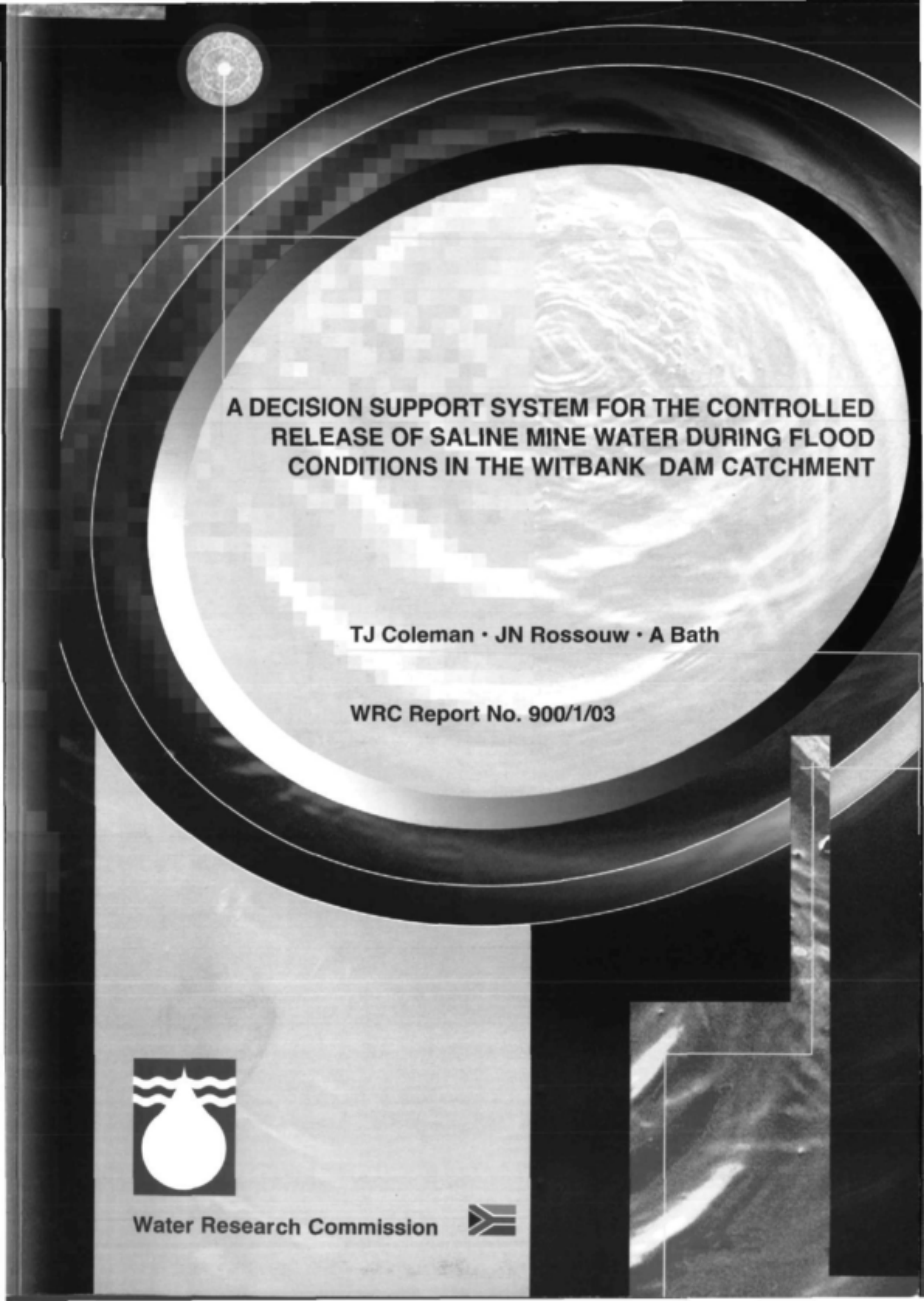

A DECISION SUPPORT SYSTEM FOR THE CONTROLLED RELEASE OF SALINE MINE WATER DURING FLOOD CONDITIONS IN THE WITBANK DAM CATCHMENT

TJ Coleman · JN Rossouw · A Bath

WRC Report No. 900/1/03

Water Research Commission

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Report to the

Water Research Commission

by

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Executive Summary

1. INTRODUCTION

The release of waste into river systems during times when assimilative capacity is available is an attractive option of disposing of excess polluted water. According to the Department of Water Affairs and Forestry's hierarchy of water management, the release of polluted water into a river system can only be considered after source controls, waste minimisation and recycling have been implemented. Any waste left has to be treated or released to the receiving water body. The costs of release are at present generally more attractive than those of treatment. The release can be in the form of a constant release as a sewage treatment plant discharge or the release can be managed to coincide with the available assimilative capacity in the receiving water body. The assimilative capacity is determined on the basis of acceptable water quality concentrations in the receiving waters. The application of the managed release approach could apply to any proposed discharge. The particular scheme discussed in this report was developed for the release of saline waste from the mining and power generation industries in the Witbank Dam Catchment.

The controlled release of excess saline water is not well developed in the water resources field in South Africa. A trial project was recently (summer of 1996/97) undertaken in the Witbank Dam catchment with considerable success. The operation of the scheme has been considerably modified since and extended to include the Middelburg Dam Catchment.

Resulting from the implementation of the scheme, two questions which needed further attention were identified. These can be summarised as follows:

- There was still uncertainty concerning the behaviour of the dam in terms of stratification and density currents. A more sophisticated two dimensional hydrodynamic impoundment model should be considered to more accurately predict the dam behaviour and hence the dam's assimilative capacity.
- Presently the scheme is operated on a daily time step. Information regarding flows and water qualities is collected daily and used to calculate the available assimilative capacity at the control points. The allocation of the waste load is also made on a daily basis. A small operational time step would result in the more efficient use of the available assimilative capacity and limit overshooting of the target concentration at the control point.

2. PROJECT AIMS

As described in the Agreement between the Water Research Commission, Wates, Meiring and Barnard (Pty) Ltd and Ninham Shand (Pty) Ltd, the aims of the project include:

- Setting up a daily time-step model for the Witbank Dam catchment. The model will, however, only be actively applied to the Steenkoolspruit sub-catchment. The calibrated model will be used to evaluate different release strategies for the sub-catchment.
- CE-QUAL-W2, a hydrodynamic impoundment model, will be set up for Witbank Dam. The model will be used to gain a better understanding of the response of the Dam to saline inflows.

By achieving these aims, the overall project objective of establishing a predictive tool to analyse and develop a better understanding of the controlled release of saline mine water will have been met.

A general rule-based system for the routine assessment of the available assimilative (dilution) capacity of the dam will be developed from the results of simulations undertaken with CE-QUAL-W2.

3. APPLICATION OF CATCHMENT MODEL

The ISIS, ACRU, HSPF and WITSKM/WITQUAL models were evaluated for possible use in operating a controlled release scheme. Although ISIS and HSPF were found to be capable of carrying out the routing, both models work off a proprietary database system. This made the linking of the CE-QUAL-W2 model to the routing component of the DSS difficult. The approach finally adopted was to use the pollutant and flow routing routines used in the WITSKM/WITQUAL modelling system.

The routing system was checked using the available flow and water quality measured at the gauging stations in the catchment as input to the catchment model. The routed flows and sulphate concentrations were checked at the Wolwekrans weir. Considering the accuracy of the available data and the small time step routing, a reasonable calibration was achieved.

The following two questions were addressed by analysing the small time step flow and conductivity data collected at B1H017 and B1H021 in the Steenkoolspruit catchment. The two questions that were addressed were:

- How frequently must information on the system variables be collected?
- How often does a decision on the releases have to be made?

The conclusions of this investigation were:

- The performance of a release scheme is sensitive to the decision time step. If a time step of 24 hours is to be used then a factor of safety should be built into the waste loads.
- To prevent overshoots on the recession limb, a projection of the end of time step flow based on the previous two time steps should be considered.

4. APPLICATION OF DAM MODEL

CE-QUAL-W2 is a two-dimensional (2-D), laterally averaged, hydrodynamic and water quality simulation model (Cole & Buchak, 1993). The model is based on the assumption that the water body shows maximum variation in water quality along its length and depth. Therefore, the model is suited to relatively long and narrow water bodies that show water quality gradients in the longitudinal and vertical directions. The model has been developed and applied to reservoirs, lakes, rivers, and estuaries. The two-dimensional model simulates the vertical and longitudinal distributions of thermal energy (water temperature) and selected biological and chemical constituents in a water body with time.

The model was applied to Witbank Dam using the measured flows and water qualities in the Boesmankransspruit, Olifants River at Wolwekrans and in the Noupoortspruit. The effect of small and large floods occurring at different times of the year on the dam were investigated. The following conclusions could be drawn:

- Timing of the flood – timing of the flood is related to the degree of stratification in the reservoir. Early in summer, the thermocline is shallow and weakly developed. A small flood can erode the thermocline and result in good mixing of the inflowing water. During summer, the reservoir is generally strongly stratified and inflowing floods tend to enter the reservoir as surface and interflow. Mixing tend to be in the surface layers. It was seen that very large floods can erode the thermocline, especially in the upper reaches of the dam and this results in deeper mixing of the inflowing floodwaters.

Floods that occur in autumn tended to enter on top of the thermocline but the later the flood, the easier it was to erode and break down the thermal stratification resulting in deeper mixing if the inflowing flood waters. Most winter inflows was colder that the water in the dam and entered the dam as underflow, following the bottom contours and accumulating in the bottom layers of the dam.

- Magnitude of the flood – the magnitude of the flood (and through flow) determined how far the inflowing water extended into the dam and how deep it mixed into the water column. Smaller floods did not extend very far into the dam before it became well mixed with the surrounding water. Larger floods extended far into the dam in some cases, it eroded the thermocline to such a degree that it mixed with the deeper layers of the dam. This was especially evident in the upper reaches of the dam.
- It is clear that the reservoir cannot be regarded as fully mixed, i.e. no or little changes in water quality along its length or depth.
- The temperature profile shows the annual change in stratification, starting with the warming of the surface water in spring, the deepening of the epilimnion during summer and then breakdown of thermal stratification when winter turnover occurs in late autumn.
- The TDS profile shows that there is a build-up of high TDS water in the bottom layers of the reservoir. The TDS in the bottom layers can only be removed if a large through flow of water occurs. It can be seen that allowing the dam to fill, (like happened early in 1993 (day 1100-1500)) resulted in a build-up of TDS in the lower layers of the dam because very little water was let out during that time other than the normal releases to Witbank Municipality and meeting other minor demands. However, that was followed by a period during which the flow of water through the reservoir increased and the TDS concentrations in the lower layers of the dam gradually decreased.
- It can be concluded that, in order to utilise floods for the controlled release of saline effluents, the flow through the reservoir should be carefully considered so that saline water is not allowed to accumulate in the bottom layers for extended periods of time.

5. OPERATION OF THE DECISION SUPPORT SYSTEM

The software required to operate a controlled release scheme needs to be able to address the daily operation of a scheme and to be able to look at possible future scenarios that could occur in the Witbank Dam. The two modes that were identified and that have been incorporated in the model are an operational and a scenario mode.

Scenario Mode

There are two ways in which the model can be run in scenario mode. The first way is to merely view the historic flow, dam capacities and water quality information at the control points and in the Witbank Dam. The method of viewing is through the catchment and dam output programs. The output is in the form of time series plots of flow and water quality at the control points and in the dam.

The other approach that can be used in scenario mode is to be able to predict what the sulphate concentration in the Witbank Dam could be sometime in the future. This capacity is useful for predicting possible conditions in the dam at the end of winter when the next year's controlled release scheme is due to begin. The methodology employed is based on a set of start conditions being selected from the historic records for the Witbank Dam and the control points. Then any time series of flows and qualities can be selected from the historic records at the inflow points to the dam and run through the catchment and dam model to predict the concentrations that could occur in the dam at the end of the specified time period.

Operation Mode

Under the operational mode, the model can be used to predict the impact of flood releases into Witbank Dam. The system is designed to predict the state of the dam two to four weeks in advance of the current state. The catchment model provides the inflow volume and water quality to the reservoir model. The system then performs a water balance for the dam; it helps with the selection of a meteorological condition for the next two to four weeks and then estimates the state of the dam four weeks into the future. The user can then examine the state of the dam to assess whether any of the water quality objectives set for the dam will be violated during that period. If so, the model can be rerun with new starting conditions.

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be made as a result of this study.

- The ISIS and HSPF models could both be used for a controlled release scheme. However, the linking of the data stored in the database of the ISIS and HSPF models to the CE-QUAL-W2 model proved to be too onerous. The flow and pollutant routing algorithms in the WITSKM/WITQUAL package were used in developing the Decision Support System.
- Considering the accuracy of the available information, a reasonable calibration of the flow and pollutant routing methods was achieved at Wolwekrans weir.
- The accurate description of the hydrograph and pollutograph of the information depends on the monitoring time step. The longer the time step the less accurate the representation of the event. The larger and more variable the flow, the bigger the discrepancy.
- the performance of a controlled release scheme is sensitive to the decision making time step. The longer the time step the poorer the performance of the scheme. In the case of the Witbank Dam catchment, a factor of safety is built into the waste load while the scheme is operating at a 24 hour time step. Flow projection techniques on the recession limb of the hydrograph should be considered to reduce the number of target concentration exceedances.
- The application of the dam model showed that the autumn floods tended to enter on top of the thermocline. However, the later the flood occurred in Autumn, the easier the thermal stratification is to break down and the deeper the mixing.
- The Witbank Dam cannot be considered as completely mixed. The model indicates that there is both a depth and a longitudinal variation in concentration.
- Consideration should be given to managing the flow through the reservoir to prevent the build up of saline water in the bottom layers. A monitoring program should be implemented on the dam to determine salinity depth profiles to verify the dam behaviour and to implement management if needed.

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

Mr HM du Plessis	Water Research Commission (Chairman)
Dr GC Green	Water Research Commission
Mr J Mare	Department of Water Affairs and Forestry
Mrs B Postma	Department of Water Affairs and Forestry
Dr M Ligthelm	Department of Water Affairs and Forestry
Mr HC van Zyl	Anglo Coal
Mr JN Viljoen	Ingwe Coal
Mr LM Nengovhela	Ingwe Coal

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(K5/900)

1 INTRODUCTION

1.1 Background

The release of waste into river systems during times when assimilative capacity is available is an attractive option of disposing of excess polluted water. According to the Department of Water Affairs and Forestry's hierarchy of water management, the release of polluted water into a river system can only be considered after source controls, waste minimisation, recycling and treatment have been implemented. Any water containing waste left after the hierarchy has been considered, can be released to the receiving water body. The costs of release are at present generally more attractive than those of treatment. The release can be in the form of a constant release as a sewage treatment plant discharge or the release can be managed to coincide with the available assimilative capacity in the receiving water body. The assimilative capacity is determined on the basis of acceptable water quality concentrations in the receiving waters. The application of the managed release approach could apply to any proposed discharge. The particular scheme discussed in this report was developed for the release of excess saline water from the mining and power generation industries in the Witbank Dam Catchment.

