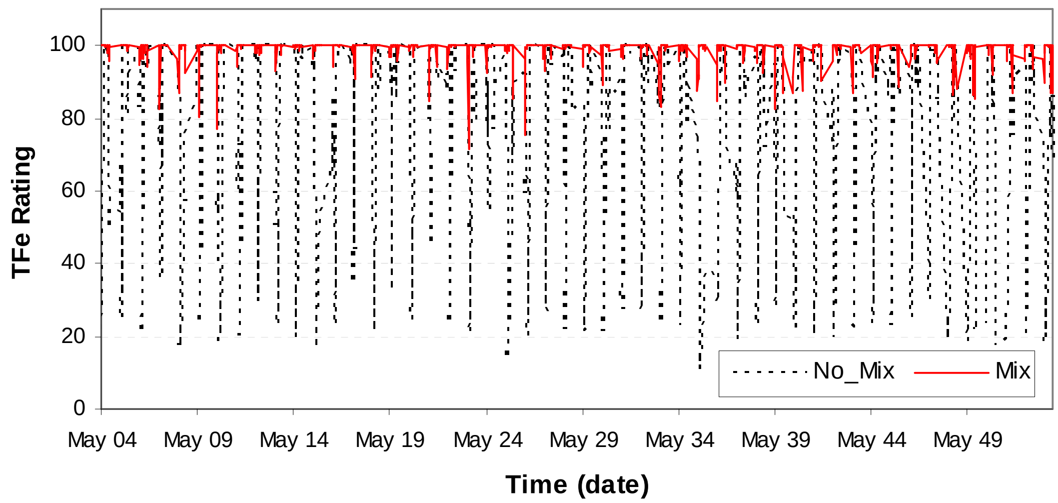



***Total iron***

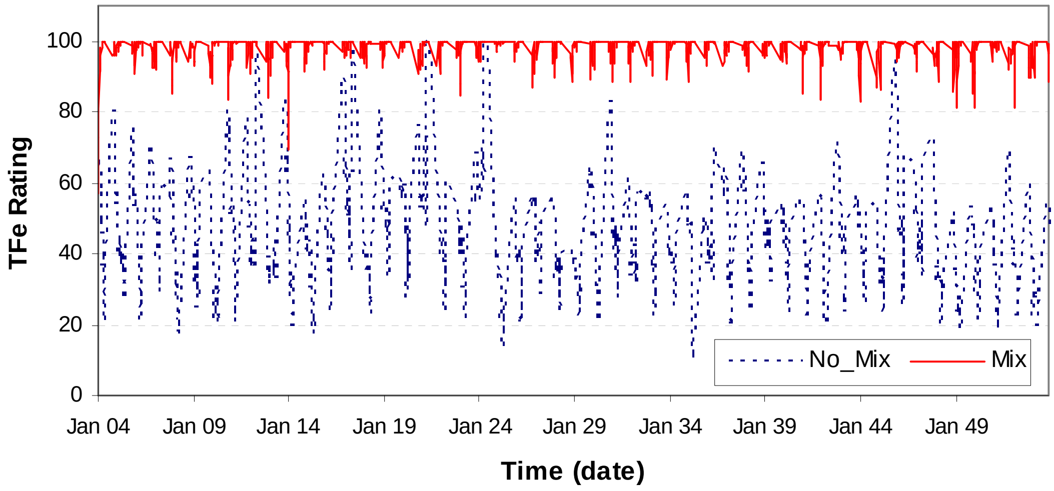
- Surface layer during warm period



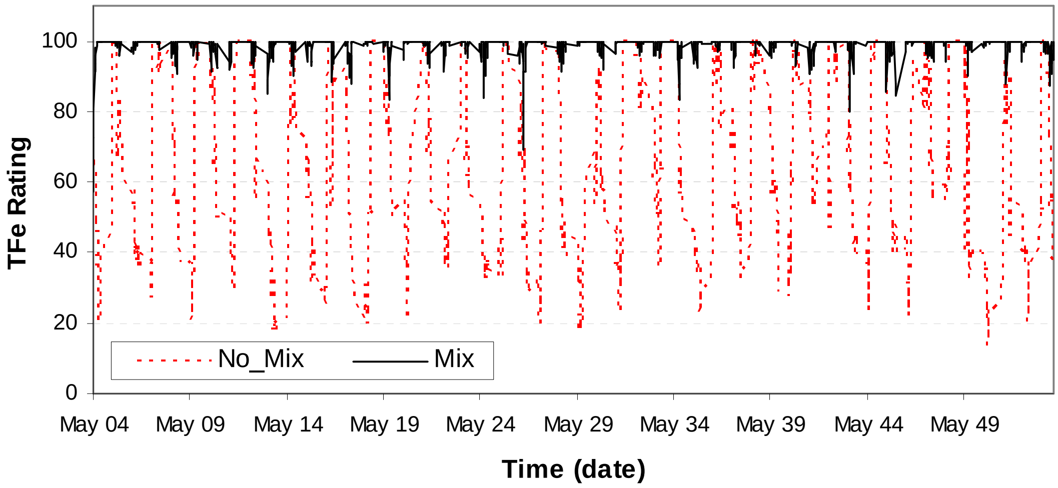

- Surface layer during cold period



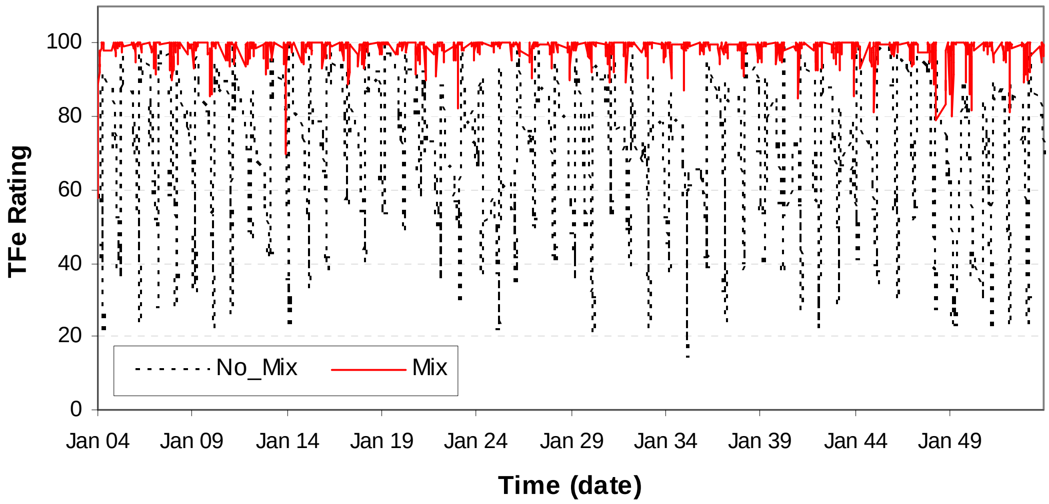
- Pumping layer during warm period



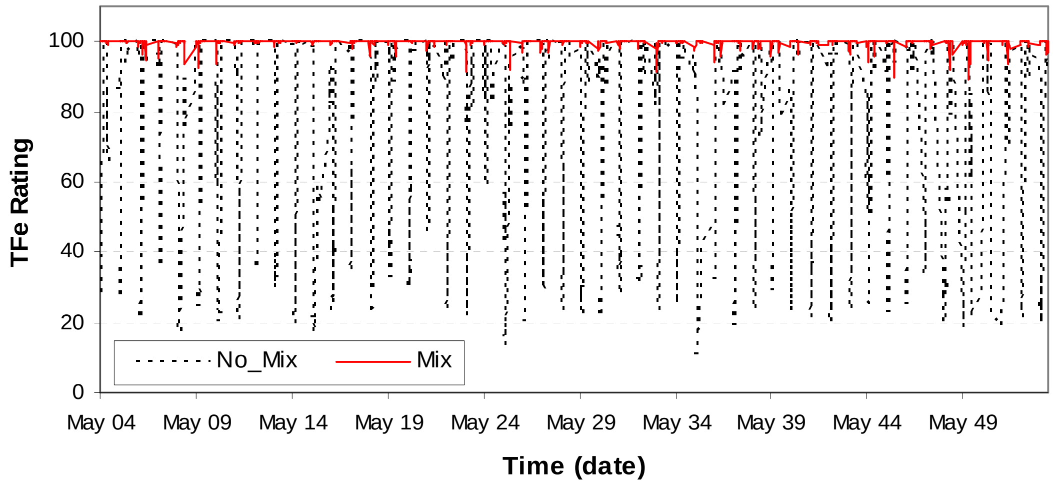

- Pumping layer during cold period




- Average of all layers during warm period

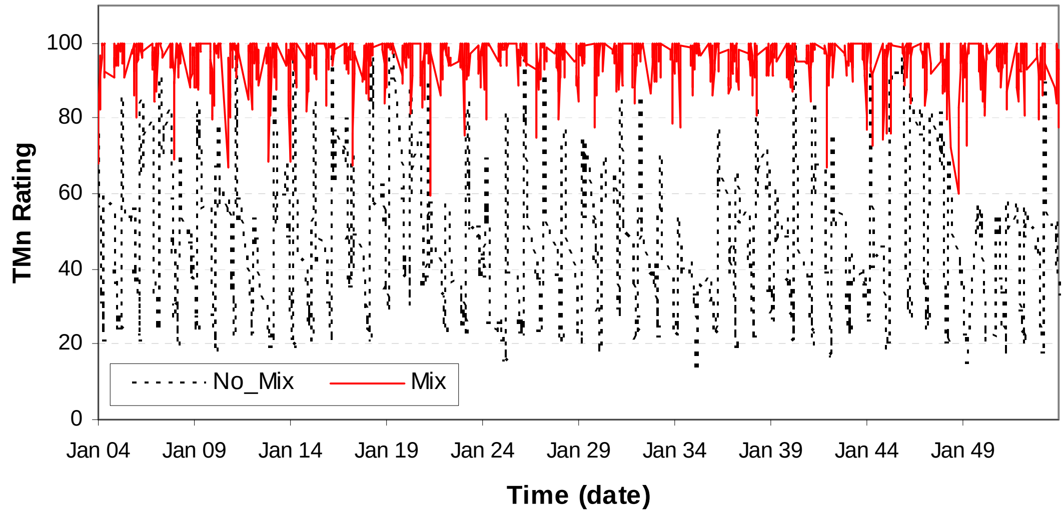


- Average of all layers during cold period

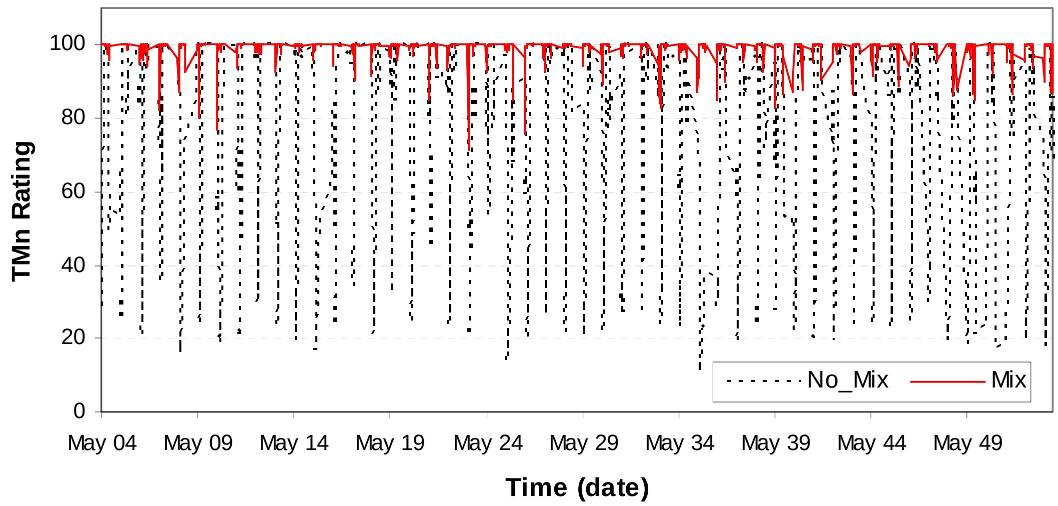