The 1995/1996 hydrological year in the Upper Olifants River Catchment was the wettest season of the 70 year record and the runoff from the Witbank Dam catchment was estimated to be 6 to 7 times the historical Mean Annual Runoff (MAR). Excess mine water was initially stored in mine workings. By March 1996, uncontrolled seepage and decant occurred from several of the mining operations. In some cases the mines had to pump excess water out into the public streams or face closure of operations. This discharge caused a deterioration in the water quality in the Witbank Dam. The mine water seepage and decant flows continued into the dry winter months, due to the elevated water table levels. A deterioration of water quality in the Witbank Dam occurred as a result of this seepage and the concomitant reduction of river flow in the dry season. The sulphate concentration increased from approximately 80 $mgSO_4/L$ to 319 $mgSO_4/L$ from April to September 1996. This was the highest level of salinity ever recorded in the Dam. Faced with these both short and medium term water problems, the coal mines, together with the power stations investigated the feasibility of controlled discharge of excess mine water during high flow conditions in the catchment. Surface water runoff models indicated that assimilative capacity would be available during average and above average runoff flows. After discussions with the Department of Water Affairs and Forestry, the scheme was implemented during the summer months of 1996/97 as a trial. The scheme was also implemented in the Middelburg Dam Catchment in 1997/98. The releases in the Middelburg Dam catchment are made on the same basis as those in the Witbank Dam Catchment.

The mining industry has investigated a broad range of water management options, ranging from improved rehabilitation of mine disturbed land, recycling and re-use of water, control of pollution at source, treatment of mine water such as neutralisation and desalination. The management of salinity in mining-dominated catchments is based on the control of salt load discharges from point and non-point sources of pollution. The assimilative capacity of natural water systems is generally dependent on the rainfall/ runoff situation in any specific hydrological year. A large dilution capacity for specific saline discharges exists during flood events. The controlled release of mine water during flood events is therefore a further management option, supplementing the above-mentioned range of management options. Excess mine water releases during flood events can supplement a water resource without necessarily having a negative impact on the quality. Large amounts of moderately polluted mine water are generated during relatively wet hydrological years. The accumulation and retention of this water in mine workings results in increased dissolution of salts and thus an ongoing deterioration in water quality. Synchronising the release of mine water with high flood conditions in the local streams, may be attractive as it will alleviate excess water accumulation on the mines, releases can be made before the water quality deteriorates, and the release becomes a supplementary source of water.

The controlled release of excess saline water is not well developed in the water resources field in South Africa. A trial project was recently (summer of 1996/97) undertaken in the Witbank Dam catchment with considerable success. The operation of the scheme has been considerably modified since and extended to include the Middelburg Dam Catchment.

1.2 Elements of a Release Scheme

The requirements for implementation of a managed release scheme can be summarised as follows:

- Determination of the extent of the area of impact of the releases.
- Determine the number and location of the scheme participants.
- Division of the catchment into Management Units and establishment of control points.
- Assess the water quality of the water to be released. The release of toxic waters such as acid mine drainage would only normally be considered after treatment.
- Compare the water quality guidelines with the release water quality to determine the water quality variables of concern.
- Based on the previous analysis, set target concentrations for the variables of concern at the control points.
- Establish a monitoring program which will include monitoring frequency, the water quality variables to be monitored and flow rates.
- Set up a model to determine the available assimilative capacity at the control points. Control points could be in rivers, dams or estuaries.
- Establish a set of rules to allocate the assimilative capacity to the scheme participants.
- Set up the necessary systems to communicate loads and releases to the participants.
- Ensure that correct licensing has taken place with the regulator.

In setting up the scheme for the Witbank Dam Catchment, many of the preliminary investigations had already been undertaken as part of various mining initiatives and studies commissioned by the Department of Water Affairs and Forestry. A Water Quality Management Plan (WQMP) had been developed which included some public participation. The WQMP included the development of a monthly time step water quality model, establishment of management units and a set of water quality objectives for each of the management units. The monthly time step model was initially used to assess the feasibility of a managed release scheme as an option to assist with the disposal of saline mine water. Once this was established, a more detailed operations model was developed to determine the waste load allocations. The WQMP was used to locate the control points, determine the water quality variables of concern and to set target concentrations at the control points. Based on this, sulphate was identified as the variable of concern and was used to determine the assimilative capacity and the waste loads.

As part of a mining project, a set of rules were established to allocate the waste load between the mines. The rules were based on the size of the mining operation, type of mining (eg. Bord and pillar, opencast) and the potential mobilisable sulphate load from the different mining areas. These rules were used for the Witbank Dam scheme.

During the first year (1996/97) the allocations to the mines were based only on the assimilative capacity of Witbank Dam. No control points were established in the upstream management units. A weekly monitoring program of the three influent streams to the dam and three points in the dam was established. The results of this monitoring program were fed into a single completely mixed cell model of the dam. The model was used to predict the dam concentrations at the end of the next week. The following shortcomings were identified in this approach:

- The weekly monitoring time period was too long.
- No consideration was given to local impacts in the upstream catchment.
- The single cell completely mixed model of the dam was too simplistic for an operational model.

In subsequent years, the release protocols were improved to protect the upstream streams and impoundments by introducing management unit level control, i.e. the assimilative capacity was determined for the individual management units as well as the dam. A daily monitoring program was established during the summer release period switching to a two-weekly program during winter. Upstream impoundments were also included where necessary. The single cell model was changed to a three cell model for the Dam.

Despite the improvements to the release protocols, there were two questions which needed further attention. These can be summarised as follows:

- There was still uncertainty concerning the behaviour of the dam in terms of stratification and density currents. A more sophisticated two dimensional hydrodynamic impoundment model should be considered to more accurately predict the dam behaviour and hence the dam's assimilative capacity.
- Presently the scheme is operated on a daily time step. Information regarding flows and water qualities is collected daily and used to calculate the available assimilative capacity at the control points. The allocation of the waste load is also made on a daily basis. A small operational time step would result in the more efficient use of the available assimilative capacity and limit overshooting of the target concentration at the control point.

This research project was initiated to further examine these issues and to provide insight into the implementation of a managed release scheme The research project is a collaborative effort between Ninham Shand and Wates, Meiring & Barnard (WMB). The experience of Ninham Shand in applying the CE-QUAL-W2 model to the modelling of pollutant movement in dams was used in applying CE-QUAL-W2 to address the dam issue. The current catchment modelling system was adapted to address the data allocation and operational time step issue by WMB.

1.3 Project Aims

As described in the Agreement between the Water Research Commission, Wates, Meiring and Barnard (Pty) Ltd and Ninham Shand (Pty) Ltd, the aims of the project include:

- Setting up a daily time-step model for the Witbank Dam catchment. The model will, however, only be actively applied to the Steenkoolspruit sub-catchment. The calibrated model will be used to evaluate different release strategies for the sub-catchment.

- CE-QUAL-W2, a hydrodynamic impoundment model, will be set up for Witbank Dam. The model will be used to gain a better understanding of the response of the Dam to saline inflows.

By achieving these aims, the overall project objective of establishing a predictive tool to analyse and develop a better understanding of the controlled release of saline mine water will have been met.

A general rule-based system for the routine assessment of the available assimilative (dilution) capacity of the dam will be developed from the results of simulations undertaken with CE-QUAL-W2.

1.4 Project Approach

The project has two parts viz. the catchment modelling and the reservoir modelling. These two components were developed separately to be brought together towards the end of the project to form the decision support system. The final product being a computer program with the two modelling systems linked.

The approach adopted for the catchment modelling was to investigate the available catchment models such as HSPF to assess their suitability for use in the catchment modelling. The most suitable modelling system or methodology was set up for the Witbank Dam Catchment and calibrated against the measured flow and sulphate concentrations. The calibrated model was then actively applied to the Steenkoolspruit catchment to investigate release strategies. Short time step (≈15 minute) flow and electrical conductivity data was available at two weirs in the catchment. This data was used to investigate the effectiveness of different release strategies in meeting the target concentrations.

The approach adopted in the reservoir modelling was to set up a two-dimensional reservoir water quality model, the CE-QUAL-W2 model, for Witbank Dam to allow the user to simulate changes in salinity along the length and depth of the reservoir under different flow conditions. Input to the model include the bathymetry, outlet position and the flow and water quality of the three influent streams to the dam. The model was calibrated against observed data in the dam. Once calibrated the model was used to assess the behaviour salinity and sulphate concentrations for different storm events entering the dam at different times of the year.

2 DAILY TIME STEP CATCHMENT MODEL

2.1 Introduction

There are a number of catchment models available, which could be considered for use in operating a controlled release scheme. Amongst the models readily available in South Africa are HSPF, ACRU, ISIS and WITSKM/WITQUAL. Although there are many more suitable models available in South Africa and internationally, the study has been restricted to an evaluation of those listed above.

In order to evaluate the models, the requirements of a model for use in the operation of a controlled release scheme should be established. Based on the experience gained in the running of the Witbank Dam release scheme, the following requirements have been formulated :-

- the rainfall runoff and pollutant washoff processes need not be modelled as frequent measurements of flow and water quality are taken at the control points and other critical points in the system. The use of rainfall measured in a raingauge network for prediction of flow rates at control points may not always produce the best estimates of flow. The accuracy will depend on the extent of the raingauge network in capturing the spatial and temporal distribution of the rainfall and the accuracy of the model used to estimate the catchment runoff. To sensibly use rainfall information, small time step (5 minutes to 10 minutes) rainfall intensities will be required. This implies instrumentation and a real time communication system. A radar system may be more suited for this level of monitoring.
- the important component is the routing of pollutants and flows through the river and dam system to predict the expected water quality and flow rates at the control points.
- the ability to be able to update the program to include waste releases from the mines or changes in operating policy.

For this particular project, the ability of linking the output from the so called catchment model to the input to the CE-QUAL-W2 will also have to be considered. Many of the models use a proprietary database system, which is not always accessible from another computer program. The data has to be transferred manually to a data file first before loading into another program. This does not result in the required smooth operation of a program to make waste load allocations.

In this chapter, discussion on flow and pollutant routing techniques is presented as background to the routing used in the models. A brief discussion of the models listed above is also included. The model evaluation is done on the basis of the potential application of the model to a controlled release scheme. The setting up and running of the catchment model is also presented.

2.2 Flow Routing

The St Venant equations of water mass and momentum conservation form the basis of many of the hydraulically based flood wave routing methods. The two equations used are given below.

continuity;

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_L$$

momentum;

$$S_f = S_o - \frac{\partial y}{\partial x} - \frac{U}{g}\frac{\partial U}{\partial x} - \frac{1}{g}\frac{\partial U}{\partial t}$$

in which Q (m^3/s) is the flow rate, A (m^2) is the flow cross sectional area, q_l (m^2/s) is the lateral input per unit flow length, x (m) is the distance, t (s) is time, y (m) is flow depth, g (m/s^2) is the acceleration due to gravity, U (m/s) is the cross sectional average velocity, S_o (m/m) is the bed slope, and S_f (m/m) is the friction slope.

The St Venant equations are non-linear partial differential equations of the hyperbolic type requiring upstream and downstream boundary conditions as well as initial conditions for their solution. Due to the computer effort and detail of the input required to solve the full St Venant equations numerically, simplified forms of the momentum equation are often used. The simplifications are shown below.

simplifications;

$$\underbrace{\underbrace{\underbrace{S_f = S_o}_{\text{kinematic}} - \frac{\partial y}{\partial x}}_{\text{non-inertia}} - \frac{U}{g}\frac{\partial U}{\partial x} - \frac{1}{g}\frac{\partial U}{\partial t}}_{\text{full dynamic}}$$

In the kinematic approximation, the acceleration and pressure terms are omitted from the momentum equation and $Sf \approx So$. For the non-inertia approximation, the acceleration terms are ignored and S_f is approximated by the pressure and gravity terms.

Of the four models listed, only the ISIS model solves the full dynamic equations. The HSPF, ACRU and WITSKM/WITQUAL models use various forms of kinematic routing. HSPF uses pure kinematic routing while ACRU and WITSKM/WITQUAL use different forms of Muskingum-Cunge routing. The kinematic and Muskingum-Cunge Routing are discussed in the next section.

2.2.1 Kinematic routing

By assuming that the friction slope S_f can be approximated by the bed slope S_o, a single valued relationship between the flow rate and depth can be assumed. This single valued relationship can be described by a steady flow friction relationship of the form $Q = K\,S_f^{\frac{1}{2}}$ where K is a conveyance factor. Replacing $\frac{\partial A}{\partial t}$ with $\frac{dA}{dQ}\frac{\partial Q}{\partial t}$ in the continuity equation gives:

$$\frac{\partial Q}{\partial x} + \frac{1}{Ce}\frac{\partial Q}{\partial t} = q_L \tag{2.2.1}$$

where $Ce = \frac{dQ}{dA}$ is the wave celerity. Inherent in the kinematic theory is that a flood wave modelled using the kinematic equations exhibits no attenuation only a steepening of the wave front as is shown in **Figure 2.2.1(a)** for a channel (after Henderson, 1966). This characteristic of kinematic routing has been shown mathematically by Henderson (1966), Stephenson and Meadows (1986), and Cunge et al (1980). The advantage of the kinematic method is that a downstream boundary condition is not required which results in a much simpler and faster numerical scheme.

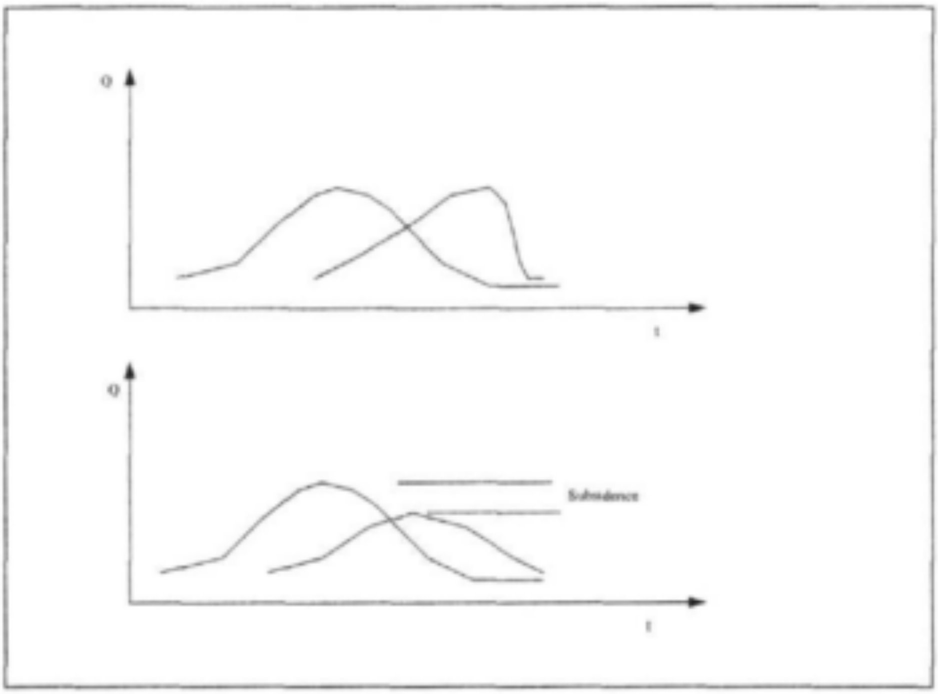

Figure 2.2.1(a) : Flood waves in a channel (after Henderson, 1966)

Henderson (1966) showed that the last two terms (acceleration terms) are generally an order of magnitude smaller than $\partial y / \partial x$. Stephenson and Meadows (1986) demonstrated by manipulating the terms in the momentum equation, that the acceleration terms are often insignificant or cancel each other out. A direct application of the kinematic routing methods must be done with caution as flood waves do exhibit attenuation as they travel along a channel.

The kinematic routing method has found use in routing excess rainfall overland off catchment surfaces. Overland flow is characterised by shallow water depths and relatively steep catchment slopes. Stephenson (1981) showed that the term $\partial y / \partial x$ is at least an order of magnitude smaller than the ground slope S_o. In a catchment, the flow depth may vary by a few millimetres over a length of 100 m while the elevation can vary by a meter or more over the same length. Various investigators have examined the conditions for which the kinematic method can be applied. Woolhiser and Ligget (1967) used a dimensional flow number:

$$k = \frac{S_o L}{Y_o Fr_o}$$

where L is the flow length of a uniform rectangular plane subject to steady rainfall, y_0 is the equilibrium flow depth at the downstream end of the plane, and Fr_0 is the corresponding

Froude number. A value of k > 10 was considered by Woolhiser and Ligget (1967) to provide a good approximation to the full hydrodynamic equations. Holden (1993), determined k values well in excess of the limit of 10 for typical roughness and slopes for a 100 m long plane with 50 mm/hr excess rain. The large k values corresponding to steep slopes and small flow depths typical of overland flow planes. Ponce et al (1978) arrived at the same conclusions for the selection of kinematic and diffusion models.

The solution to the kinematic routing equation can be formulated by expressing the continuity equation in finite difference form using a Preissmann box scheme (Preissmann, 1961). Consider the computational cell on the x-t plane shown in **Figure 2.2.2(a)**. φ and Θ are weighting coefficients, and the subscripts 1, 2, 3, and 4 are used to represent the conditions at the corners of the computational cell. This results in the following equation;

$$Ce\frac{\varphi\left(Q_3-Q_1\right)+\left(1-\varphi\right)\left(Q_4-Q_2\right)}{dx}+\frac{\theta\left(Q_2-Q_1\right)+\left(1-\theta\right)\left(Q_4-Q_3\right)}{dt}=Ceq_L$$

where Ce is the average celerity for the computational cell. The above expression can be rearranged (Koussis, 1983) into the following form;

$$Q_4 = C_1 Q_1 + C_2 Q_2 + C_3 Q_3 + C_4 q_L \qquad (2.2.1)$$

where;

$$C_1 = \frac{\theta + \varphi Cr}{(1 + Cr) - (\theta + \varphi Cr)}$$

$$C_2 = \frac{Cr - (\theta + \varphi Cr)}{(1 + Cr) - (\theta + \varphi Cr)}$$

$$C_3 = \frac{\left(1 - (\theta + \varphi Cr)\right)}{(1 + Cr) - (\theta + \varphi Cr)}$$

$$C_4 = \frac{Ce\, dt}{(1 + Cr) - (\theta + \varphi Cr)}$$

where Cr is the Courant number = $\frac{Ce\Delta t}{\Delta x}$.

The solution to the above set of equations has been investigated for a variety of combinations of φ and θ. The parameter φ controls the stability of the numerical scheme and θ the dispersion.

2.2.2 Muskingum-Cunge routing

The Muskingum-Cunge routing method is a compromise between computational effort, accuracy and the representation of attenuation or diffusion. The method has found wide acceptance in runoff and drainage systems models (Koussis, 1983; Holden, 1993; Coleman and Stephenson, 1993; Price and Mance, 1978).

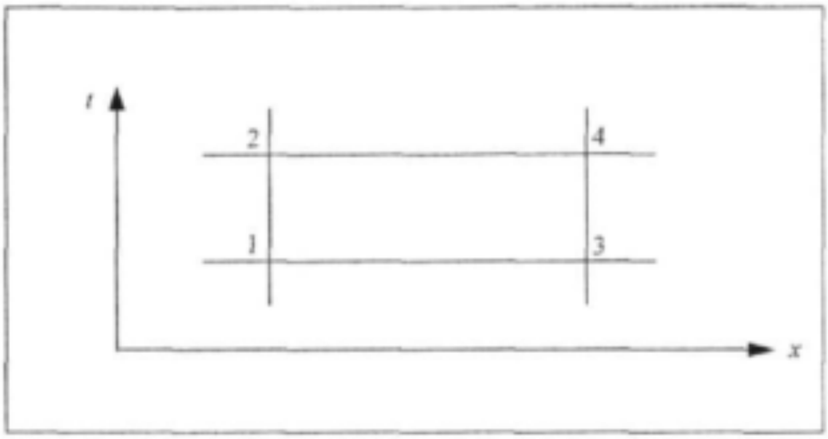

Figure 2.2.2(a) : Computational cell

Koussis (1983) and Cunge (1969) carried out a Taylor expansion for the numerical scheme given in the above equation of the grid function Q around the point 1 of the computational cell up to second order accuracy. This leads to an equation of the form;

$$\frac{\partial Q}{\partial t} + Ce\frac{\partial Q}{\partial x} = D_n \frac{\partial^2 Q}{\partial x^2} + q_L Ce$$

where the *numerical diffusion coefficient* D_n (m^2/s) *is given by;*

$$D_n = \frac{Ce\Delta x}{2}\left[(1 - 2\theta) + Cr(1 - 2\varphi)\right]$$

The form of the above equation is similar to the advection-diffusion equation that can be derived from the non-inertia simplification of the momentum equation. The advection-diffusion equation is;

$$\frac{\partial Q}{\partial t} + Ce\frac{\delta Q}{\delta x} = D_h \frac{\partial^2 Q}{\partial x^2} + Ce\, q_l$$

where D_h (m^2/s) is the physical diffusion coefficient given by $Q/2TS_f$, where T (m) is the top width of the flow. The crux of the Muskingum-Cunge routing approach is to equate the estimate of the numerical diffusion coefficient D_n to the physical diffusion D_h. This results in;

$$\frac{Q}{2TS_f} = \frac{Ce\Delta x}{2}\left[(1 - 2\theta) + Cr\,(1 - 2\varphi)\right]$$

and solving for θ gives;

$$\theta = \frac{1}{2}\left[1 - 2Cr\left(\varphi - \frac{1}{2}\right) - \frac{Q}{T\Delta XCeS_f}\right] \qquad (2.2.2)$$

The use of $\varphi = 0.5$ in the above set of equations results in the standard Muskingum routing formulation for rivers. The value of θ is however kept constant for a particular reach and is determined from input and output hydrographs. Ponce (1986) compared Muskingum-Cunge approach applied to the routing of overland flows to the more traditional kinematic routing methods. He found that for the overland system analysed, the method had better convergence properties than the traditional explicit methods and the simulations were independent of grid size. Similar results were found by Holden and Stephenson (1988) for overland flow planes. Weinmann and Laurenson (1979) found for channels that the Muskingum-Cunge routing method performed well when compared to the solution to the full dynamic model if the parameters are chosen correctly. Holden (1993) carried out extensive testing of the numerical stability and diffusion characteristics of the Muskingum-Cunge formulation. The most successful scheme was found to be with $\varphi = 0$ and allowing θ to vary according to equation 2.2.2. This results in the following set of equations for the coefficients of equation 2.2.1 and for θ.

$$C_1 = \frac{\theta}{(1 + Cr - \theta)}$$

$$C_2 = \frac{Cr - \theta}{(1 + Cr - \theta)}$$

$$C_3 = \frac{(1 - \theta)}{(1 + Cr - \theta)}$$

$$C_4 = \frac{Ce\Delta t}{(1 + Cr - \theta)}$$

$$\theta = \tfrac{1}{2}\left[1 + Cr - \frac{Q}{T\Delta X Ce S_f}\right] \quad 0 \le \theta \le 1$$

The above set of equations requires for their solution a representative celerity and flow for a computational cell. Holden (1993) examined two possible formulations for determining the average computational cell celerity <Ce> and flow <Q> viz.

$$\langle Ce\rangle = \frac{(Ce_1 + Ce_2 + Ce_3 + Ce_4)}{4} \qquad \langle Q\rangle = \frac{(Q_1 + Q_2 + Q_3 + Q_4)}{4} \tag{2.2.3}$$

$$\langle Ce\rangle = \frac{(Ce_1 + Ce_2 + 2Ce_3)}{4} \qquad \langle Q\rangle = \frac{(Q_1 + Q_2 + 2Q_3)}{4} \tag{2.2.4}$$

The formulation shown in equation 2.2.3, because of the unknown celerity and flow at point 4, requires an iterative solution. The formulation in 2.2.4 results in an explicit solution. Experiments by Coleman and Stephenson (1993) and by Holden (1993) found that there was little difference in the solutions between the implicit and explicit formulations for the cell celerity and flow. For the explicit formulation however an iterative solution has to be used for the first time step if the channel is initially dry, i.e. $Q_1 = Q_3 = 0$. In the case of channels there is an upstream inflow hydrograph to be routed, implying $Q_2 > 0$ for first time step.

2.3 Pollutant Routing

The methods that can be used to route pollutants through conduits and dams range from the completely mixed tank approach, through plug flow to the longitudinal dispersion equation. In the case where the two dimensional movement of pollutants is required to be modelled in a channel, a stream tube approach can be used or a two dimensional version of the longitudinal dispersion equation.

The choice of routing algorithms depends on the modelling objective, detail to which the flow routing is described by the hydraulic components of the model and the nature of the pollutant being modelled. The routing used in a controlled release scheme must account for the timing of the pollutant concentration in travelling from inlet to outlet of a river reach. The salinity related variables modelled can be considered conservative so entrainment, deposition and decay processes can be ignored.

The longitudinal dispersion equation is often used in conjunction with the flow routing equations to route pollutants down a river channel. The equation is given by:

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}=E\frac{\partial^2 C}{\partial x^2} \qquad (2.3.1)$$

where C (mg/ℓ) and U (m/s) are the cross sectional average values of the pollutant concentration and flow velocity respectively. E(m^2/s) is the dispersion coefficient.

There are simplifications of the above equation. These are the plug flow and completely mixed tank approaches. In the case of the plug flow equation the dispersion term is ignored and equation 2.3.1 reduces to:

$$\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}=0$$

In the completely mixed tank approach, the mixing of pollutants in the reach is assumed to be complete and instantaneous with the concentration in the water volume stored in the channel equal to the outlet concentration. A mass balance around such a channel leads to the equation:

$$\frac{d(VC)}{dt}=Qin\,Cin-QC$$

where V (m^3) is the volume of water in storage; Q (m^3/s) is the outflow rate and C (mg/ℓ) is the concentration in the storage and in the outflow from the tank, Qin (m^3/s) in the inflow rate and Cin (mg/ℓ) is the pollutant concentration in the inflow.

The completely mixed tank approach is used in HSPF, the plug flow in WITSKM/WITQUAL and the ISIS model solves a form of the longitudinal dispersion equation which includes a source and sink term. The ACRU model does not include the modelling of pollutants.

2.3.1 Comparison of Routing Methods

The application of the plug flow and completely mixed tank methods results in simpler and quicker numerical schemes but with some loss in accuracy. The results produced by these two methods will be compared to those produced by the dispersion equation to assess the extent of the loss in accuracy. The case of a slug of a conservative pollutant having a concentration of 100 mg/ℓ input into a 3,0 m wide and 500 m long rectangular channel is considered. The slug of dye is injected into the flow for 5 minutes. The flow case considered is steady uniform flow i.e. the flow velocity and cross sectional area are constant in space and time. This will simplify the analysis but still allow for meaningful conclusions to be made.

For the case described above, the dispersion equation has an analytical solution given by:

$$C(t)=\frac{C_o}{2}\left[erf\frac{(x-u(t-p))}{\sqrt{4D(t-p)}}-erf\left(\frac{x-ut}{\sqrt{4Dt}}\right)\right]$$

Where C_o is 100 mg/ℓ, p is the duration of the dye injection (5 minutes), and erf is the error function given by:

$$erf(z)=\frac{2}{\sqrt{\Pi}}\int_0^z \exp(-\varepsilon^2)\,d\varepsilon$$

Completely Mixed Tank Approach

For a constant volume V_o in the channel:

$$\frac{C_{t+\Delta t}-C_t}{\Delta t}=\frac{Q(C_{IN}-C_t)}{V_o}$$

$$C_{t+\Delta t}=C_t+\left[\frac{Q(C_{in}-C_t)}{V_o}\right]\Delta t$$

The concentrations at 500 m were predicted using the dispersion and completely mixed tank approach for flow rates of 3 m^3/s and 6 m^3/s. The flow velocities were 1,0 m/s and 2,0 m/s for a flow depth of 1,0 m. Dispersion coefficients of 5 m^2/s, 15 m^2/s and 30 m^2/s were used for each of the flow rates. The ratio of the predicted peak concentration C_m using the completely mixed routing method to the concentration C_d given by the dispersion equation at 500 m are listed in **Table 2.3.1(a)**. The completely mixed tank approach was applied with the whole channel length active as a single cell.

Table 2.3.1(a) : Ratio of C_m to C_d at 500 m

Flow (m^3/s)	Velocity (m/s)	Dispersion Coefficient (m^2/s)	C_m/C_d
3	1	5	0,47
		15	0,58
		30	0,72
6	2	5	0,71
		15	0,72
		30	0,72

The ratios listed in **Table 2.3.1(a)** shows that the completely mixed routing approach attenuates the incoming pollutograph substantially. The timing of the peak concentrations and the hydrograph shape is also not well predicted using the completely mixed approach. This is shown in **Figure 2.3.1(a)** for the case of a 3 m^3/s flow rate, velocity of 1,0 m/s and a dispersion coefficient of 15 m^2/s. The effect of modelling the channel reach as a series or cascade of completely mixed cells is also shown on **Figure 2.3.1(a)**. The greater the number of cells the closer the pollutograph approaches the pollutograph generated by the dispersion equation.