***Total manganese***

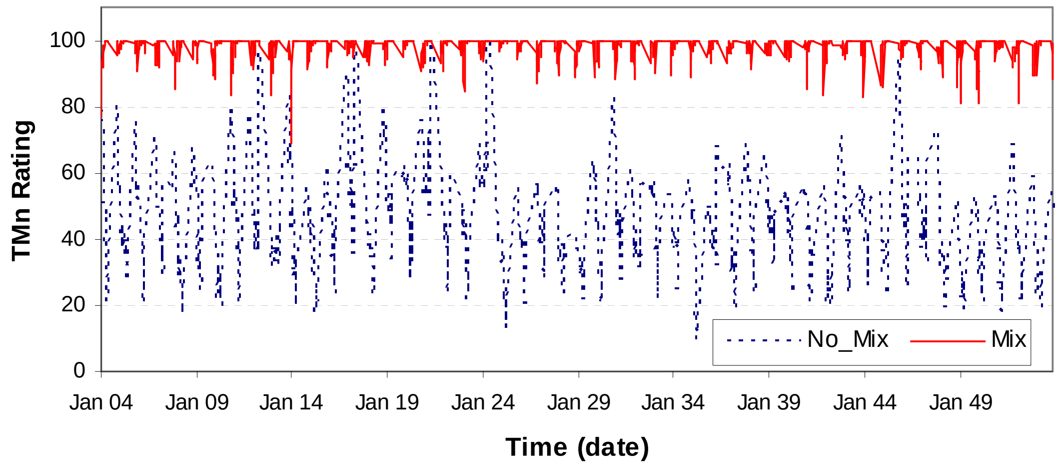
- Surface layer during warm period



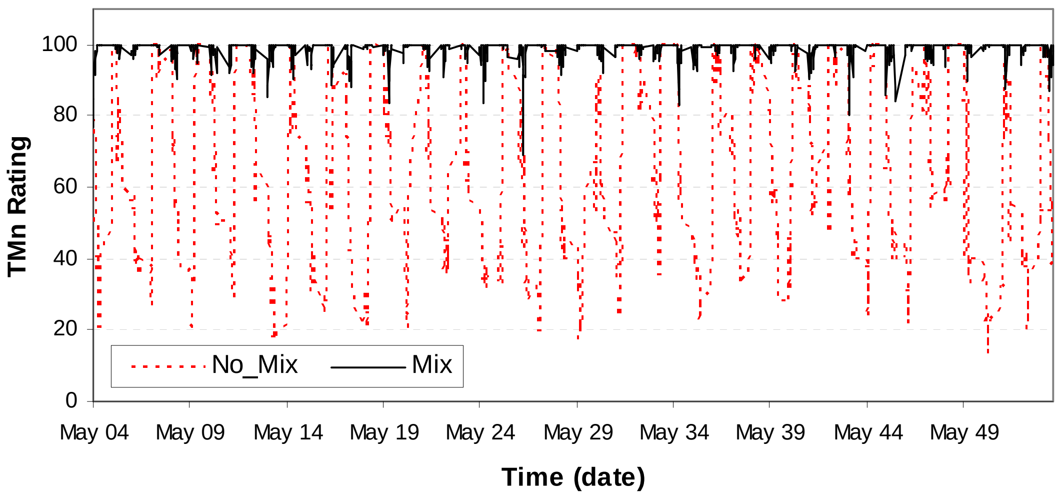

- Surface layer during cold period



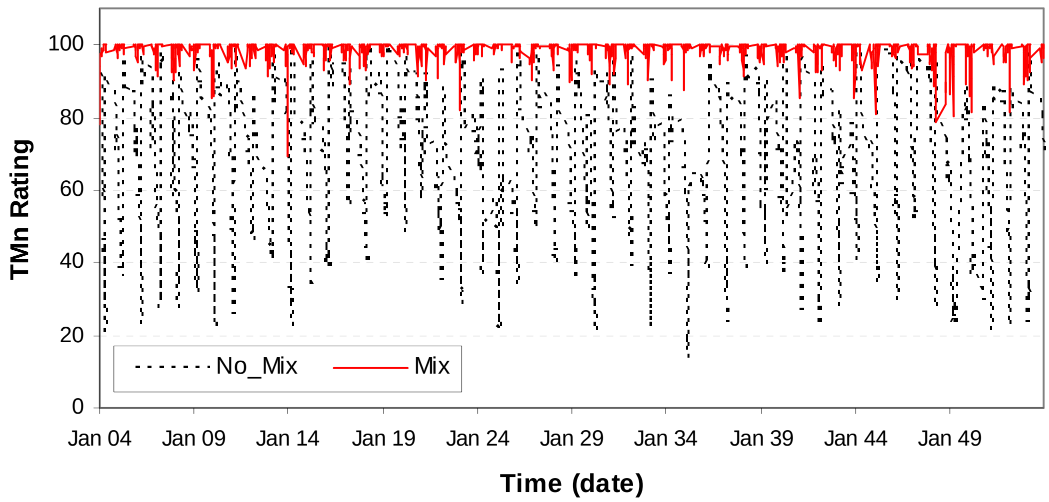
- Pumping layer during warm period



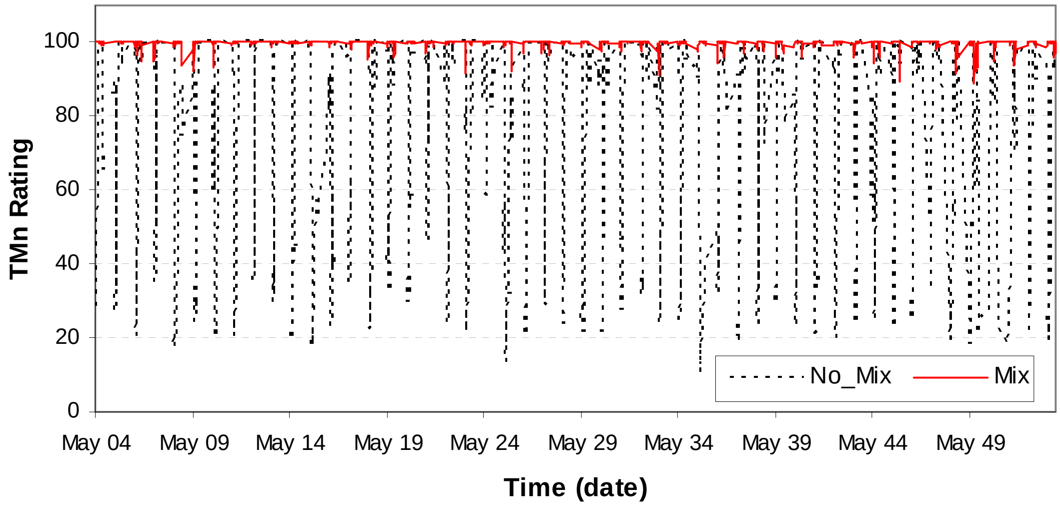

- Pumping layer during cold period




- Average of all layers during warm period



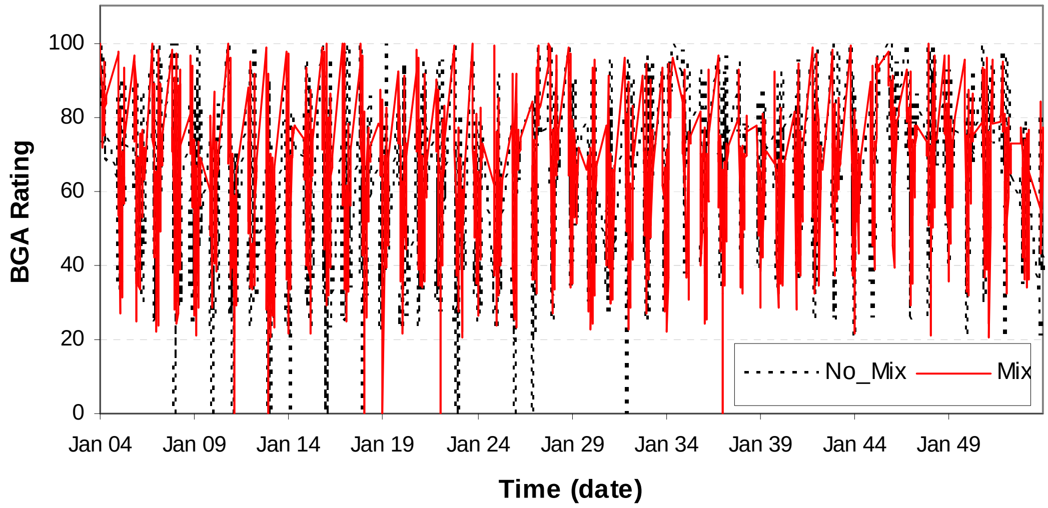
- Average of all layers during cold period



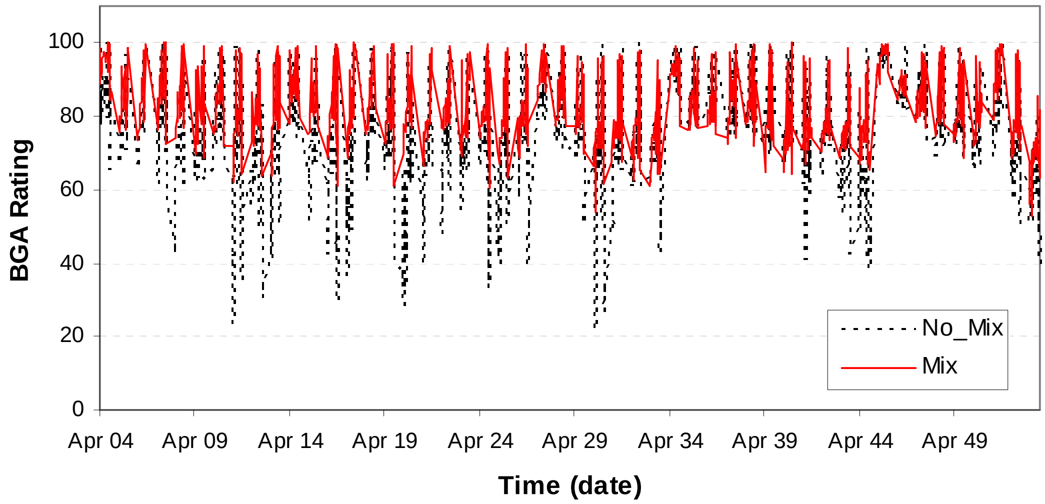
## B. Ratings of water quality parameters for Cressbrook Storage