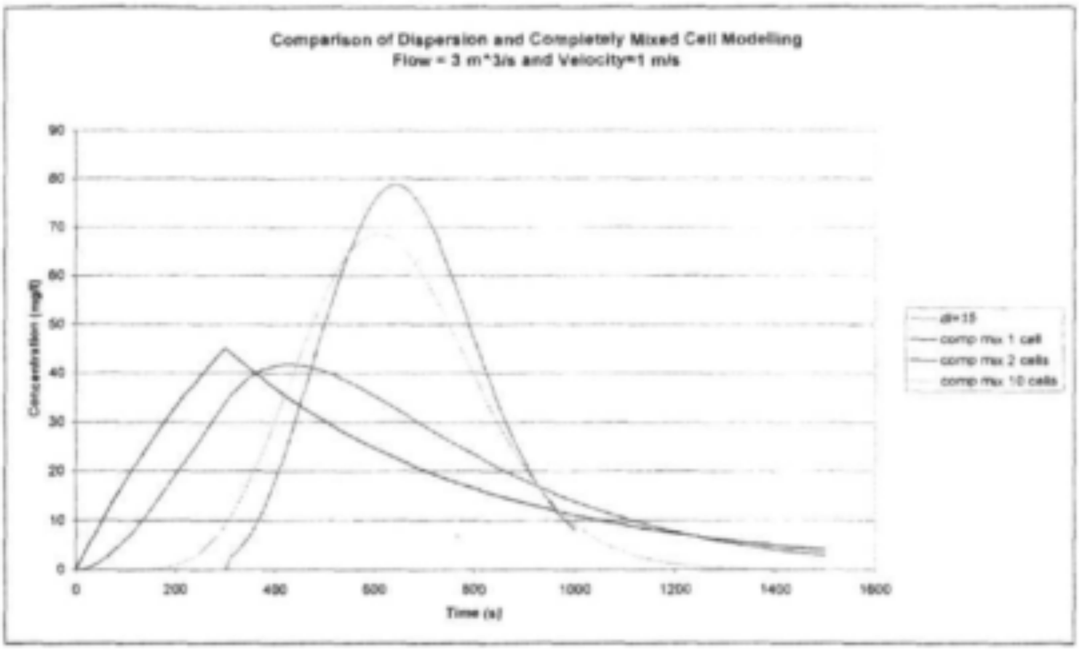

Figure 2.3.1(a) : Plot of pollutograph routed using the completely mixed and dispersion routing methods

Plug Flow

By ignoring the dispersion term, the plug flow equation is $\frac{\partial C}{\partial t}+U\frac{\partial C}{\partial x}=O$ where U (m/s) is the flow velocity, t (s) is time, x (m) is distance along the channel and y (m) is the flow depth. As the flow is steady uniform, the 5 minute duration slug of dye will maintain its shape as a plug and travel along the channel with the flow velocity U. A plot comparing the results of dispersion and plug flow routing for the 500 m long channel is shown in **Figure 2.3.1(b)**.

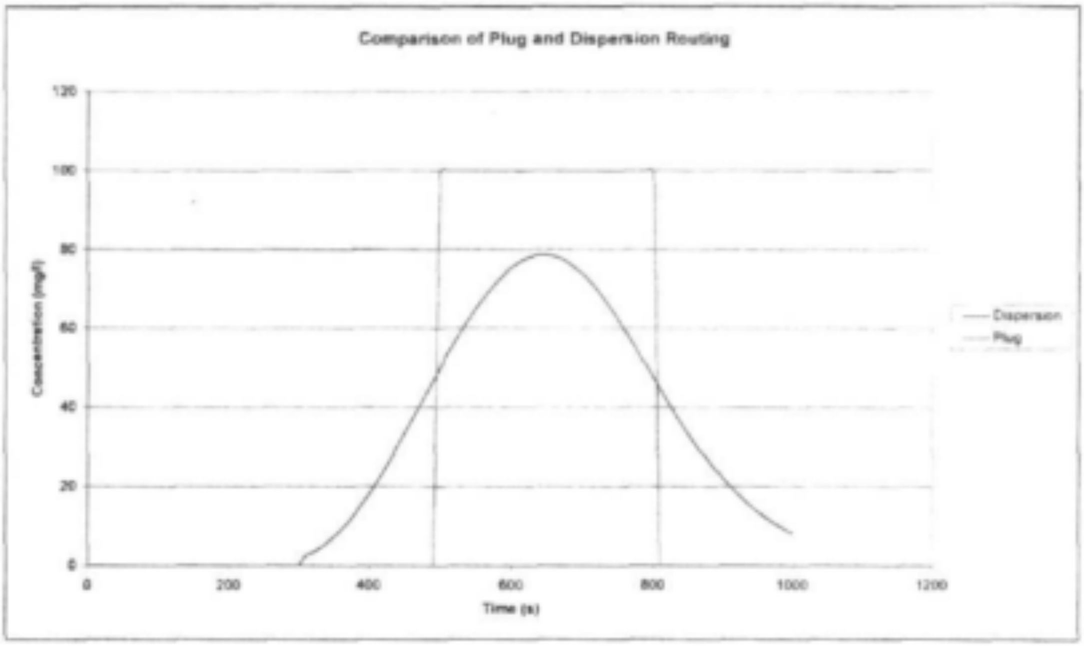

Figure 2.3.1(b) : Plot comparing dispersion and plug flow routing

The ratios of the routed peak concentration for dispersion (Cd) to that for plug flow (Cp) are listed in **Table 2.3.1(b)**. The results show that for high velocity and low dispersion coefficients, the plug flow routing method predicts the peak concentrations within 5% of the dispersion routing peak.

Table 2.3.1(b) : Ratio of C_P/C_D at 500 m

Flow (m^3/s)	Velocity (m/s)	Dispersion Coefficient (m^2/s)	C_p/C_d
3	1	5	1,04
		15	1,28
		30	1,58
6	2	5	1,01
		15	1,01
		30	1,03

A guide as to when the plug flow equation can be used can be developed by considering the Peclet number UL/D and the travel time (L/U) of a pollutant slug down a channel. The ratio of the peak concentrations for different travel times and Peclet numbers are shown plotted in **Figure 2.3.1(c)**.

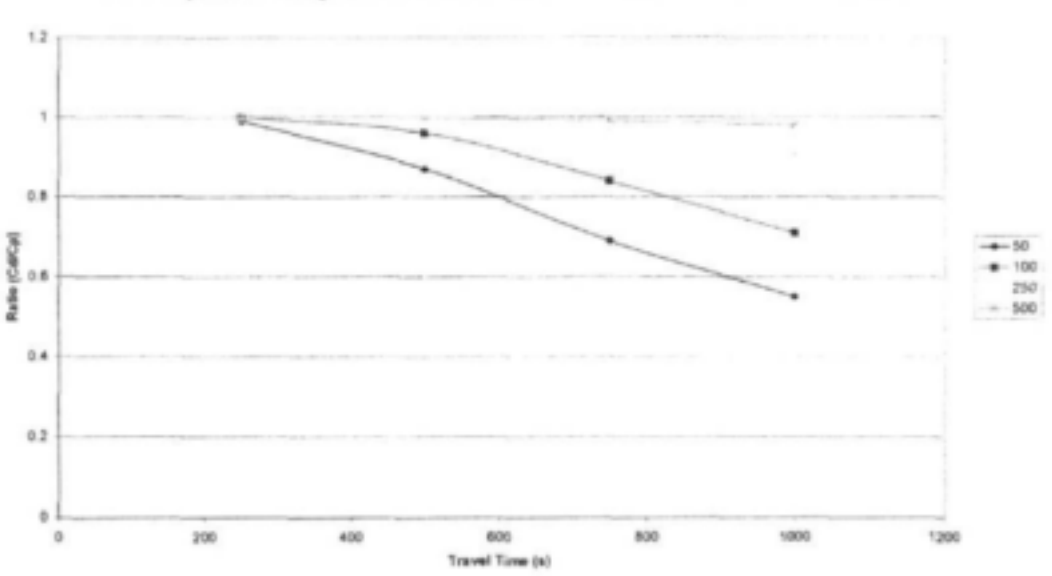

Figure 2.3.1(c) : Ratio of C_P/C_D for different Peclet Numbers (UL/D) and travel times (L/U)

2.4 Discussion of suitability of available models

2.4.1 HSPF

HSPF is a comprehensive water quality and quantity model. The model is essentially a daily time step model although the model can run at a smaller time step. HSPF has a number of modules, which can be used to address a particular problem. The main modules are summarised in **Table 2.4.1(a)**.

Table 2.4.1(a) : Description of main modules in HSPF

Module	Description
PERLND	Simulates a pervious land segment – includes water budgeting, erosion/sedimentation, quality parameters such as pesticides, nutrients and conservation elements
IMPLND	Simulates an impervious land segment – includes water budgeting, erosion/sedimentation and pollutant washoff
RCHRES	Simulates a free-flowing reach of mixed reservoir – includes modelling of hydraulic behaviour, advection of pollutants, both conservation and non-conservative.

The modelling of the routing of pollutants in the river reaches is done using the completely mixed tank approach. The hydraulic routing down rivers is done using kinematic routing where the relationship between outflow rate from the reach and volume of water in the reach is specified as table which is input to the model. The Manning equation can be used to determine depth-flow and hence volume relationship for a reach. The reaches are assumed to be prismatic. The routing techniques are adequate if the rivers are divided into a sufficient number of reaches to ensure accurate modelling.

The mine releases can be represented as a point source input into the reaches but will have to be stored as a time series in the HSPF database. The problem is the input of mine release volumes and concentrations into the database from the controlled release software.

HSPF uses the WDM database system developed specifically for handling time series data. At the time of evaluating HSPF, access to the database was by means of a set of FORTRAN routines or use could be made of the program ANNIE. The GENSCN and BASINS3 interfaces have since been developed. However the problem of easy data access to the WDM database system to obtain the necessary input for CE-QUAL-W2 was considered by the project team to be to onerous to further consider the use of HSPF for controlled release.

2.4.2 ACRU

The ACRU model has been developed by the Department of Agriculture at the University of Natal in KwaZulu-Natal. The emphasis of the daily time step ACRU model lies in the modelling of the rainfall-runoff processes on catchments and irrigation scheduling. The model parameters have been linked to soil types and a menu system has been developed to select the catchment soil types and hence the model parameters. The Muskingum Cunge routing technique is used in ACRU for the routing of flows. The ACRU model however has no water quality component. In particular the routing of pollutants is not considered in the model. The use of ACRU was therefore not considered. The model was used to assist with the patching of the flow records in this project.

2.4.3 WITSKM/WITQUAL

The WITSKM/WITQUAL modelling package was developed to model rainfall-runoff and washoff from urban areas. The model includes water budgeting for pervious and impervious areas and the washoff pollutants from catchment surfaces as well as flow and pollutant routing in trapezoidal channels and pipes. The pollution routing used in the model is plug flow while Muskingum-Cunge routing is used as the flow routing technique. The author, TJ Coleman, is familiar with the code and was able to extract the necessary routing subroutines from the code for use in the development of the Decision Support System for Controlled release.

2.4.4 ISIS

ISIS is used for modelling steady and unsteady flows in networks of open channels and flood plains. The model is sold under licence from Halcrow and HR Wallingford Ltd. An annual licence fee which includes support has to be paid. The flow rating algorithms offered in the model are a solution of the full St Venant equations, Muskingum and Muskingum Cunge routing. If the full dynamic routing is used, a set of cross sections are input to the model at appropriate points in the river system. Ideally information on the bridges and culvert crossings should also be input. The data input is large but the effort need only be expended at the start-up.

The user interface is "user friendly" and written for the Windows operating system. The program has extensive output graphics showing hydrographs, pollutographs, flow depths and long sections of the stream. The program has the ability to export simulation results to text files which could be input to the dam model.

A definite possibility, although the annual licence fee (~R40 000) and the need to use the software developers for program adaptation made the use of this program unattractive for the controlled release application.

2.5 Calibration of Catchment Model

The positions of the gauging weirs and mine discharge points in the Witbank Dam catchment are shown in **Figure 2.5.1(a)**. The project aim was to set up a catchment model and to carry out a preliminary calibration of the model. The model results being used as input to the CE-QUAL-W2 model of the dam. As the routing component of the model is the most important, use was made of the measured flows and sulphate concentrations at the weirs for use in the model. The period for which all the gauges had flow records is from 1 January 1991 to 22 February 2000. Not all the catchments such as the Boesmanskransspruit, Tweefonteinspruit and the Rietspruit have a history of measured flows except for the period 1997/98 to 1999/2000 when a daily flow reading was taken for the release scheme. In these cases, the average daily flow rates were modelled using ACRU for the period 1 January 1991 to 22 February 2000. Some level of calibration was achieved by using the measured values taken for the release scheme.

There is limited water quality data available at the gauges. Prior to the release scheme, grab samples were taken at a time period of between one week to four weeks. During the release scheme a daily sampling interval was introduced during the summer release period. This information was used to calibrate the pollutant routing algorithms used in the model.

The calibration was checked against the flow rates and sulphate concentrations measured at the Wolwekrans weir. A scatter plot of observed versus simulated flow rates for the period January 1991 to February 2000 is shown plotted in **Figure 2.5.1(b)** and a time series of simulated and observed flows in **Figure 2.5.1(c)**. The plots show that the model under-simulates the measured flood peaks. This is due to the measuring capacity of the flow gauging stations being exceeded. The capacity of B1H020 on the Koringspruit was frequently exceeded.

The calibration of the pollutant routing algorithms was checked at Wolwekrans weir. A plot of the full time series of observed and simulated sulphate concentrations covering the period November 1997 to February 2000 is shown in **Figure 2.5.1(d)**. For clarity, the complete time series shown in **Figure 2.5.1(d)** is divided into two series shown in **Figure 2.5.1(e)** and **Figure 2.5.1(f)**.