***Cyanobacteria***

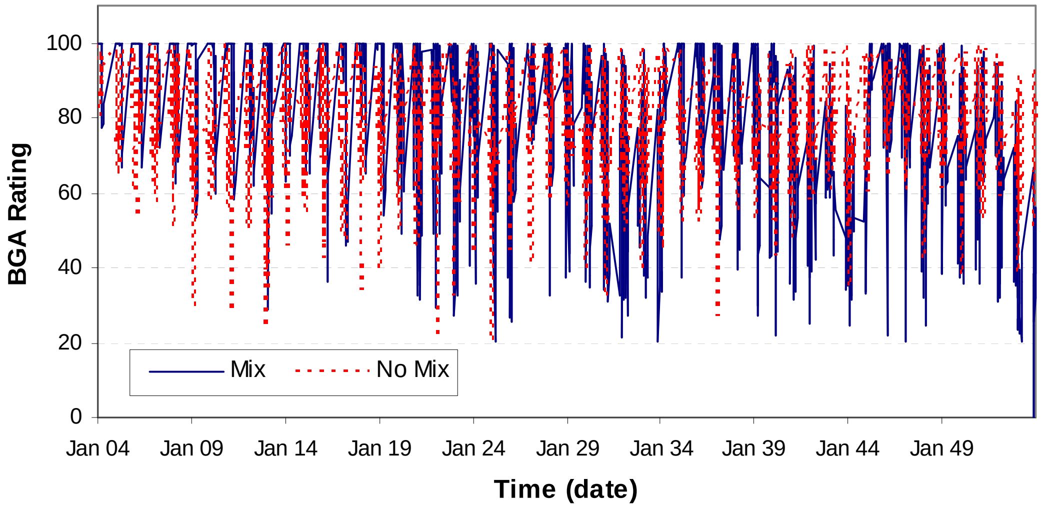
- Surface layer during warm period



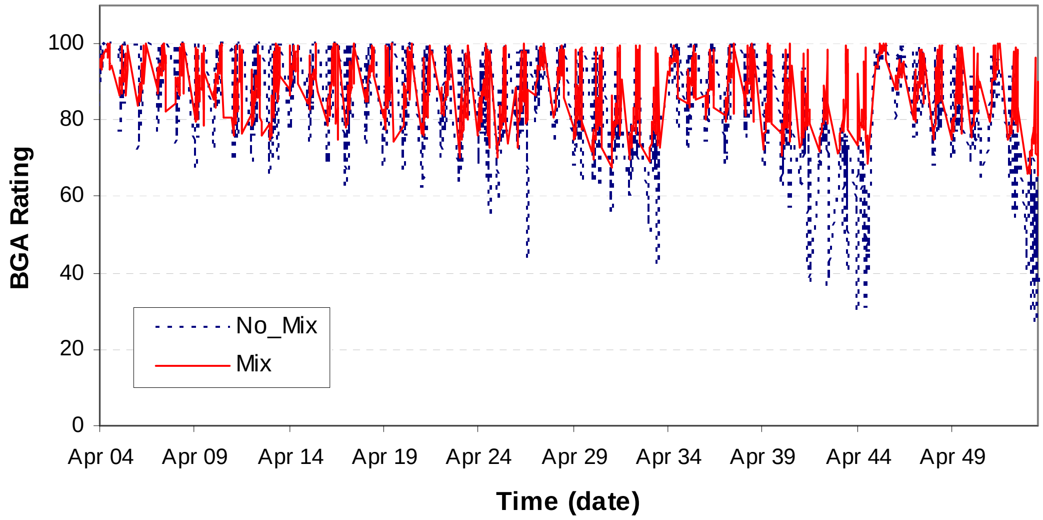

- Surface layer during cold period



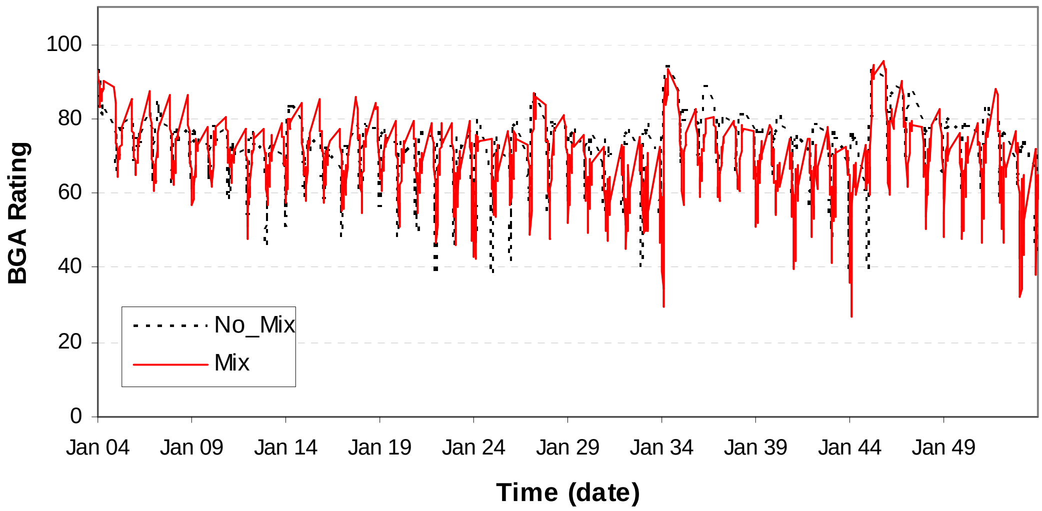
- Pumping layer during warm period



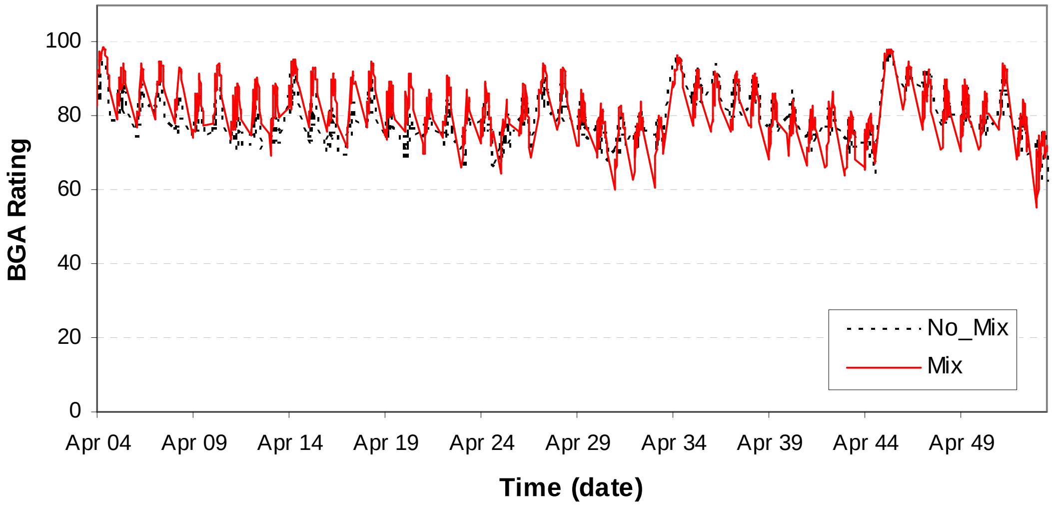

- Pumping layer during cold period




- Average of all layers during warm period

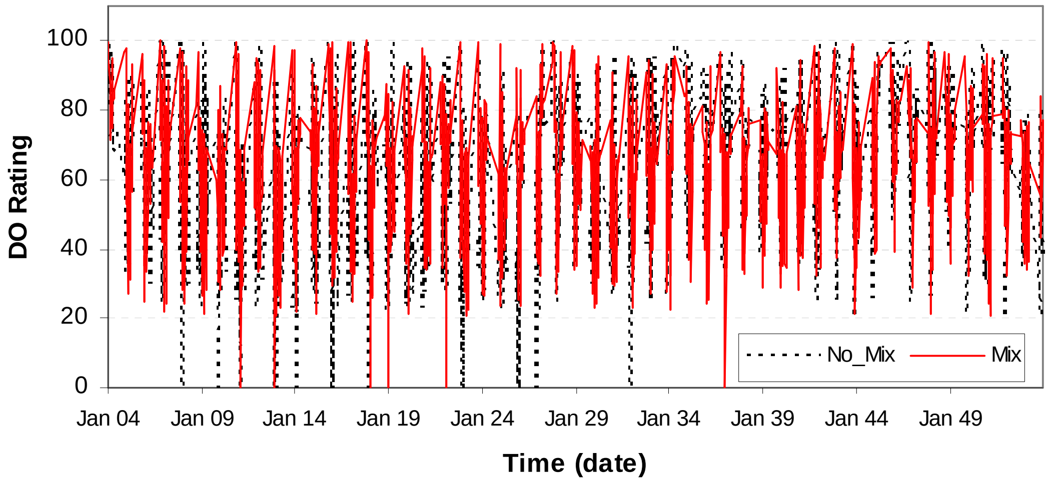


- Average of all layers during cold period

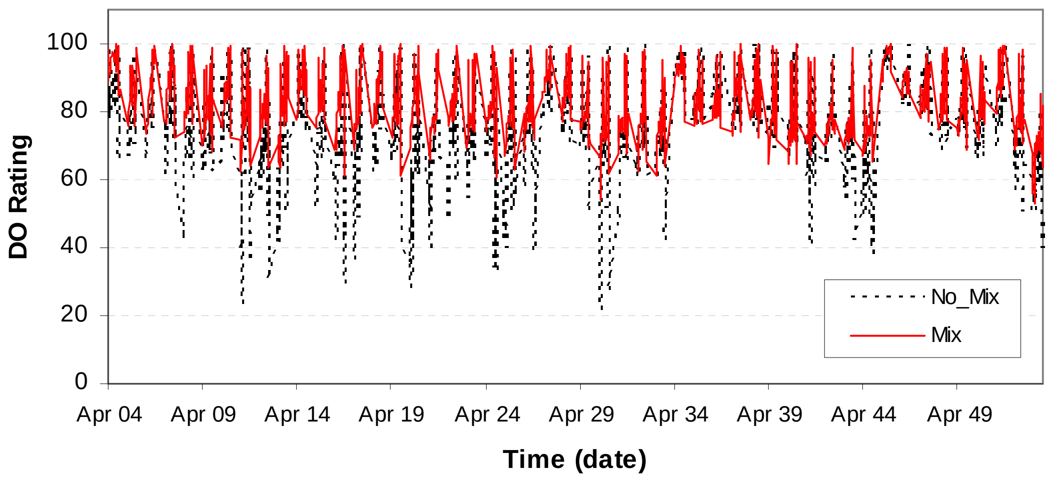



***Dissolved oxygen***

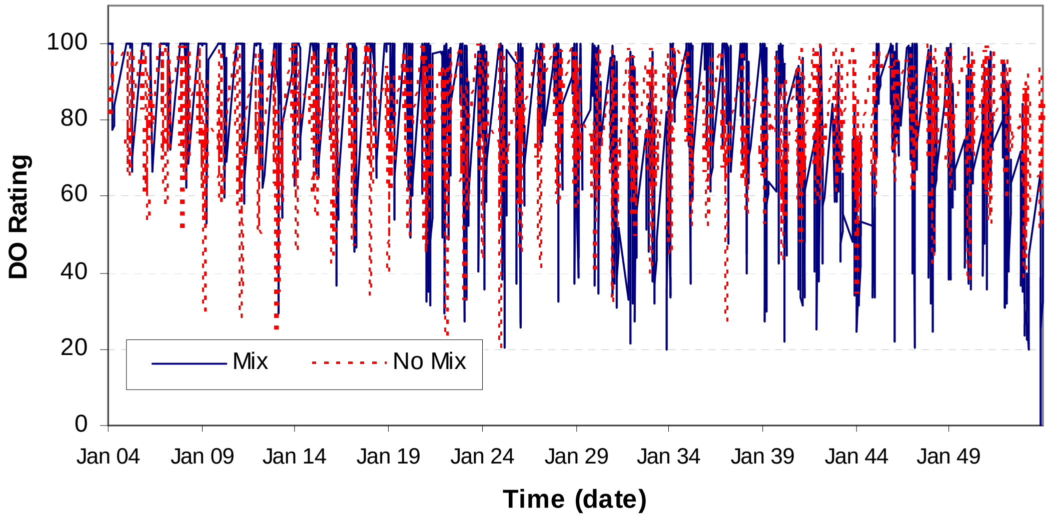
- Surface layer during warm period



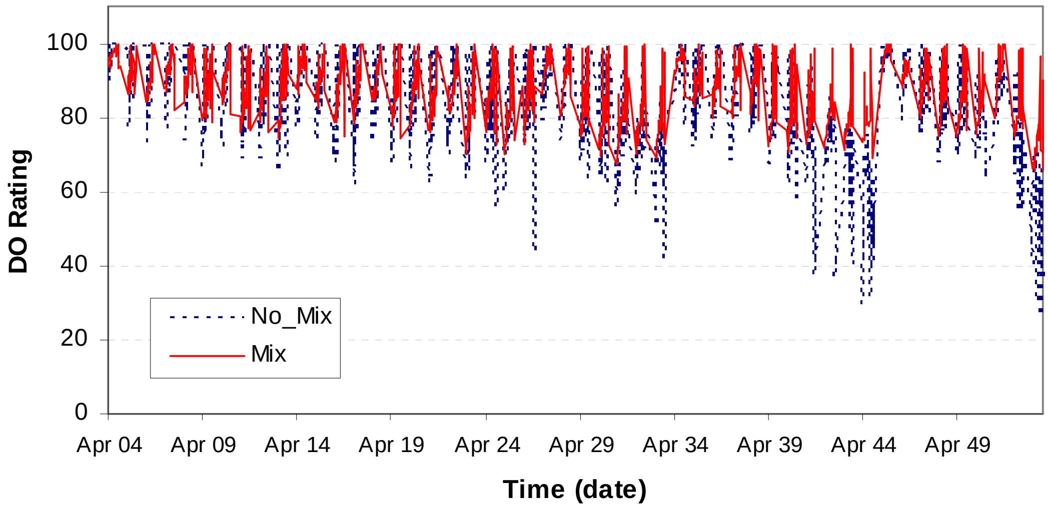

- Surface layer during cold period



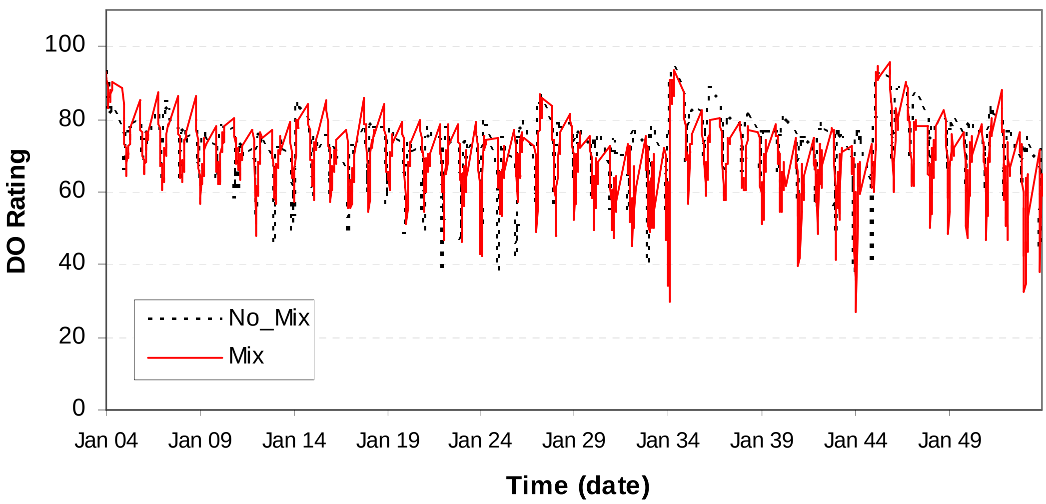
- Pumping layer during warm period



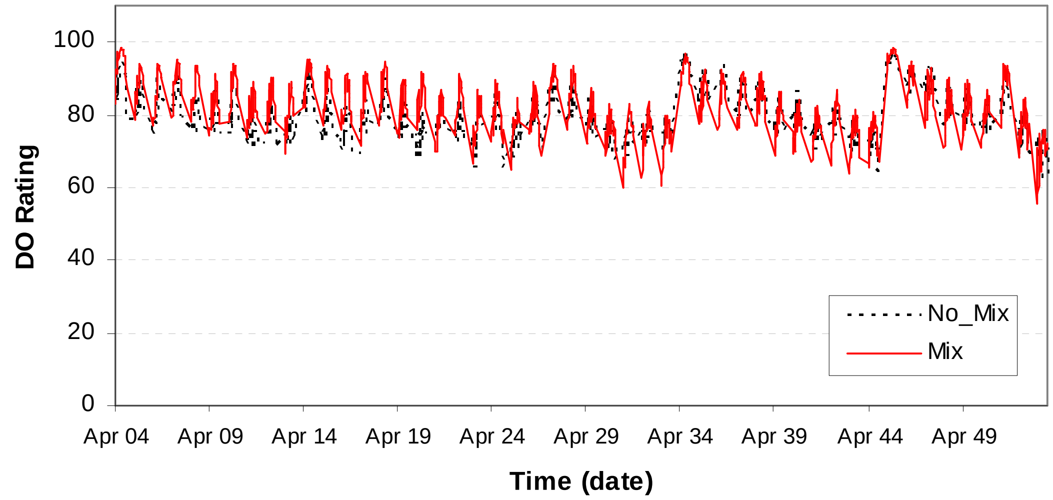

- Pumping layer during cold period




- Average of all layers during warm period

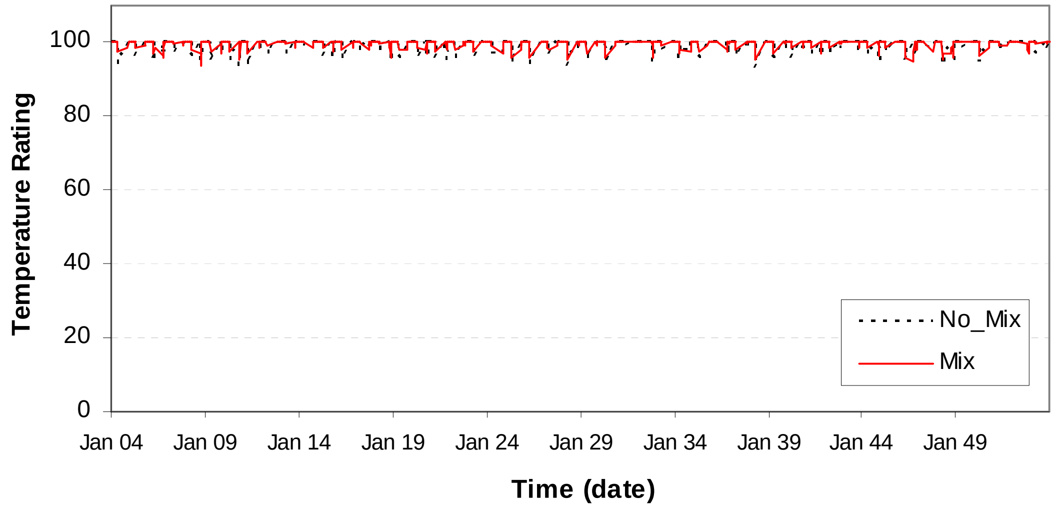


- Average of all layers during cold period

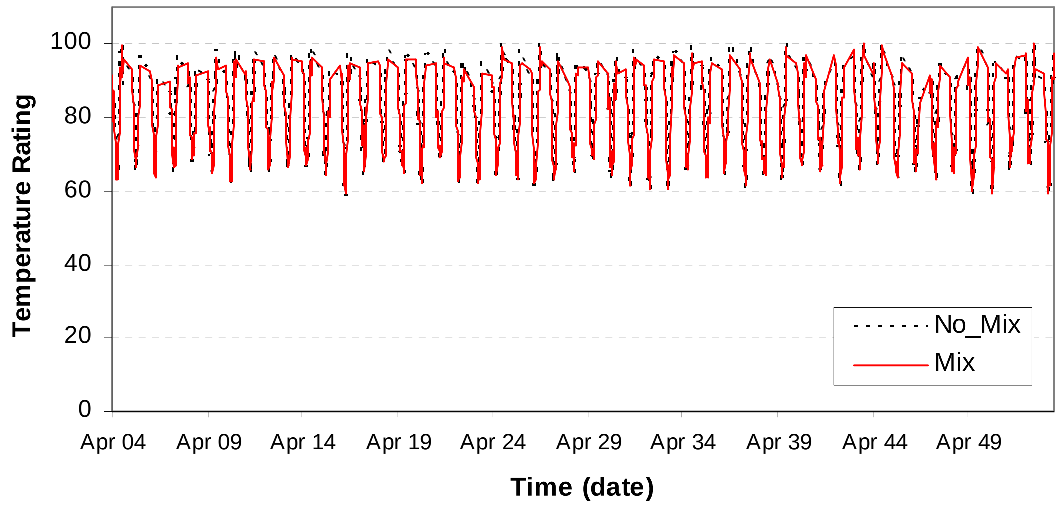



***Water temperature***

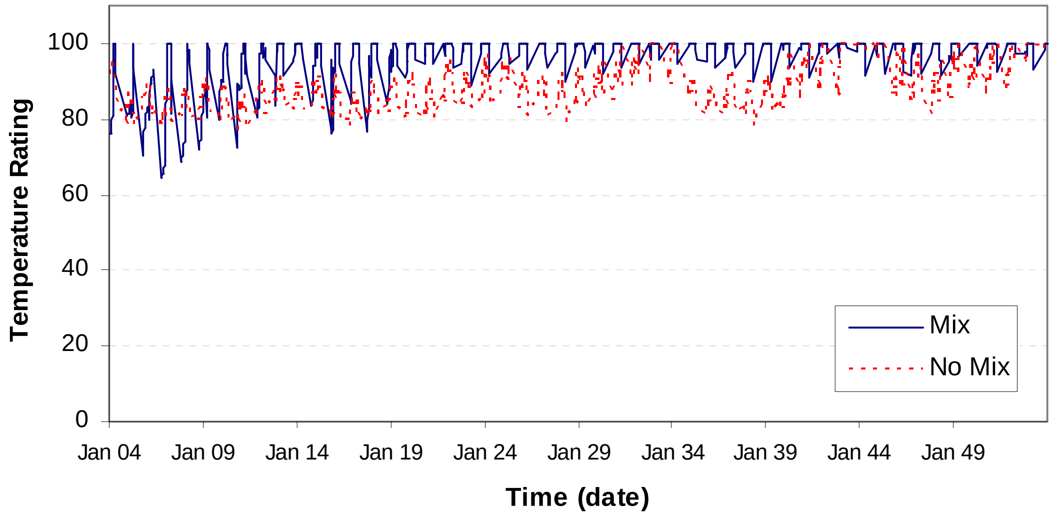
- Surface layer during warm period



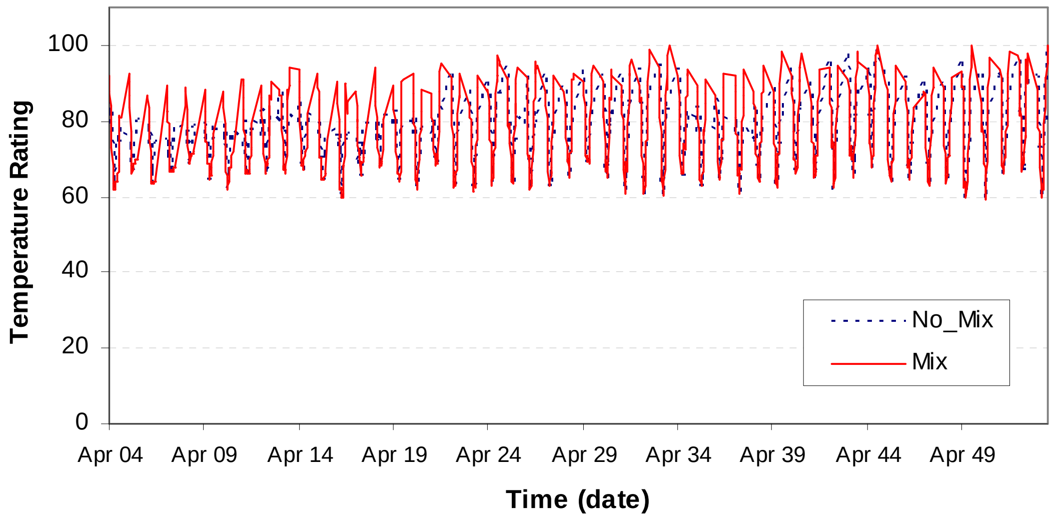

- Surface layer during cold period



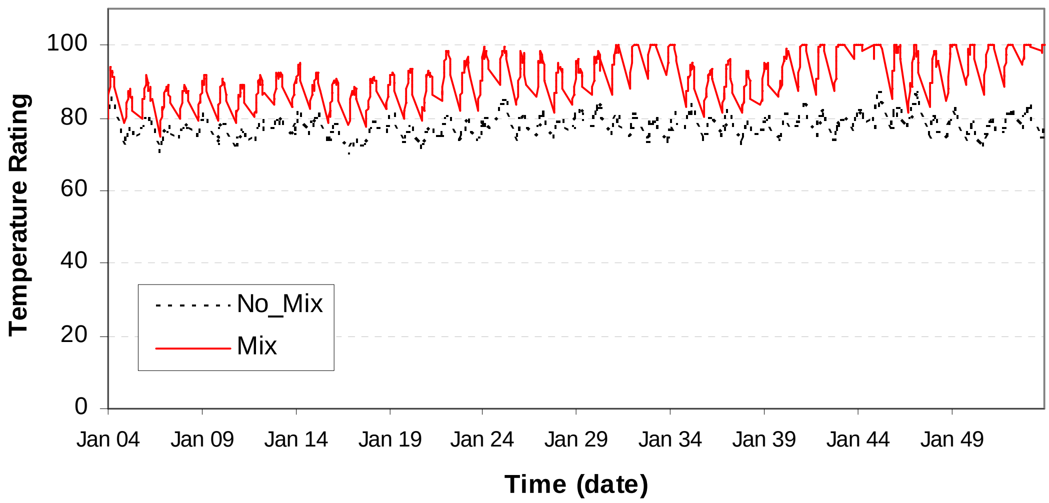
- Pumping layer during warm period



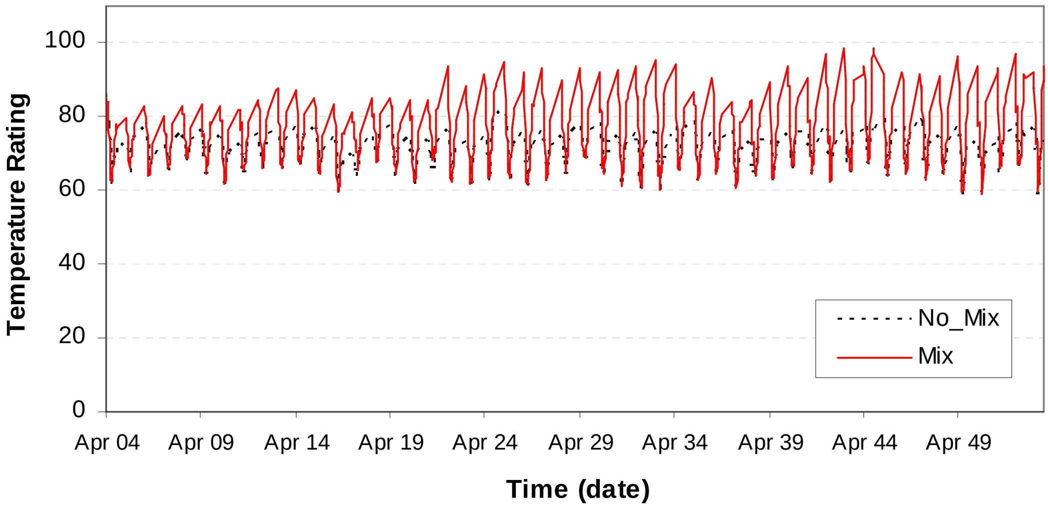

- Pumping layer during cold period




- Average of all layers during warm period

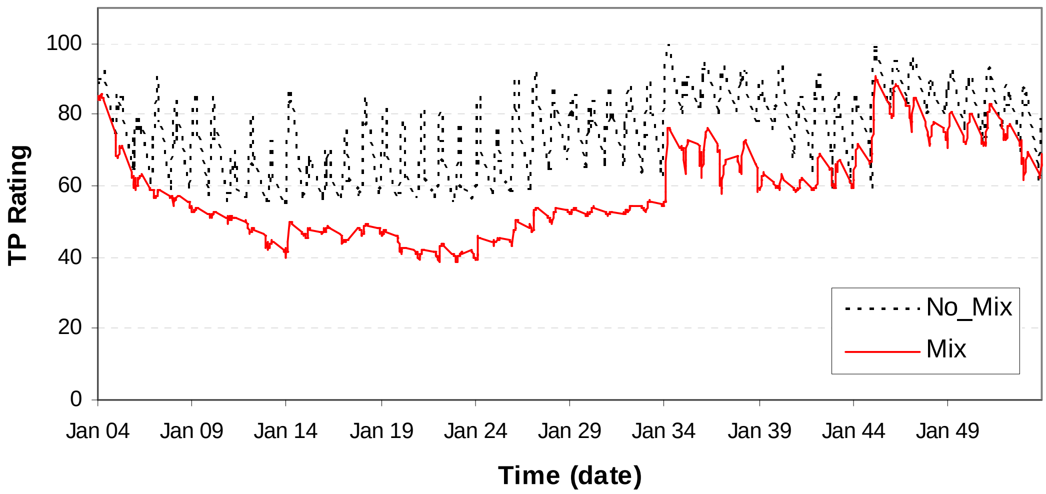


- Average of all layers during cold period

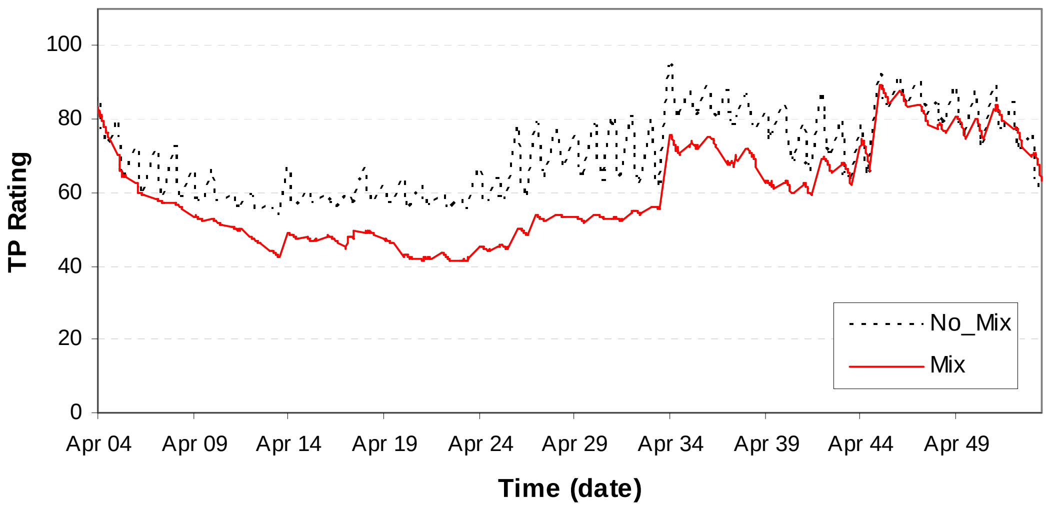



***Total phosphorus***

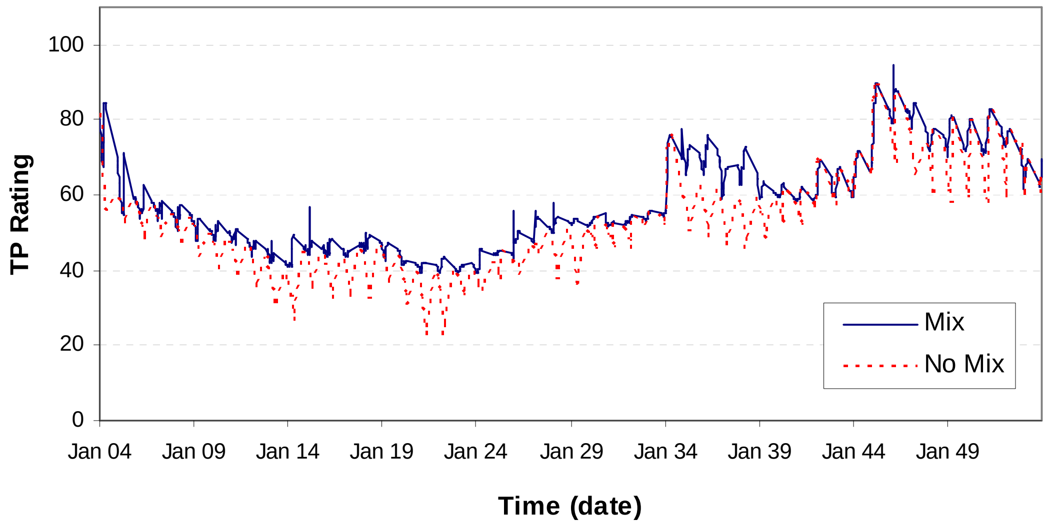
- Surface layer during warm period



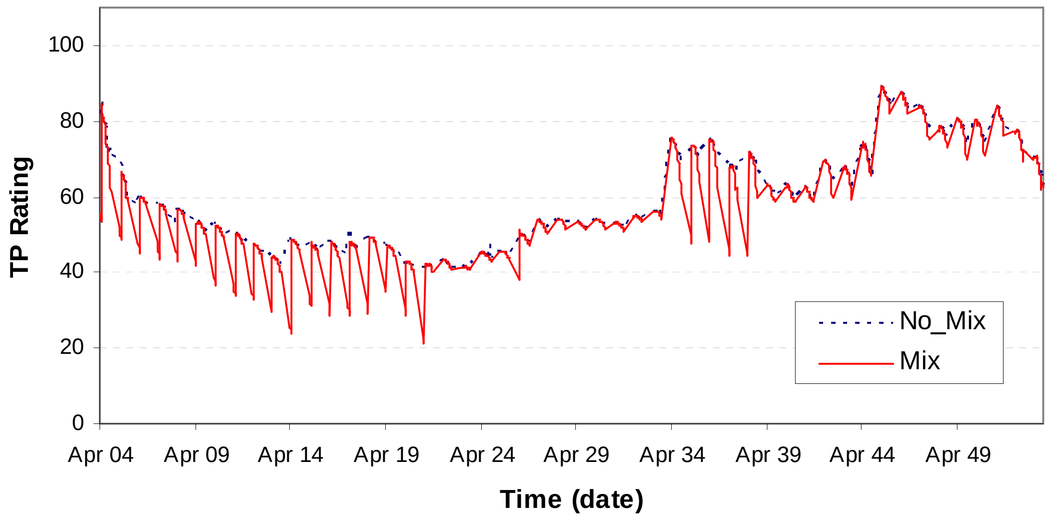

- Surface layer during cold period



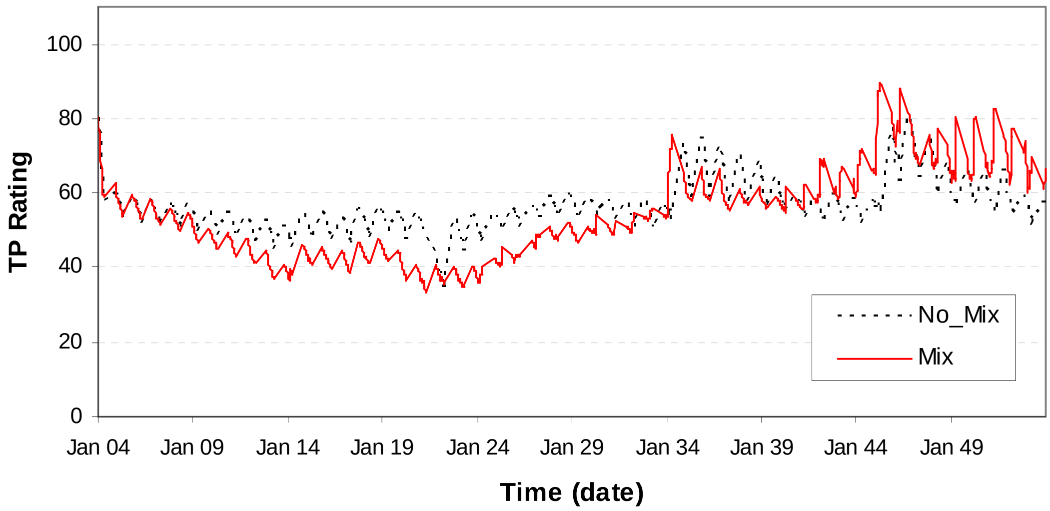
- Pumping layer during warm period



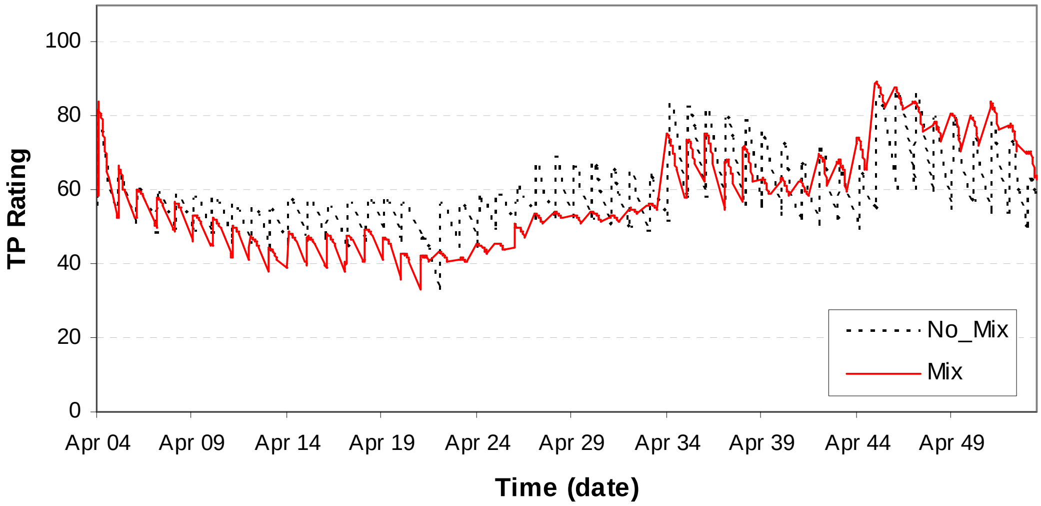

- Pumping layer during cold period




- Average of all layers during warm period

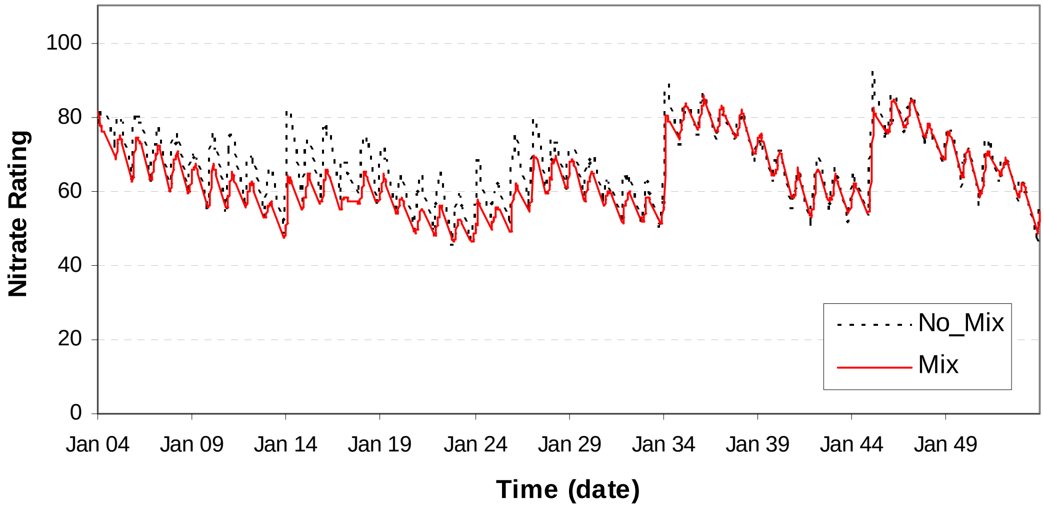


- Average of all layers during cold period

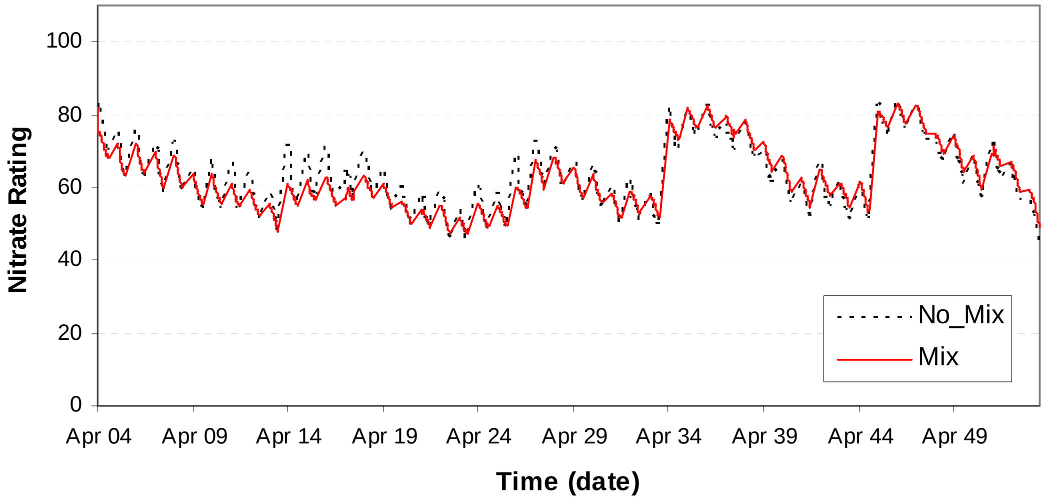



***Nitrate***

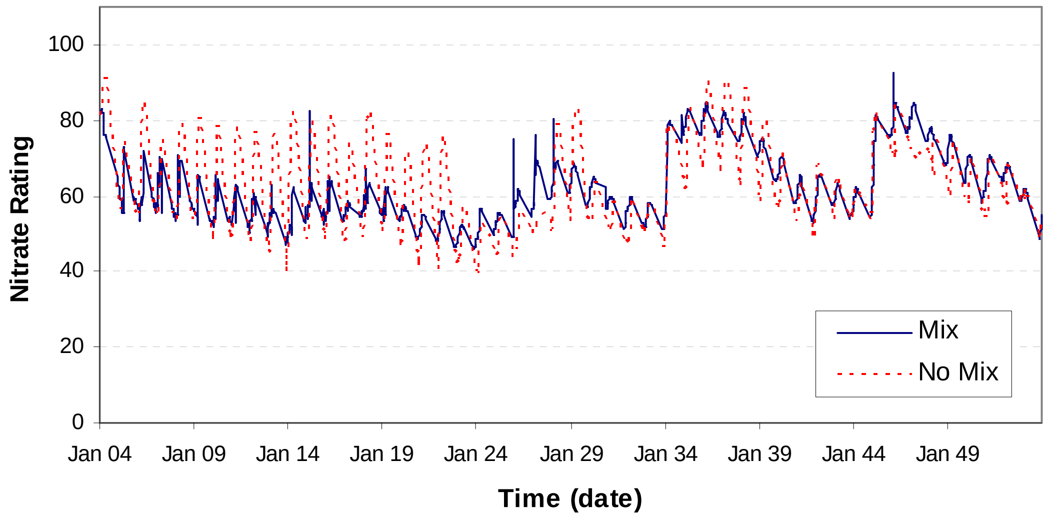