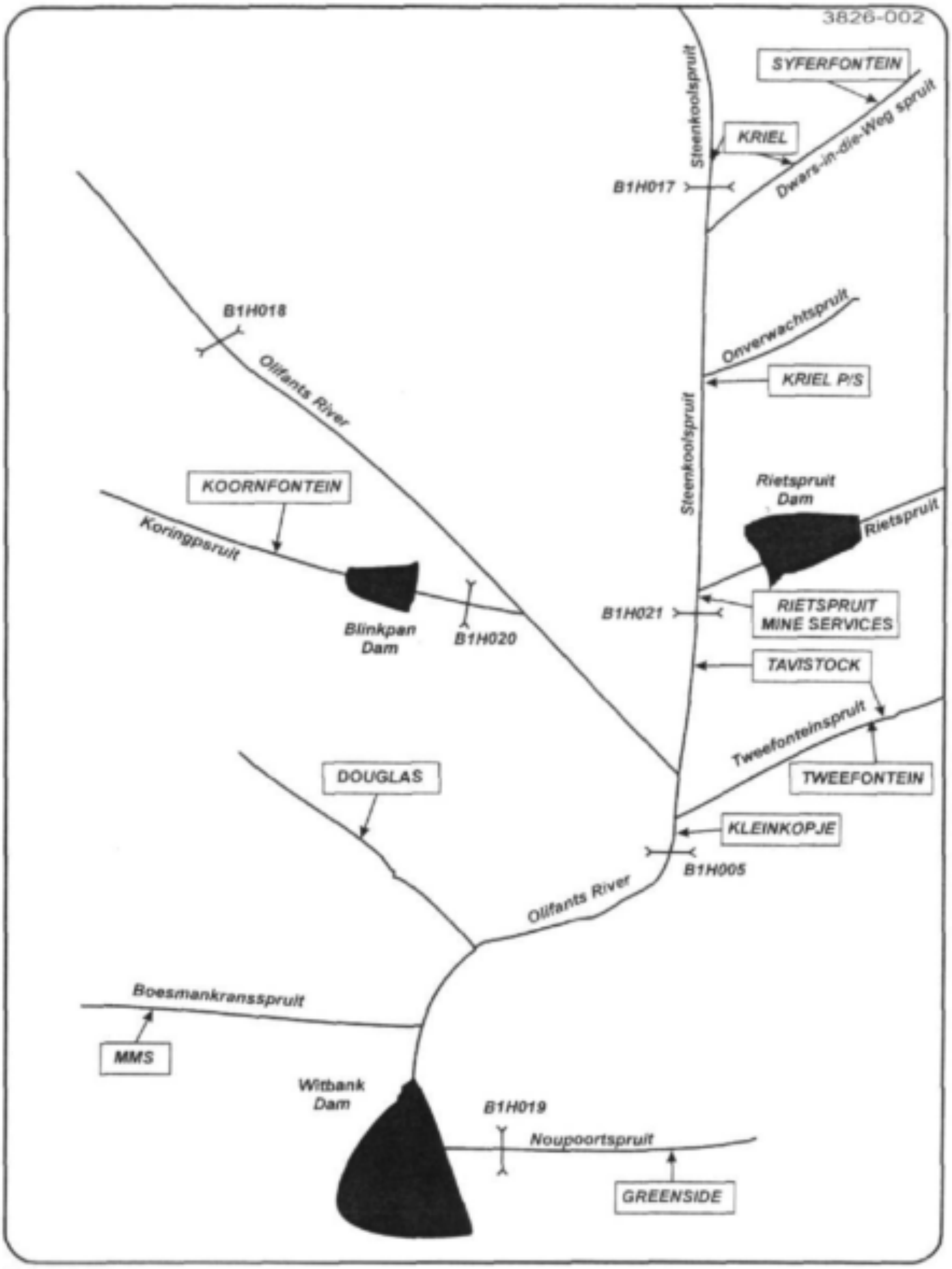

Figure 2.5.1 (a) : Witbank Dam Catchment - Mine and weir locations

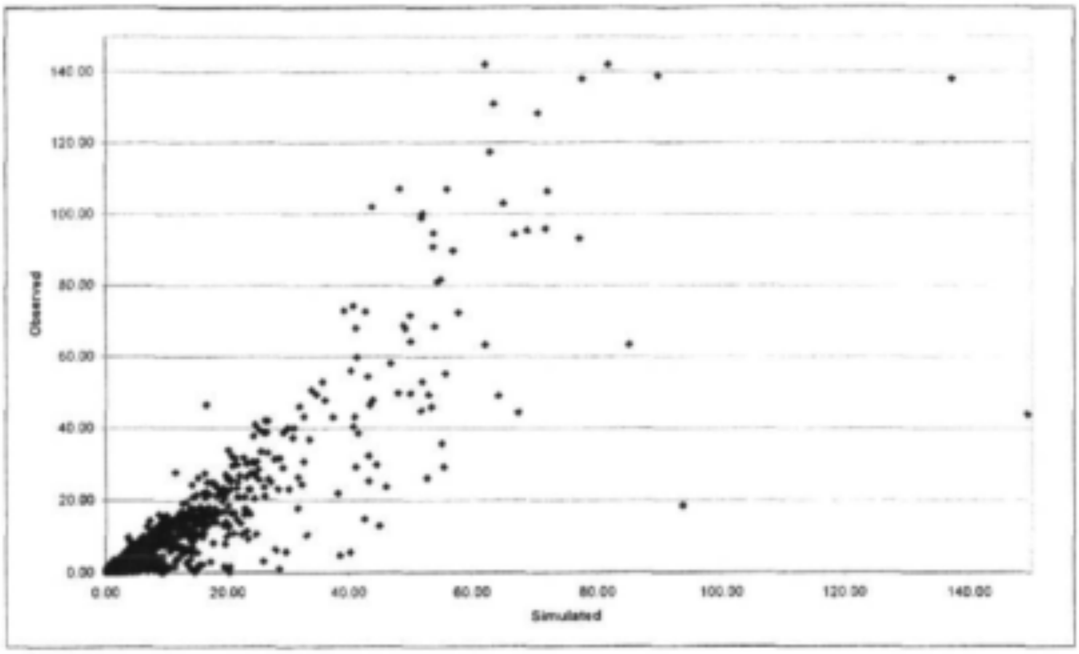

Figure 2.5.1(b) : Scatter Plot of Simulated and Observed Flows at Wolwekrans Weir

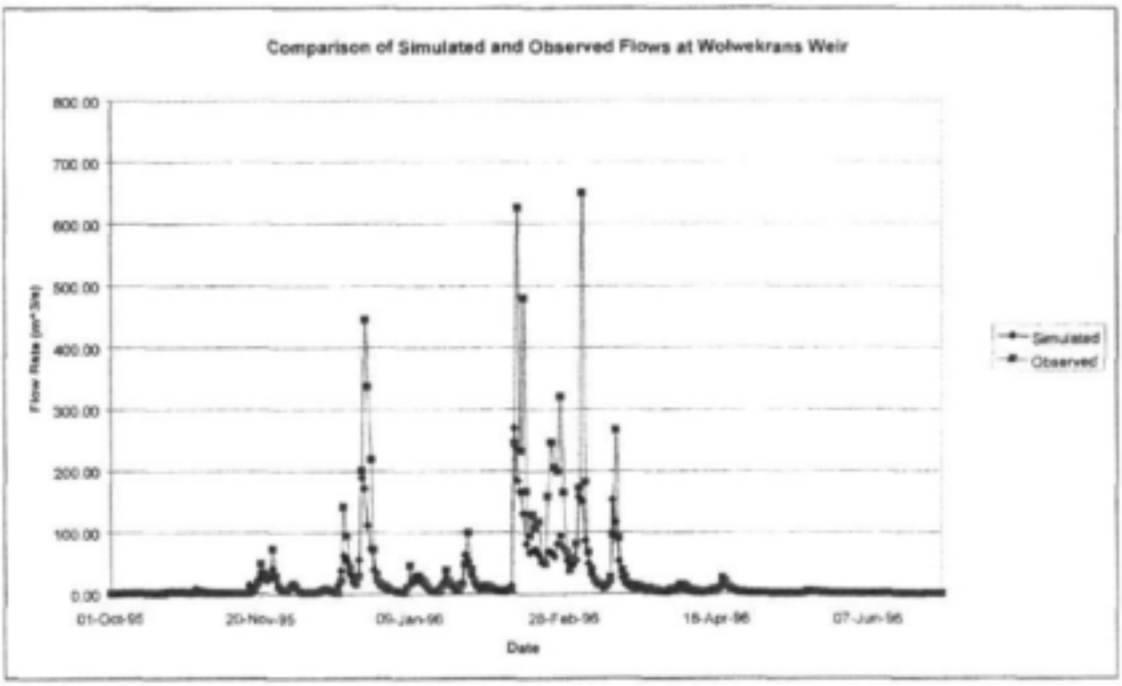

Figure 2.5.1(c) : Comparison of Simulated and Observed Flows at Wolwekrans Weir

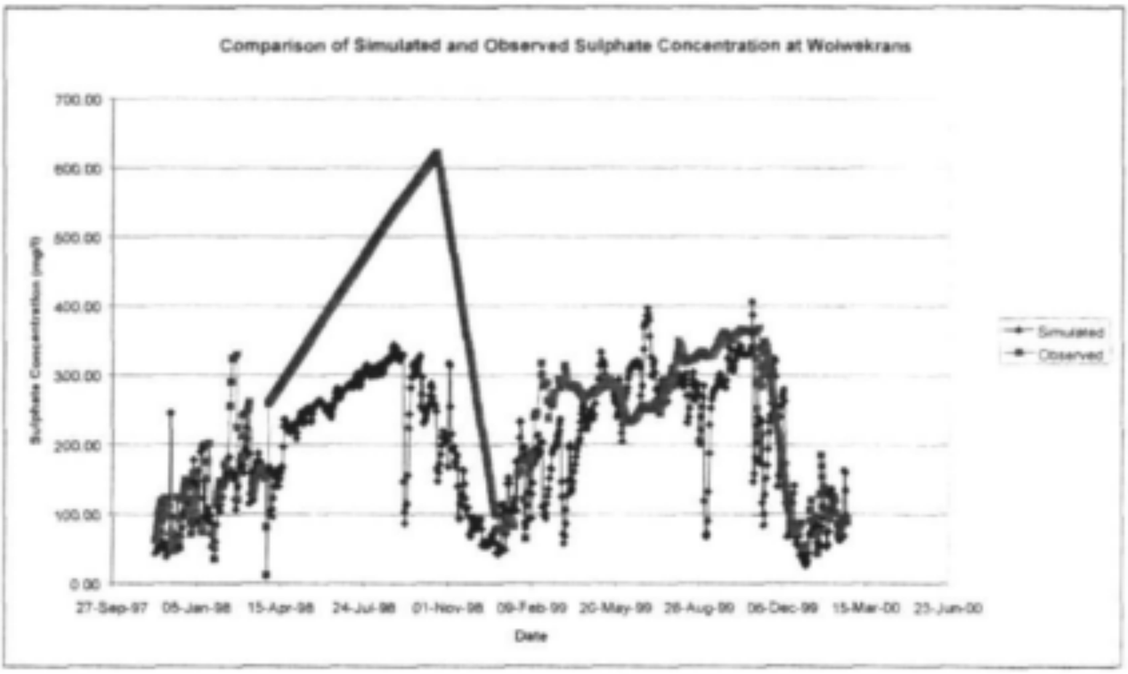

Figure 2.5.1(d) : Comparison of Simulated and Observed Sulphate Concentration at Wolwekrans weir

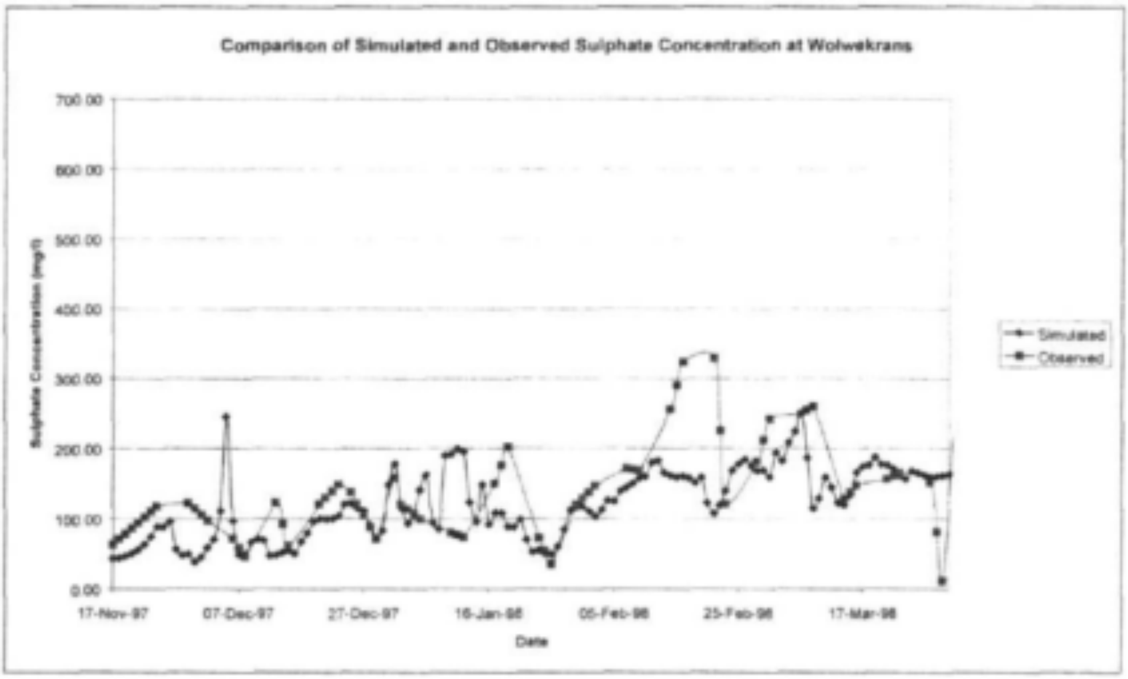

Figure 2.5.1(e) : Comparison of Simulated and Observed Sulphate Concentration at Wolwekrans weir (November 1997 to April 1998)

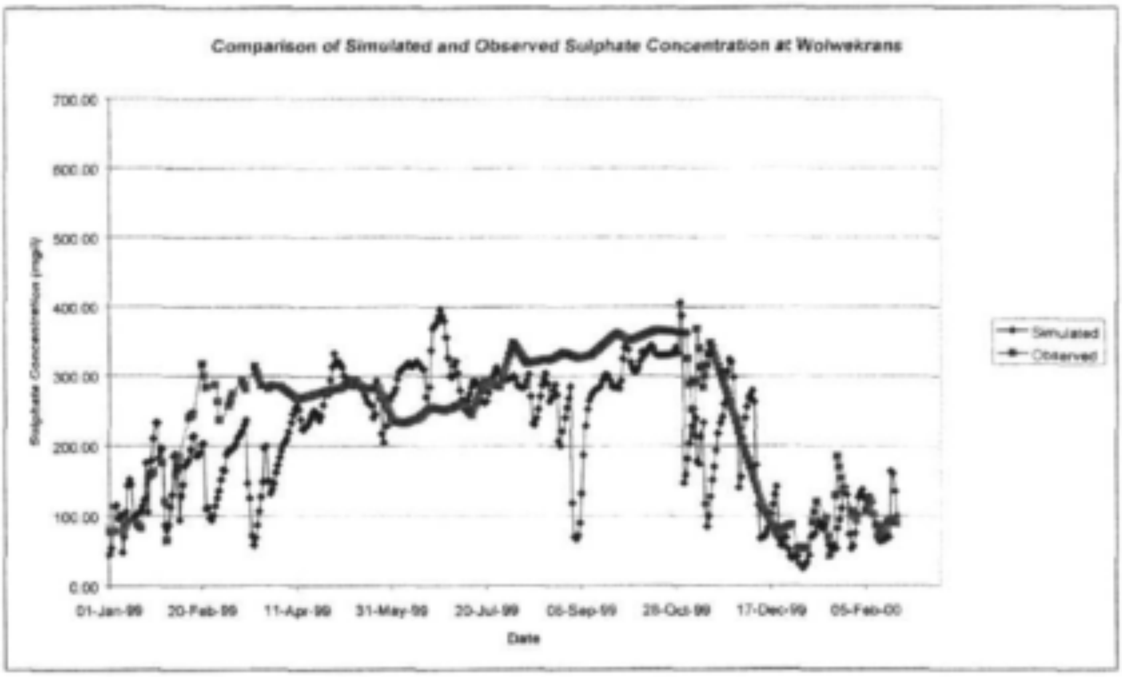

Figure 2.5.1(f) : Comparison of Simulated and Observed Sulphate Concentration at Wolwekrans (January 1999 to February 2000)

The calibration runs showed that the flow routing algorithm could adequately predict the timing of the flow rates at the Wolwekrans weir. The simulated flow rates generally underpredicted the observed at Wolwekrans weir. The extent of the underprediction is greatest during the high flow rates when the capacities of the upstream weirs are exceeded. Consideration must be given to extending the rating curves of these weirs to allow better predictions of the high flow rates to be made. Overall the Muskingum Cunge routing method was shown to perform adequately for the routing of flows. The method was found to be quick and requires relatively few input parameters.