- Surface layer during warm period



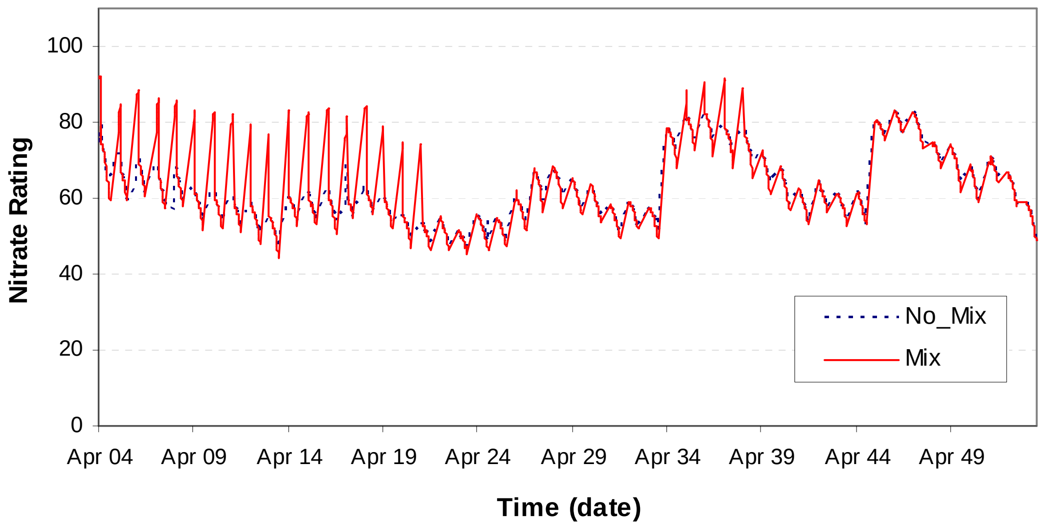

- Surface layer during cold period



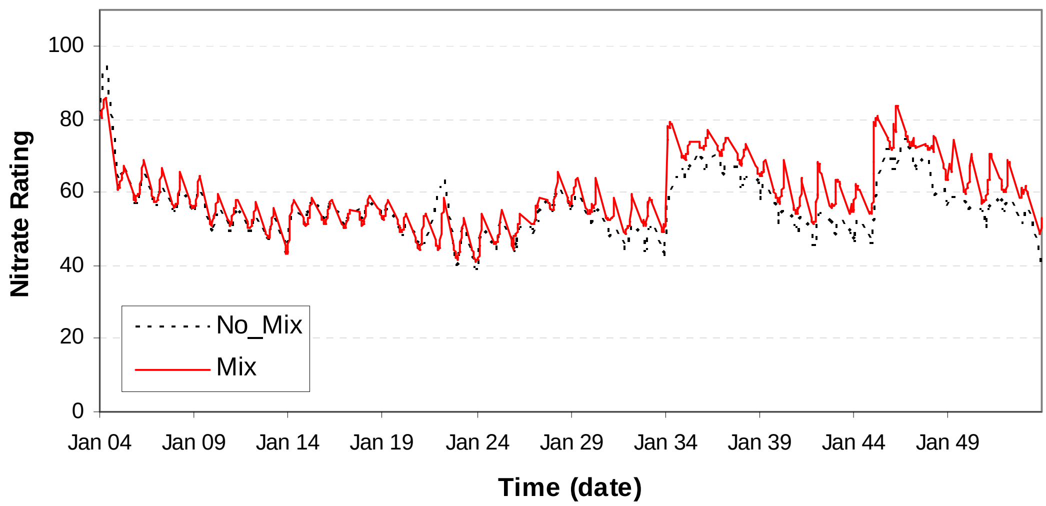
- Pumping layer during warm period



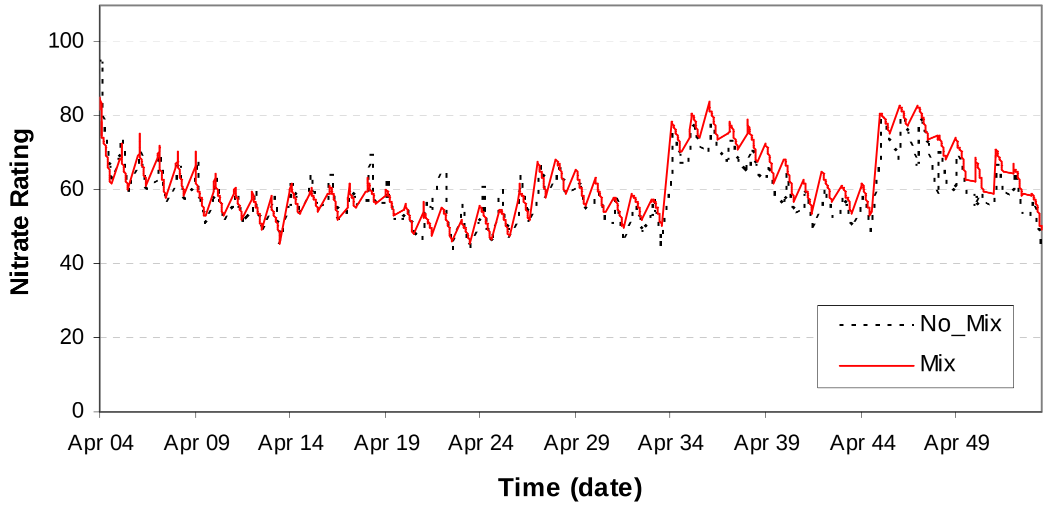

- Pumping layer during cold period




- Average of all layers during warm period

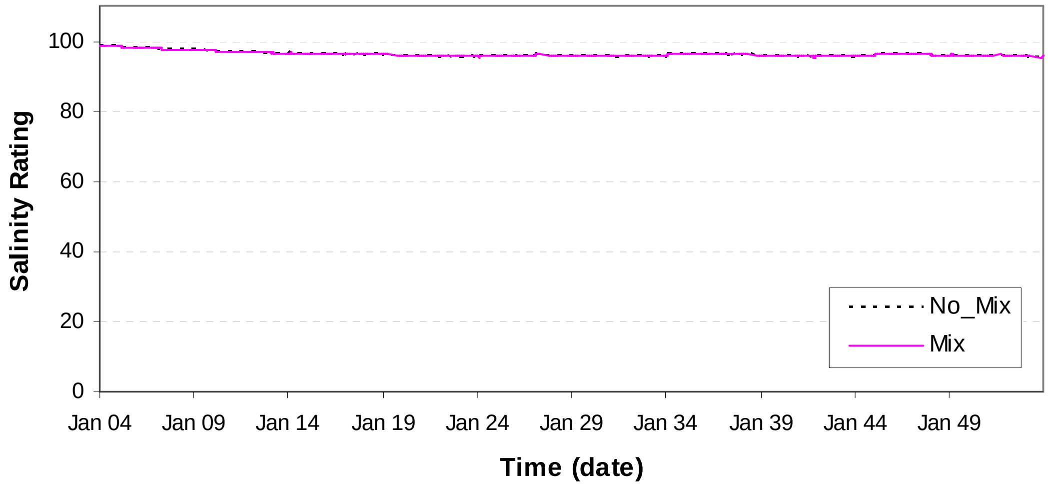


- Average of all layers during cold period

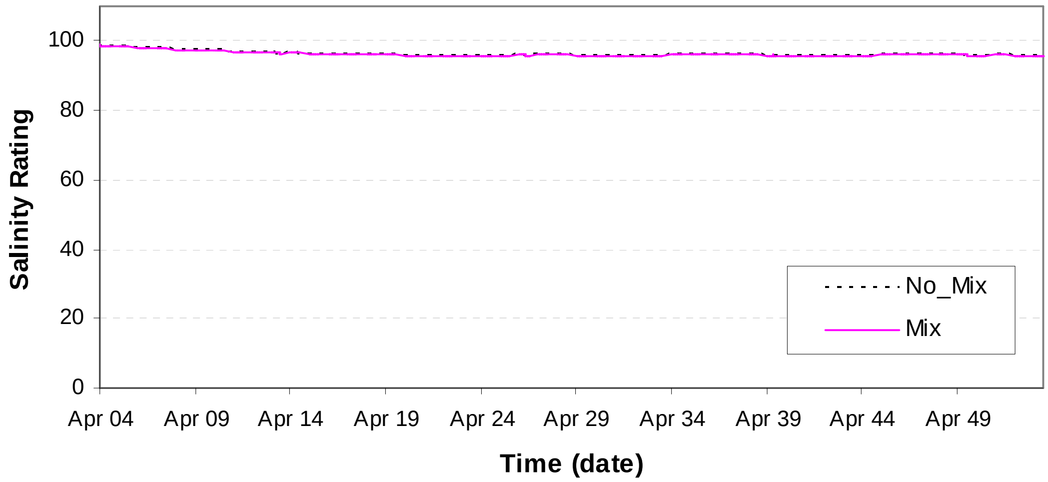



***Salinity***

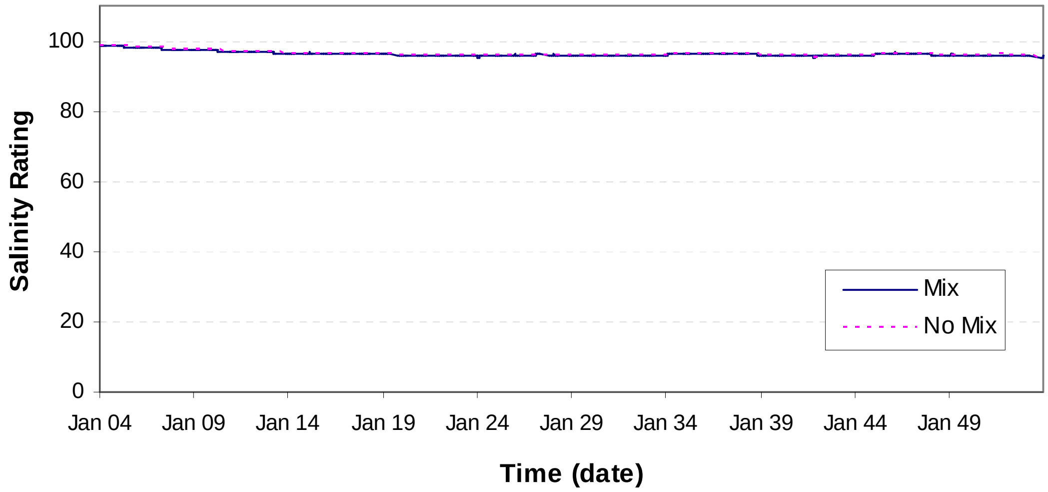
- Surface layer during warm period



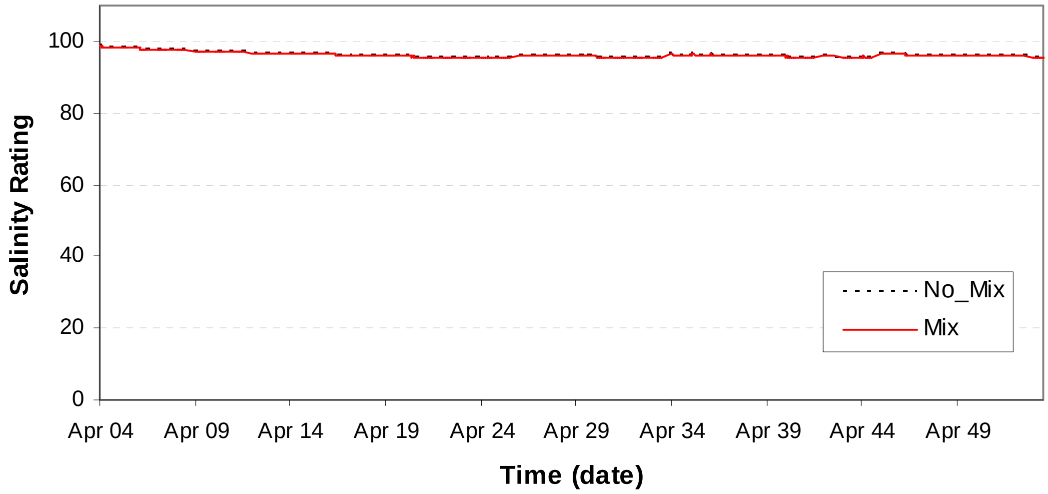

- Surface layer during cold period



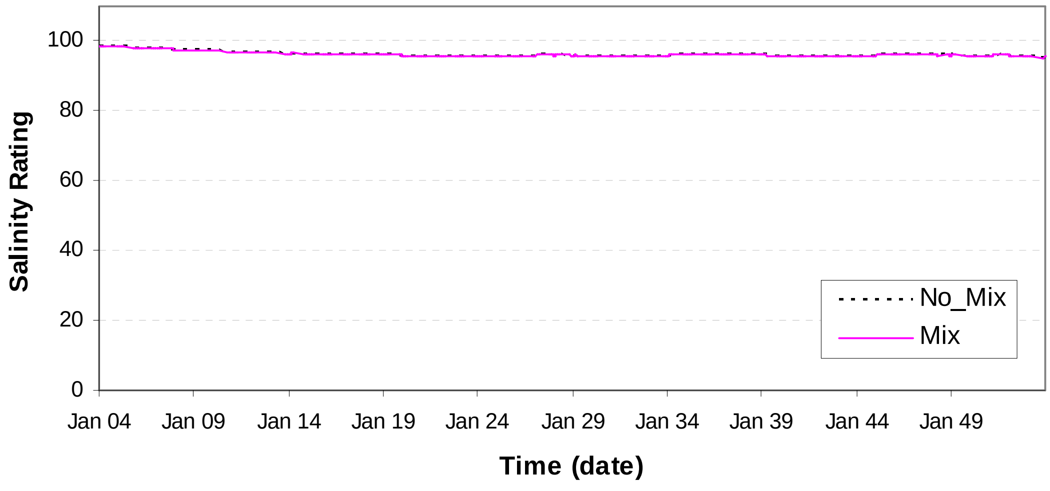
- Pumping layer during warm period



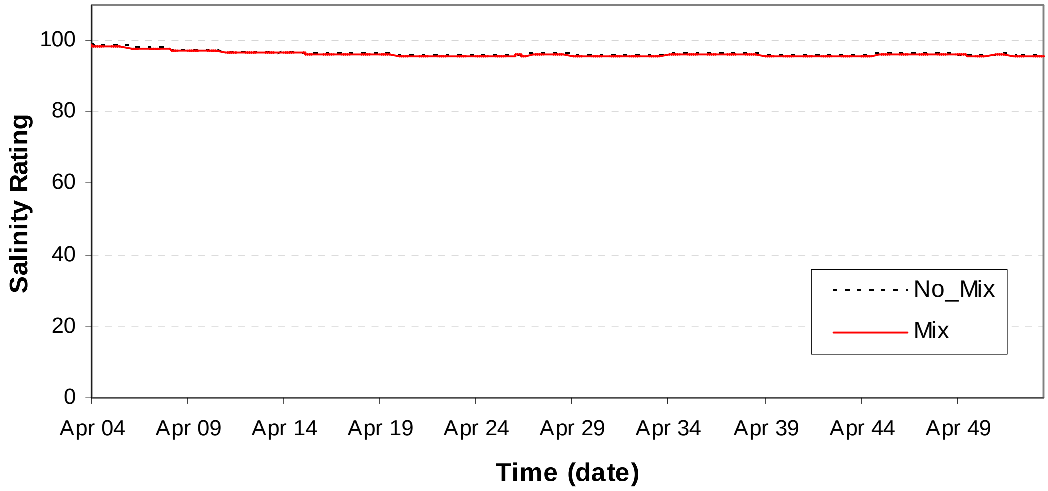

- Pumping layer during cold period




- Average of all layers during warm period

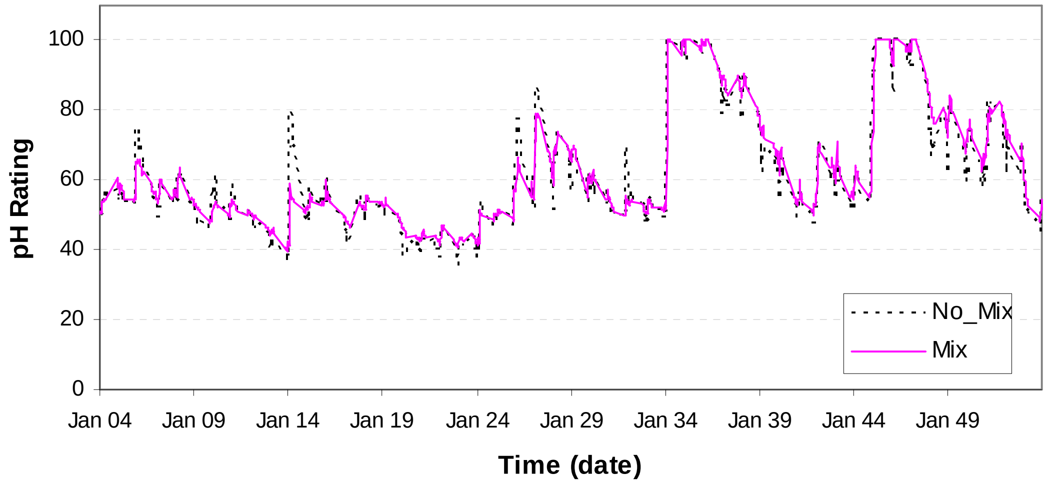


- Average of all layers during cold period

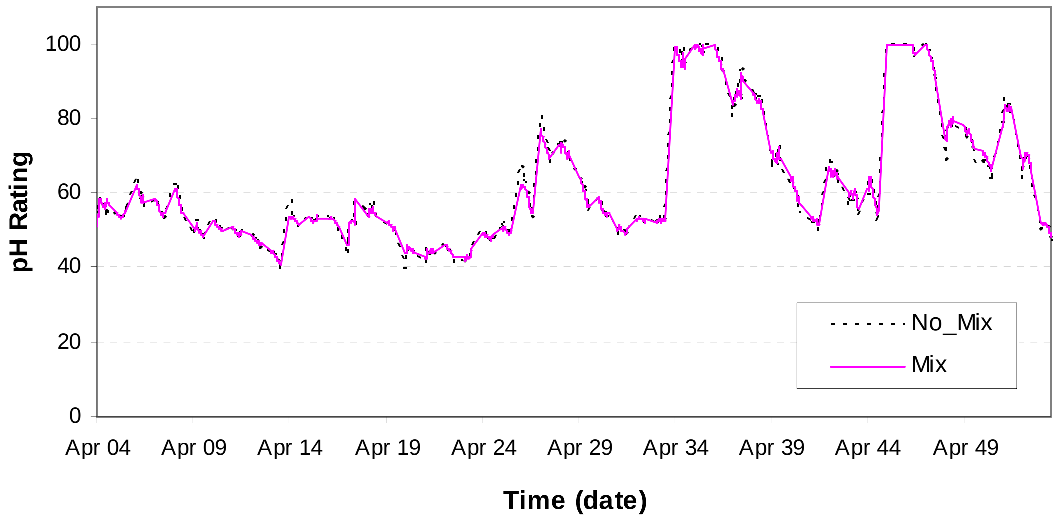



***pH***

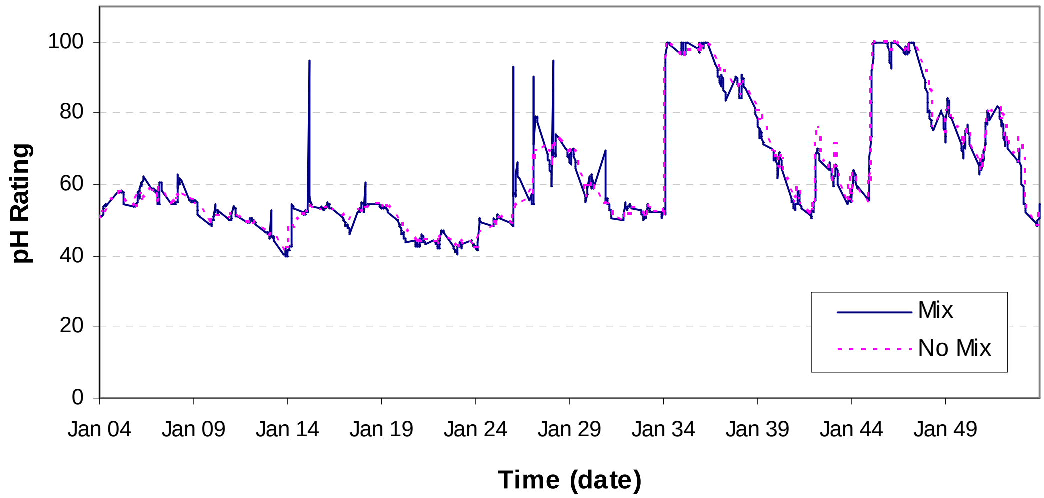
- Surface layer during warm period