The pollutant routing was not as effective as the flow routing. The routing was able to predict the changes in sulphate concentrations at the Wolwekrans weir during the summer flow months. The model did not predict the changes in concentrations as well during the low flow period as for the higher summer flow situations. However, given the space data available and that much of the data had to be gap filled for input to the routing algorithms, the pollution routing approach is considered adequate. Also the most important period in terms of controlled release is the summer rainfall period when the routing performed the best.

2.6 Investigation into Local Impacts

2.6.1 Introduction

A controlled release scheme is similar to controlling an industrial process. Information has to be collected on the system variables so that a decision can be made as to how to adjust the system inputs (mines and power station discharges) to maintain the system performance indicators at the required level. The system variables are the flow and water quality parameters, which in the case of the Witbank Dam release scheme is sulphate. The performance indicator is the sulphate concentration in the system.

To successfully manage the releases a set of compliance points and control points have to be selected. The compliance points are used to measure the performance of the release scheme while the control points are use to collect information to control the system. In the case of the Witbank Dam scheme, the compliance and control points are the same. The control points are at the outlet of the management units in the upstream catchment and at three points in the dam. Target sulphate concentrations at the control points are used as performance criteria and to determine the waste load that can be released.

The two questions that immediately arise are :-

- How frequently must information on the system variables be collected to adequately represent their variation?
- How often does a decision on the releases have to be made to meet performance criteria?

These two questions were addressed by undertaking a detailed analysis of a portion of the Steenkoolspruit sub-catchment.

2.6.2 Frequency of Monitoring System Variables

To investigate the time step needed at which to collect flow and water quality information, use was made of 15 minute time step electrical conductivity (EC) and flow depth data collected at the B1H017 and B1H021 gauges on the Steenkoolspruit. The EC data was converted to sulphate concentration using regression relationships developed as part of the controlled release scheme. The time period covered by the continuous monitoring equipment was from March 1999 to February 2000. There are gaps in the time series data due to instrumentation malfunction and theft. The runoff event in March 1999 and those in December 1999 to February 2000 at B1H017 were used in the analysis. At B1H021 the events in the time periods March 1999 and November 1999 were used in the analysis. The time series are shown plotted in **Figure 2.6.2(a)** (B1H017) and **Figure 2.6.2(b)** (B1H021).

To investigate the effect of different sampling time steps, the 15 minute time series at the two gauges was used as a baseline time series. Three further time series were extracted from the baseline time series, assuming that the flow and EC were sampled at 6 hour, 12 hour and 24 hour time intervals. These extracted time series are shown plotted together with the baseline time series in **Figures 2.6.2(c)** to **2.6.2(f)** for B1H017 and **2.6.2(g)** to **2.6.2(j)** for B1H021.

The plots show that as the sampling time step increases, the match between the extracted and the baseline time series deteriorates. To further compare the effect of the different sampling intervals, the runoff volumes and sulphate loads were determined for each of the events at B1H017 and B1H021. The results are listed in **Table 2.6.2(a)**.

Table 2.6.2(a) : Comparison of Runoff Volume (million m^3) and sulphate load (t) for different sampling intervals

Sampling Interval	Volume (million m^3)	Sulphate Load (t)
B1H017		
March 1999		
Baseline	0,26	13,4
6 hrs	0,27	13,8
12 hrs	0,25	12,6
24 hrs	0,28	14,1
Dec 1999 – Feb 2000		
Baseline	20,1	633,9
6 hrs	19,5	617,7
12 hrs	20,7	653,6
24 hrs	11,9	515,4

Sampling Interval	Volume (million m^3)	Sulphate Load (t)
B1H021		
March 1999		
Baseline	0,95	68,87
6 hrs	0,96	69,54
12 hrs	0,99	72,82
24 hrs	1,00	69,95
November 1999		
Baseline	3,95	274,07
6 hrs	3,78	257,18
12 hrs	3,65	246,09
24 hrs	3,43	251,02

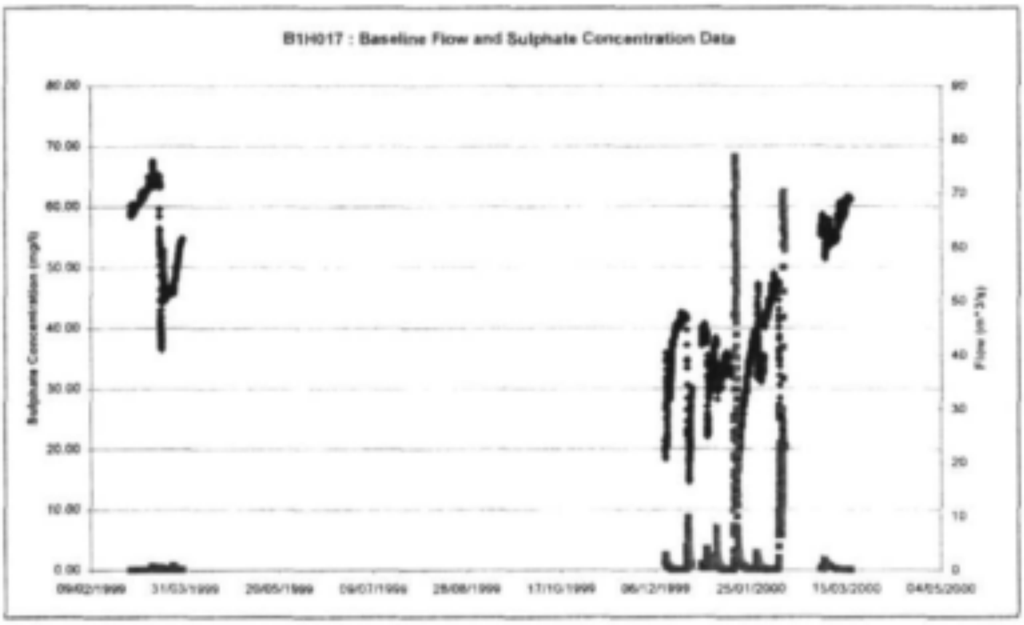

Figure 2.6.2(a) : Baseline flow and sulphate concentration time series for B1H017

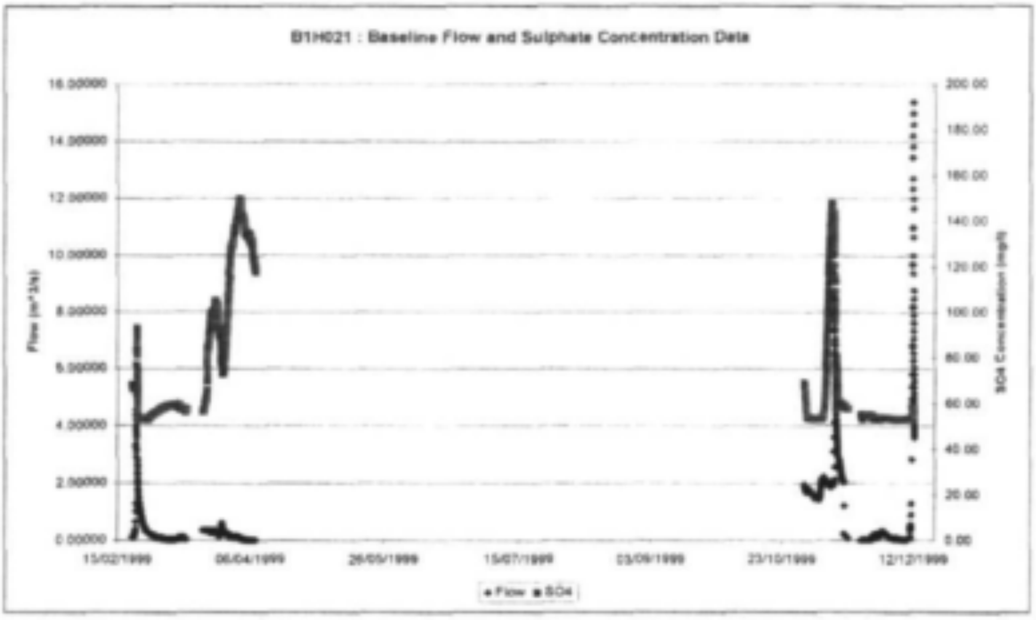

Figure 2.6.2(b) : Baseline flow and sulphate concentration time series for B1H021

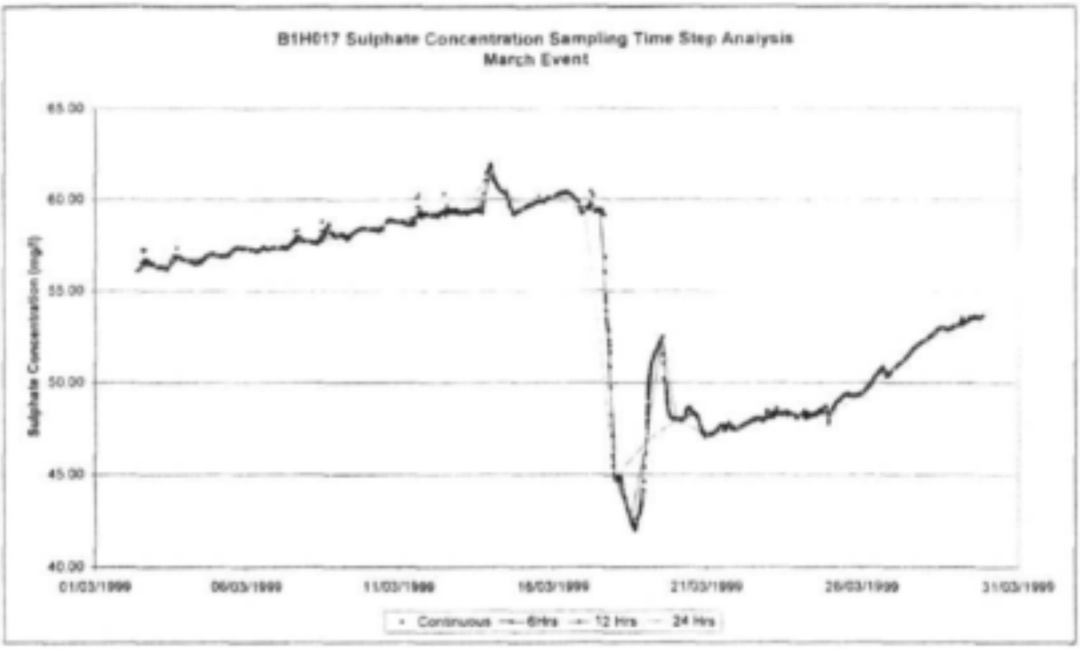

Figure 2.6.2(c) : Sampling Time Step Analysis for Sulphate concentrations for B1H017 for March 1999

Figure 2.6.2(d) : Sampling Time Step Analysis for B1H017 for sulphate concentration for events during the period December 1999 to February 2000

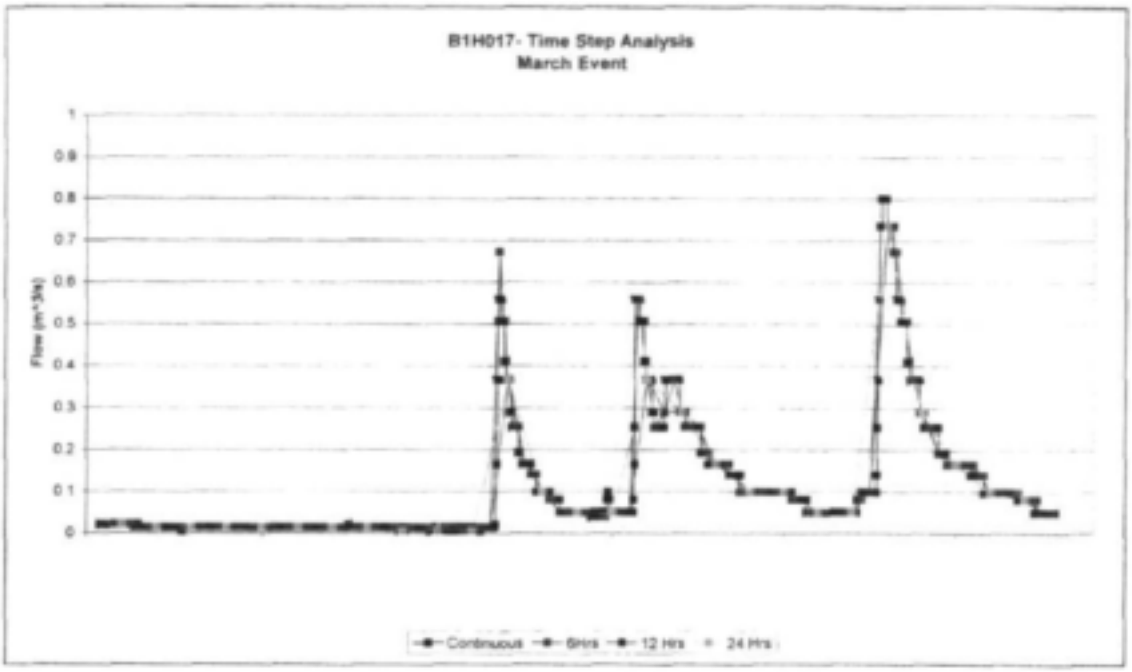

Figure 2.6.2(e) : Sampling time step analysis for flow at B1H017 for March 1999

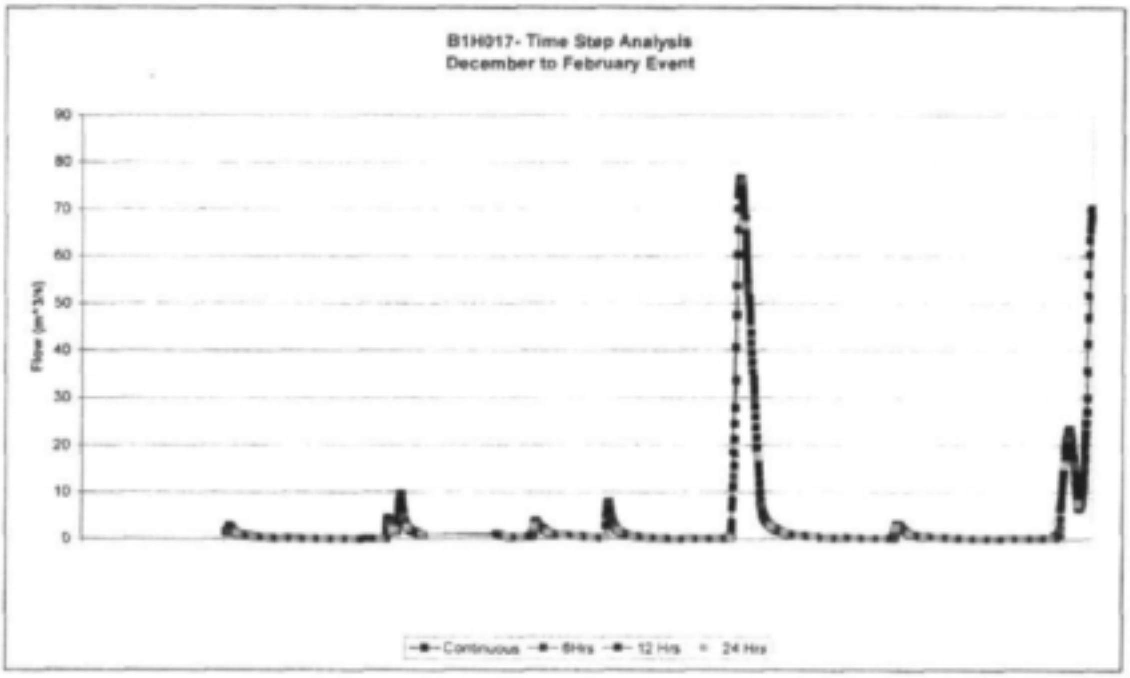

Figure 2.6.2(f) : Sampling time step analysis for flow at B1H017 for events during the period December 1999 to February 2000

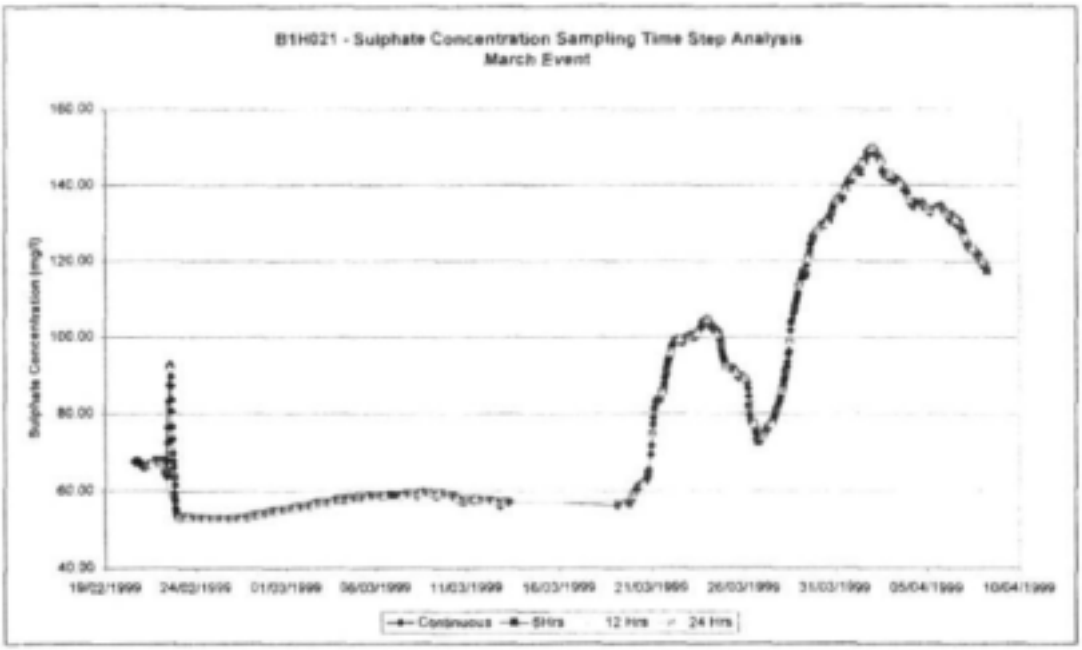

Figure 2.6.2(g) : Sampling Time Step Analysis for sulphate concentration at B1H021 (March event)

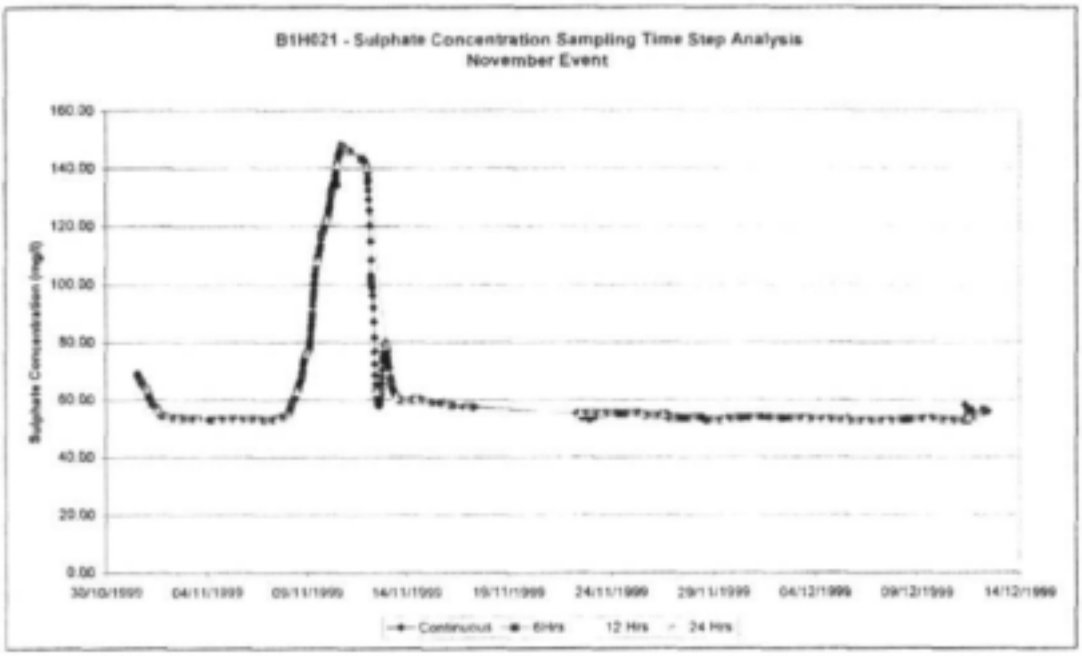

Figure 2.6.2(h) : Sampling Time Step Analysis for sulphate concentration at B1H021 (November event)

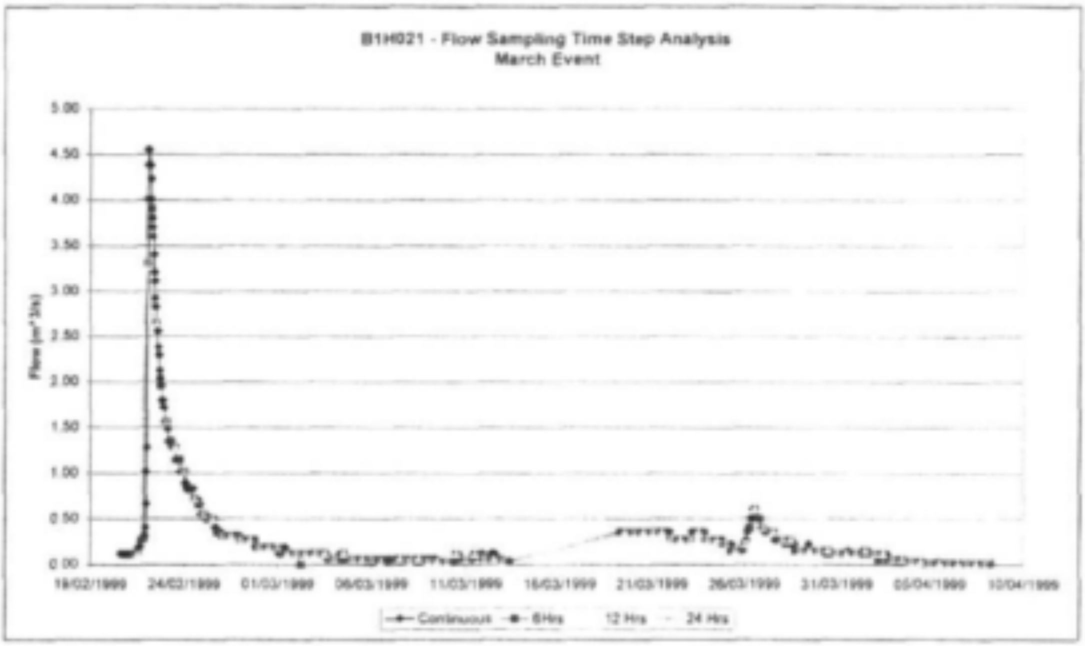

Figure 2.6.2(i) : Sampling time step analysis for flow at B1H021 (March event)

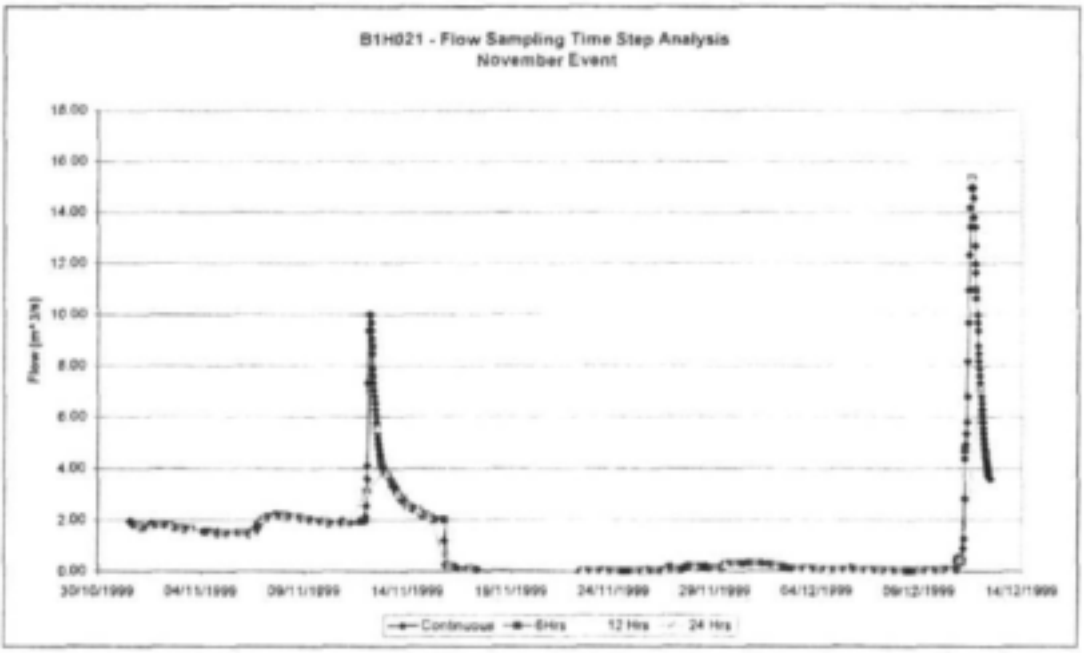

Figure 2.6.2(j) : Sampling time step analysis for flow at B1H021 (November event)

The results in **Table 2.6.2(a)** show that the 24-hour time step was the least accurate. The difference between the baseline and the other extracted series increases the larger the event. The percentage difference in volume for the event in March ranged from 3,8% to 5,3% at both gauges. However, for the December 1999 to February 2000 period, the percentage difference in volume at B1H017 ranges from 3% to 40% while at B1H021 for November the percentage difference ranges from 4,3% to 13%. The reasons for the discrepancy between the two gauges are that the volumes and loads at B1H017 for the November to February 2000 period are accumulated over a much longer time period than at B1H021.

2.6.3 Investigation of Decision Time Step

The decision time step is how frequently the releases are revised to achieve the performance criteria. Presently the mine releases are revised every 24 hours. The baseline 15 minute time series of flow rates and sulphate concentrations at B1H017 were used to investigate different frequencies of making decisions. The B1H017 gauge was selected ahead of the B1H021 gauge as the time series are not influenced by mine releases.

Two time steps viz a 6 hours and 24 hour decision making period were investigated. The releases were assumed to have been made from the Kriel Colliery situated adjacent to the B1H017 gauge. A target sulphate concentration of 140 mg/l and a concentration of 420 mg/l for the mine release were used to calculate the waste load and discharge volume that can be released. The waste load was assumed to be released at a constant rate over the decision making time step. A new set of sulphate concentrations were then calculated from the baseline sulphate concentration to include the release load. This new set of concentrations could then be compared to the target concentration to see the extent of the overshooting and undershooting for the two decision making time steps.

The results of the analysis are shown plotted for the two time steps and two events measured at B1H017 in **Figures 2.6.3(a)** to **2.6.3(d).** The plots show that better control is exercised with the 6 hour decision making time step with the frequency and the extent of the over and under shooting lower than for the 24 hour decision making time step. The undershooting occurs when there is an increase in the flow rate during the decision making time step. This results in an increase in the assimilative capacity and the target concentration not being reached. The overshooting of the target concentration occurs on the recession limb of the hydrographs. As the flow reduces the assimilative capacity reduces and if the releases are not adjusted to allow for this, the target concentration is exceeded.

2.6.4 Conclusions

The conclusions that can be drawn from this analysis are:

- The performance of a release scheme is sensitive to the decision time step. If a time step of 24 hours is to be used then a factor of safety should be built into the waste loads.
- To prevent overshoots on the recession limb, a projection of the end of time step flow based on the previous two time steps should be considered.