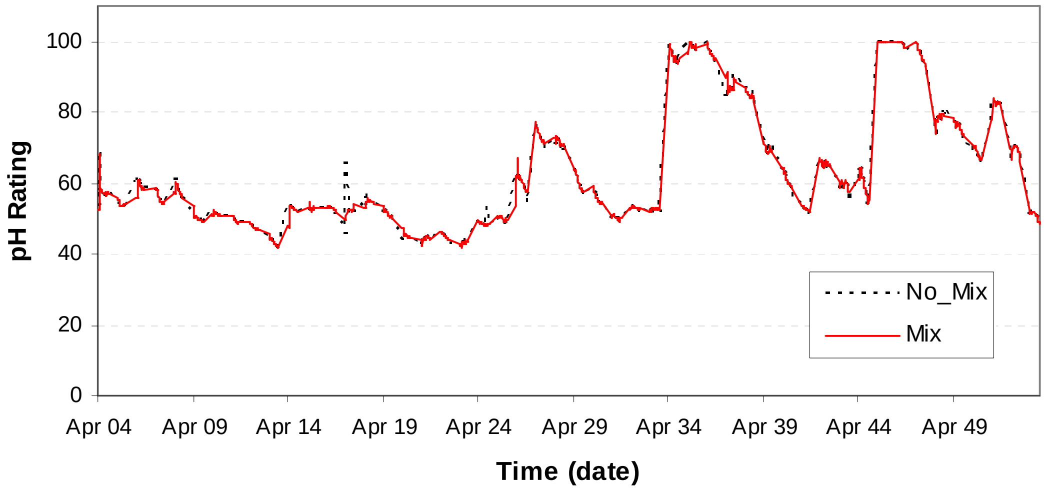

- Surface layer during cold period



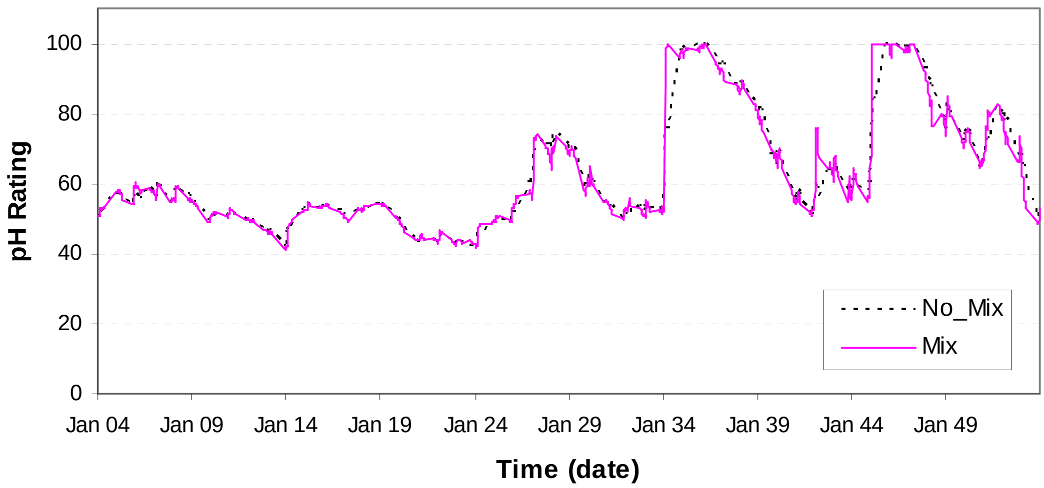
- Pumping layer during warm period



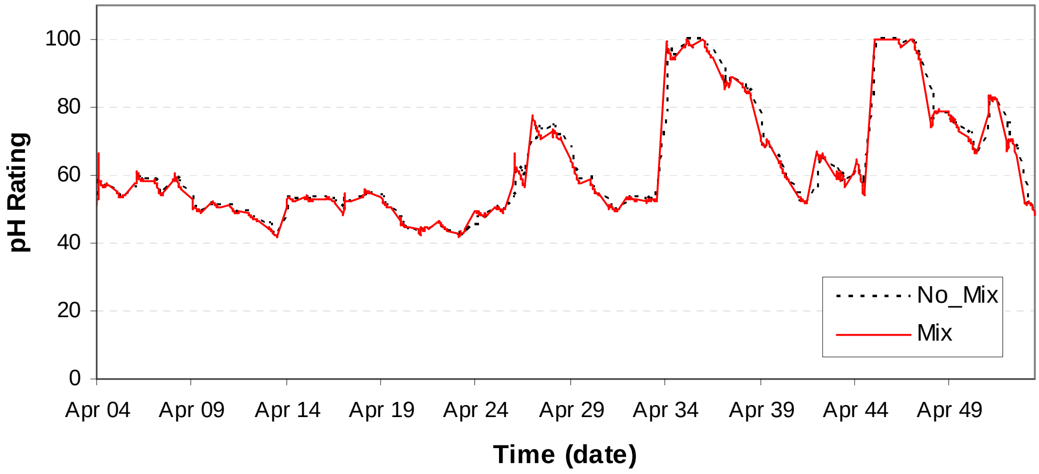

- Pumping layer during cold period




- Average of all layers during warm period

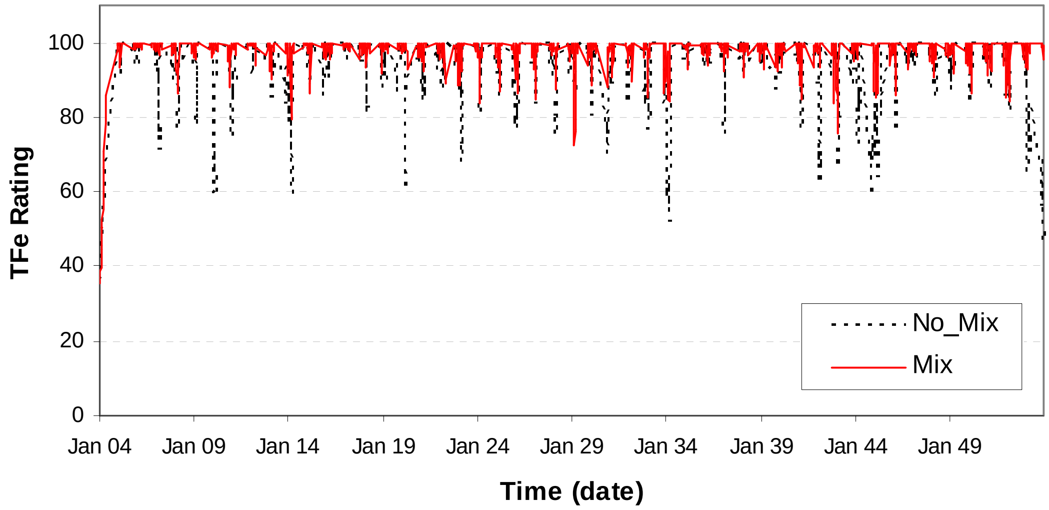


- Average of all layers during cold period

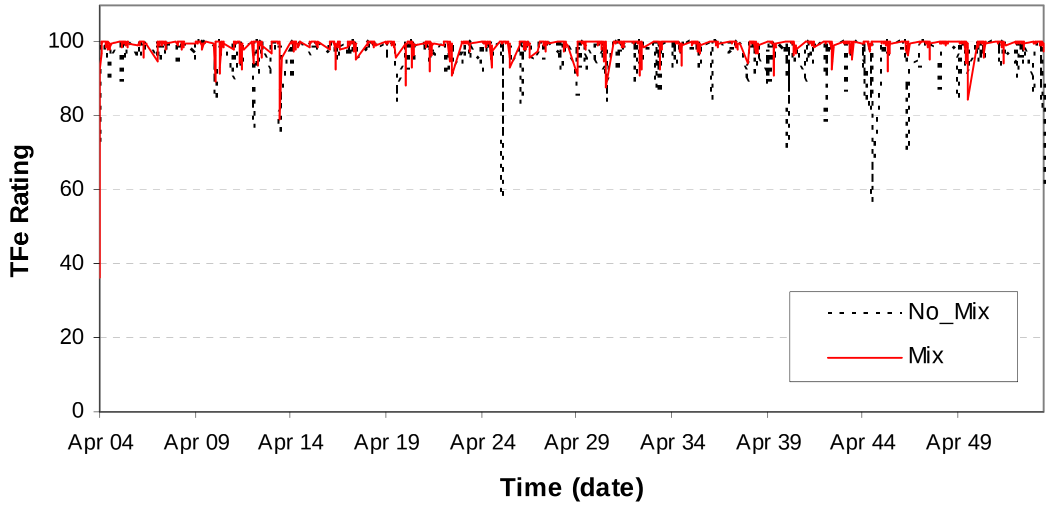



***Total iron***

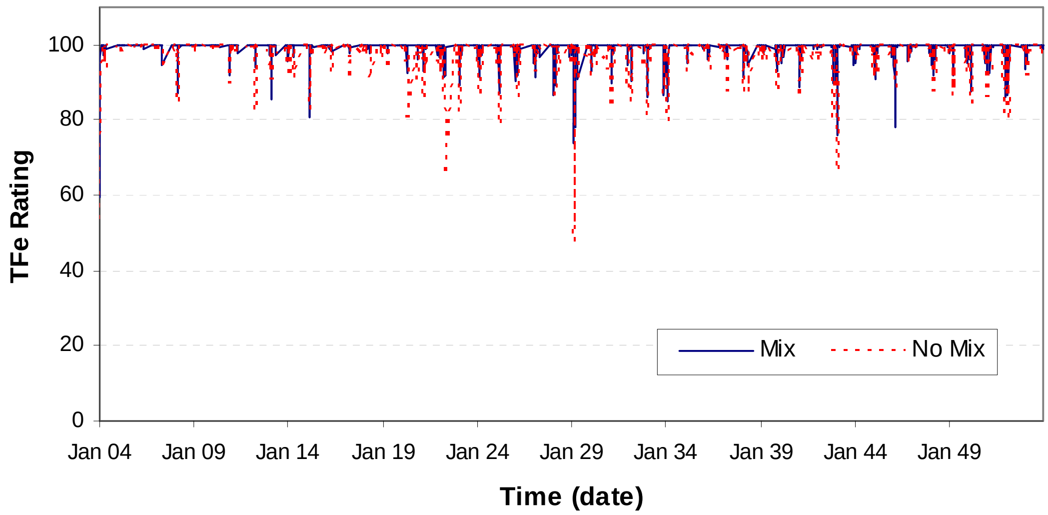
- Surface layer during warm period



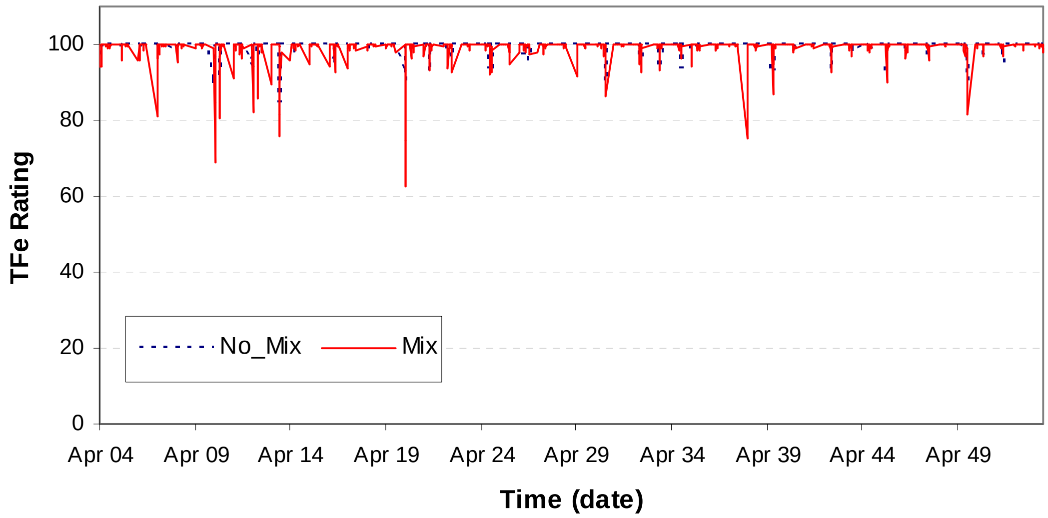

- Surface layer during cold period



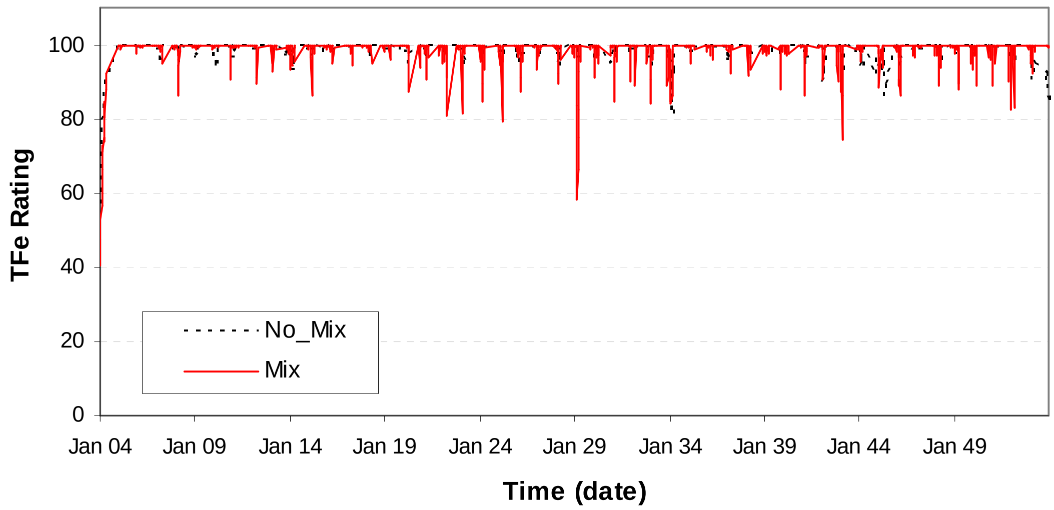
- Pumping layer during warm period



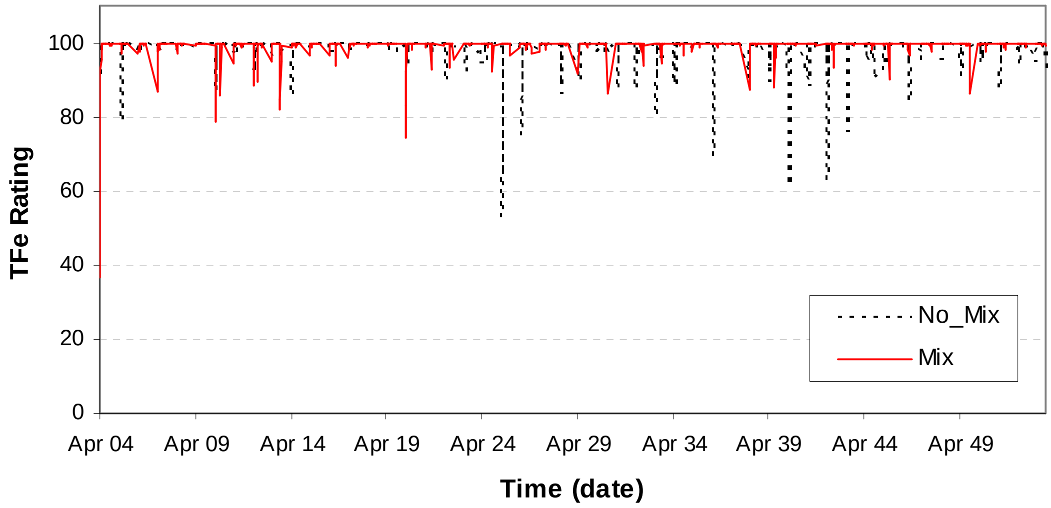

- Pumping layer during cold period




- Average of all layers during warm period

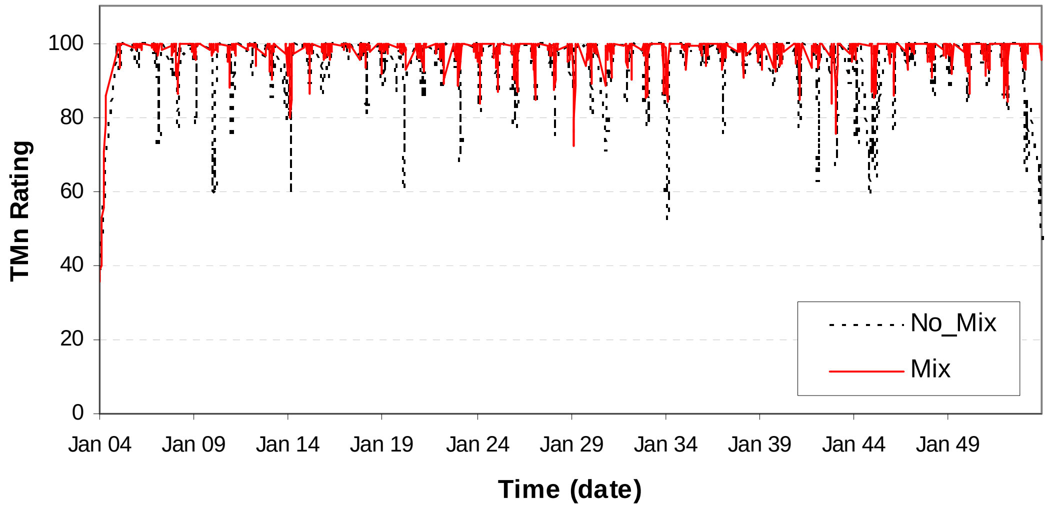


- Average of all layers during cold period

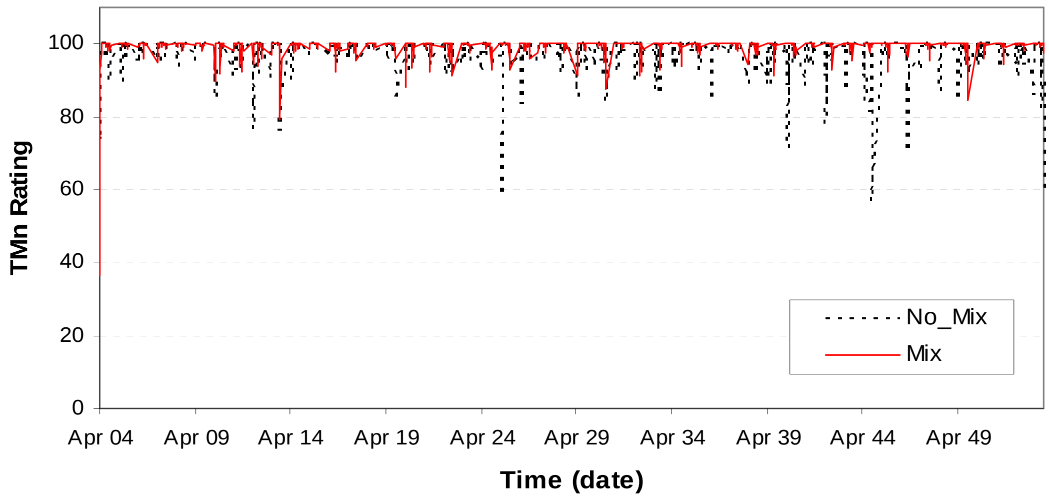



***Total manganese***

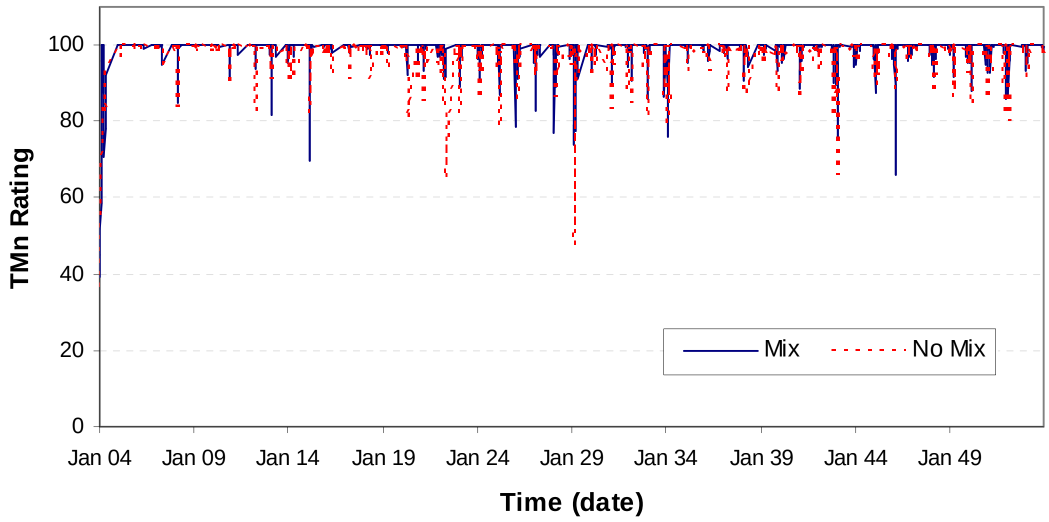
- Surface layer during warm period



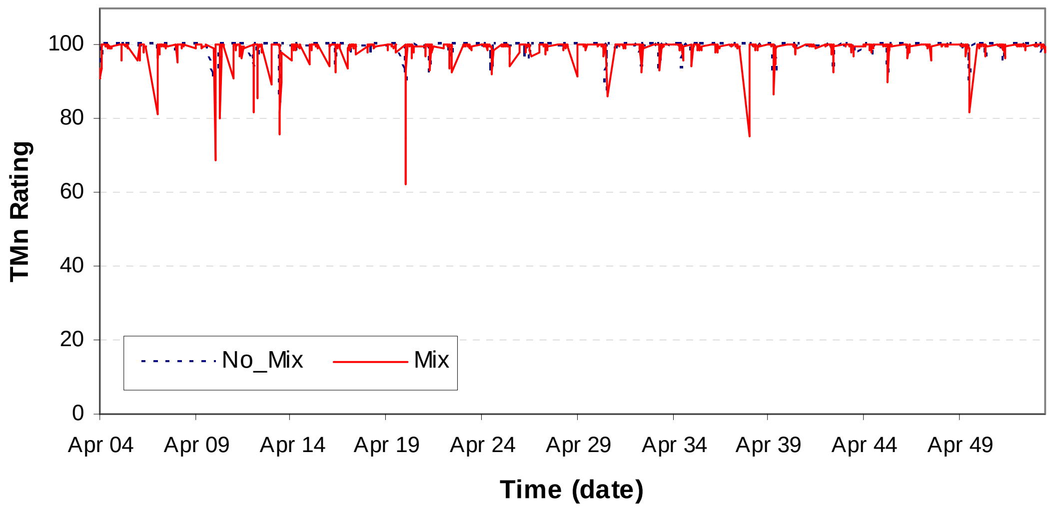

- Surface layer during cold period



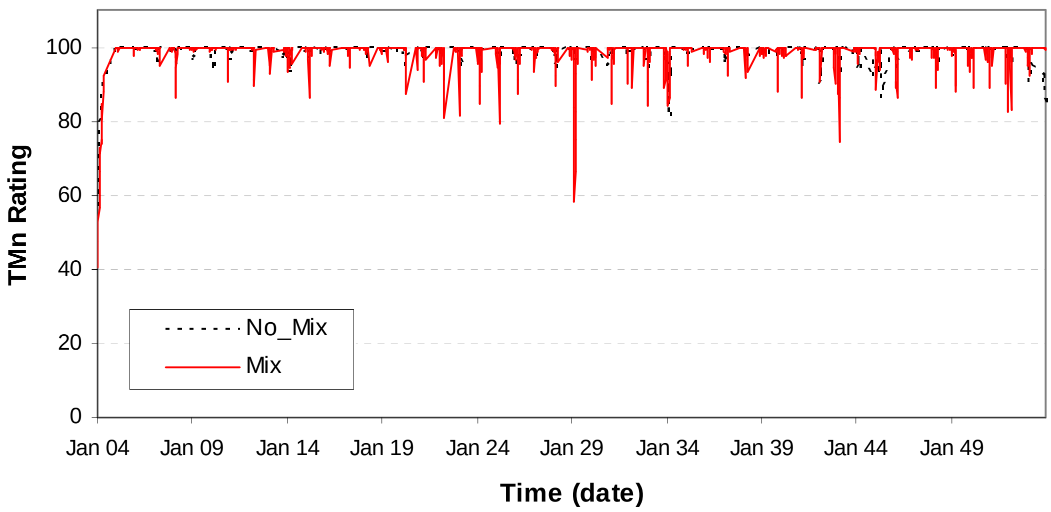
- Pumping layer during warm period



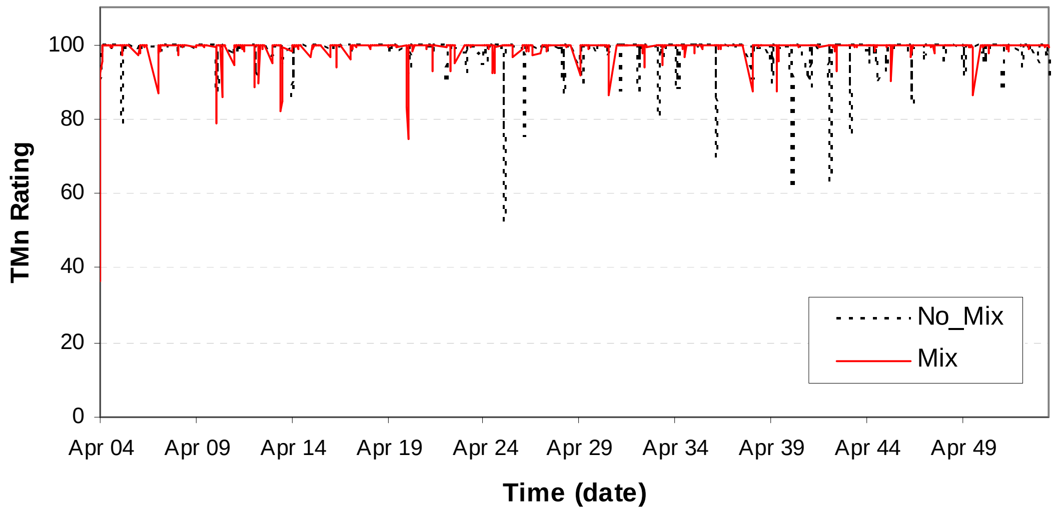

- Pumping layer during cold period




- Average of all layers during warm period



- Average of all layers during cold period



# Appendix D Conversions

## ALGA CONVERSION

| No. | Name of Species | Low Concentration | High Concentration |
|---|---|---|---|
| | | | |
| 1 | *Anabaena circinalis*<br>*Anabaena s f spiroides* | 1000 gyres/mL = 10 ug chl-a/L<br>18000 cells/mL = 10 ug chl-a/L<br>**1800 cells/mL = 1 ug chl-a/L** | 1400 gyres/mL = 10 ug chl-a/L<br>25200 cells/mL = 10 ug chl-a/L<br>**2520 cells/mL = 1 ug chl-a/L** |
| 2 | *Anabaena flos-aquae or*<br>*Anabaena aphanizomoides* | 760 gyres/mL = 10 ug chl-a/L<br>19760 cells/mL = 10 ug chl-a/L<br>**1976 cells/mL = 1 ug chl-a/L** | 2300 gyres/mL = 10 ug chl-a/L<br>59800 cells/mL = 10 ug chl-a/L<br>**5980 cells/mL = 1 ug chl-a/L** |
| | ***AVERAGE*** | **1888 cells/mL = 1 ug chl-a/L** | **4250 cells/mL = 1 ug chl-a/L** |
| 3 | *Aphanizomenon flos-aquae*<br>a. Single filament (60 cells) | 1200 filaments/mL = 10 ug chl-a/L<br>72000 cells/mL = 10 ug chl-a/L<br>**7200 cells/mL = 1 ug chl-a/L** | 4200 filaments/mL = 10 ug chl-a/L<br>252000 cells/mL = 10 ug chl-a/L<br>**25200 cells/mL = 1 ug chl-a/L** |
| | b. Filements (60-70 cells)<br>(take max 70 cells) | 1200 filaments/mL = 10 ug chl-a/L<br>84000 cells/mL = 10 ug chl-a/L<br>**8400 cells/mL = 1 ug chl-a/L** | 4200 filaments/mL = 10 ug chl-a/L<br>294000 cells/mL = 10 ug chl-a/L<br>**29400 cells/mL = 1 ug chl-a/L** |
| | ***AVERAGE*** | **7800 cells/mL = 1 ug chl-a/L** | **27300 cells/mL = 1 ug chl-a/L** |
| 4 | *Microcystis aeruginosa* | 200 um colonies = 10000 cells<br>3 colonies/mL = 10 ug chl-a/L<br>30000 cells/mL = 10 ug chl-a/L<br>**3000 cells/mL = 1 ug chl-a/L** | 90 um colonies = 1000 cells<br>40 colonies/mL = 10 ug chl-a/L<br>40000 cells/mL = 10 ug chl-a/L<br>**4000 cells/mL = 1 ug chl-a/L** |
| 5 | *Cylindropermopsis raciborskii*<br>(average anabaena & Aphanizomenon) | **4544 cells/mL = 1 ug chl-a/L** | **14725 cells/mL = 1 ug chl-a/L** |