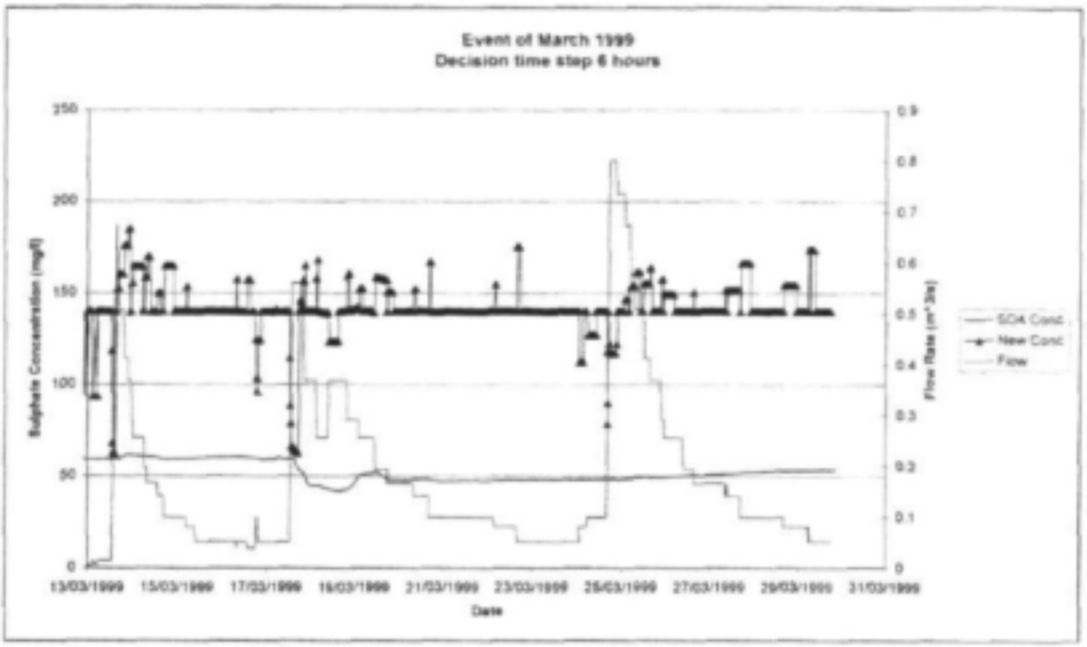

Figure 2.6.3(a) : Performance of a 6 hour decision time step for March event

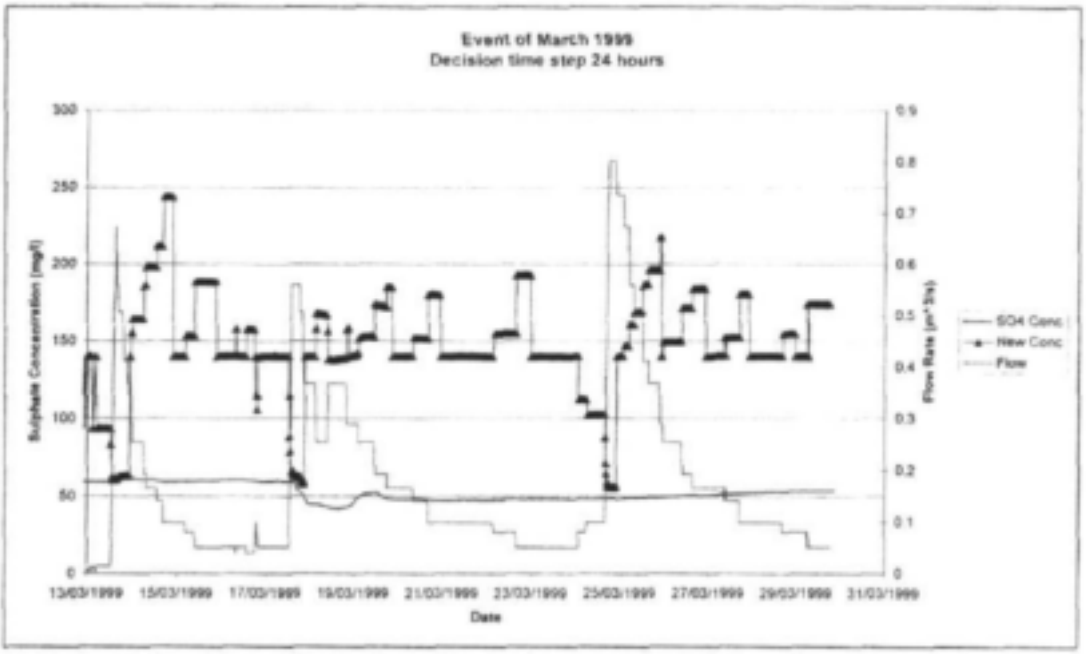

Figure 2.6.3(b) : Performance of a 24 hour decision time step for March event

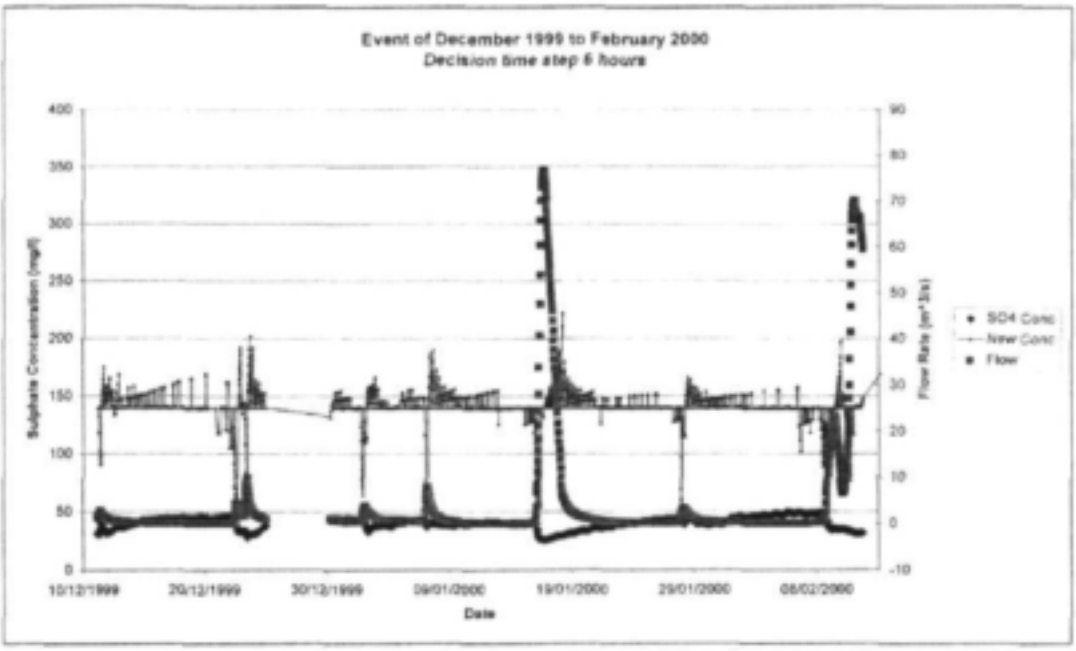

Figure 2.6.3(c) : Performance of a 6 hour decision time step for December to February event

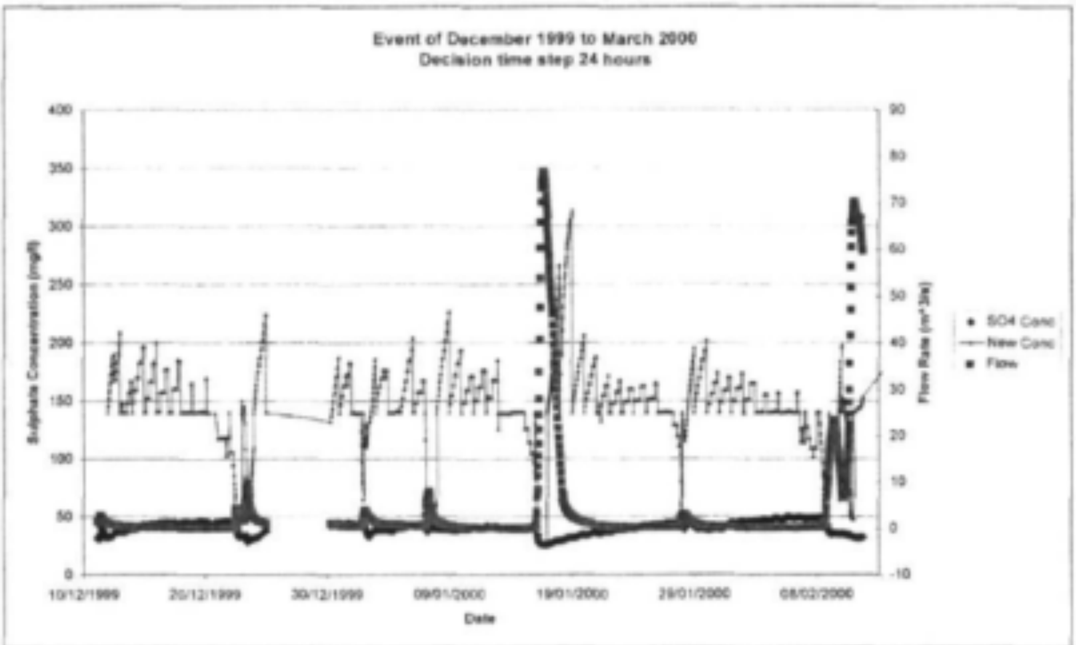

Figure 2.6.3(d) : Performance of a 24 hour decision time step for December to February event

3 CONFIGURATION AND CALIBRATION OF IMPOUNDMENT MODEL

3.1 Introduction to the CE-QUAL-W2 Hydrodynamic and Water Quality Model

CE-QUAL-W2 is a two-dimensional (2-D), laterally averaged, hydrodynamic and water quality simulation model (Cole & Buchak, 1993). The model is based on the assumption that the water body shows maximum variation in water quality along its length and depth. Therefore, the model is suited to relatively long and narrow water bodies that show water quality gradients in the longitudinal and vertical directions. The model has been developed and applied to reservoirs, lakes, rivers, and estuaries. The two-dimensional model simulates the vertical and longitudinal distributions of thermal energy (water temperature) and selected biological and chemical constituents in a water body with time.

The original version of the model was known as *LARM* (Laterally Averaged Reservoir Model) and developed in 1975 by Edinger and Buchak. The first application of the model was on a reservoir with a single main branch. Modifications to the model allowed for multiple branches and the ability to handle estuarine boundary conditions. Water quality simulation capabilities were later added by the Water Quality Modelling Group at the US Army Engineer Waterways Experimental Station in Vicksburg, Mississippi and was known as *CE-QUAL-W2* Version 1. Considerable modifications were made to the model to improve the structure of the code and decrease the data storage requirements. These modifications resulted in Version 2 of the model. The latest enhancements to the model include: dynamic adjustment of the time step, selective withdrawal algorithm, higher order transport scheme, and improved volume balance and mass balance algorithms (Cole and Buchak, 1993).

Features of the CE-QUAL-W2 model:

- The hydrodynamic routines predict the water surface elevations, velocities and temperatures. The heat exchange routine, in contrast to other hydrodynamic models, has modest input requirements.
- The water quality algorithms allow the simulation of up to 21 water quality constituents in addition to water temperature.
- The model has been modified so that simulations can be run over long time periods, which can extend up to ten years (to assess long-term trends in water quality).
- The ability of the model to simulate upstream and downstream head boundary conditions allows the use of the model for estuaries, or reservoirs in which the inflow volumes are unknown.
- The branching algorithm allows the model to be used in reservoirs, which have a complex layout such as dendritic reservoirs, or estuaries with multiple freshwater inflows. Selective withdrawal algorithms calculate the vertical extent of the withdrawal zone based on outflow velocity and water density.
- The water body may be configured using segments of unequal length and layers of unequal thickness. The model adjusts the location of the surface layer and upstream segment to account for a rising or falling water level.
- The model uses a variable time step algorithm, which ensures numerical stability even during extreme hydrological inflow events.

Model limitations include:

- The lateral averaging assumes that the variations in water velocity, water temperature and constituents across the width of a water body are negligible. In South Africa, this "limitation" has not influenced the application of the model to reservoirs.
- The availability of input data: This is often a constraint in the use of a hydrodynamic model where insufficient data are available for calibration.

CE-QUAL-W2 is distributed with documentation and a selection of case studies from the US. One of the most detailed case studies in South Africa is described in Görgens *et al.*, 1993 and Bath *et al.*, 1998. In South Africa, CE-QUAL-W2 has been used to provide information for the management of water resources and detailed water quality assessment:

- *Inanda Dam, Mgeni River.* The bulk supply reservoir experiences extended periods of stratification, sediment release of contaminants, and high algal growth. These factors have affected the treatment of water for domestic supply. The nutrient/algal interactions of Inanda Dam were simulated to provide information on: algal dynamics, draw off depth, sediment interactions, reservoir draw-down, reservoir hydrodynamics, and the phosphorus regime of the reservoir (Bath, *et al.*, 1998).
- *Vaal Barrage, Vaal River.* The salinity of the water body is governed to a large extent by saline tributary inflows and low salinity releases from the Vaal Dam. The hydrodynamic and salinity behavior of the Barrage was simulated to provide information on the influence of freshening releases, optimization of releases, and diversion canal options (Bath, *et al.*, 1998).
- *Vaal Barrage, Vaal River.* The calibrated version of the model was used to provide detailed information to guide the operation of the water body and minimize the water quality impacts on water treatment and downstream water users (Bath & Quibell, 1998; http://www-wrc.ccwr.ac.za/sanciahs/bath.htm).
- *Roodeplaat Dam, Pienaars River.* The reservoir shows pronounced thermal and chemical stratification for almost nine months each year. The model was used to simulate the thermal stratification and dissolved oxygen regime of Roodeplaat Dam. This information was then used to assess the influence of destratification on the nutrient/ algal regime of the impoundment (Bath, *et al.*, 1998).
- *Rooipoort Dam, Olifants River.* A reservoir is proposed to be constructed on the Olifants River at Rooipoort to supply potable water to Pietersburg, in the Northern Province. The model was used to provide preliminary information on the thermal stratification, hydrodynamic response, and salinity gradients within the reservoir. The information provided by the model was used to identify key water quality issues that include: location of the off-take tower, draw off depth, preliminary water treatment process design, and management guidelines for the upstream catchment (Ninham Shand, 1993b; Bath, *et al.*, 1998).
- *Laing Dam, Buffalo River.* During periods of low flow, Laing Dam receives drainage of high salinity from point and non-point sources. This gives rise to elevated salinity and density stratification within the reservoir. A simulation was performed successfully to determine the influence of low salinity transfers from the Kubusi River catchment on the receiving water quality behavior of Laing Dam (NS, 1993a; Ninham Shand, 1998).
- *Mearns Dam, Mooi River.* It is proposed that an impoundment be built on the Mooi River to divert water into the Mgeni River system. The model was used to investigate the time varying water quality in the impoundment, the influence of the hydrodynamic mixing conditions in the impoundment, and the impact on downstream water quality (Ninham Shand, 1996).

- *Fika Patso Dam, Nomahadi River.* W2 was calibrated for the bulk supply impoundment to provide detailed information on the possible influence of water quality on the treatment for potable use. The impoundment is one of the highest bulk supply impoundments in South Africa (situated just under 2000 metre above sea level). The model provided information, which was used in the design of the water treatment works, operation of the impoundment, and in the development of a management guide for the upstream catchment (Bath & Timm, 1993).
- *MetsiMatso Dam, Metsi Matso River.* Swartwater Dam is a highly eutrophic bulk supply impoundment. The water quality has become so degraded that the water treatment works was unable to meet the quality requirements for domestic use. W2 was used to guide the operation of the impoundment, and also in the development of a management guide for the upstream catchment (Bath & Timm, 1993).
- *Wriggleswade, Nahoon and Bridle Drift Dams.* The model has been used to investigate the eutrophication and hydrodynamic response of these bulk supply impoundments serving the water supply to the greater East London area (Ninham Shand, 1998).

3.2 Obtaining CE-QUAL-W2 source code

The project team obtained Version 2 of the CE-QUAL-W2 model, its supporting software and user manual from the Waterways Experimental Station of the US Army Corps of Engineers. In mid June 1998, Dr Bath had a series of meetings with the developers of the model in the USA. During these meetings, the latest source code was reviewed and discussed. Certain changes were made to the code to enhance the application for Witbank Dam. The source code was then compiled into an executable file and used to check for execution errors.

Version 3 of the model was released recently (mid 2000). The major enhancement has been the incorporation of sloping riverine sections that allows a user to integrate river, reservoir, lake and estuarine systems (Wells & Cole, 2000). It appears that the input file formats may not have changed that much between Version 2 and 3. In future, version 3 of the model could be used for Witbank Dam to assess the impact of the controlled release scheme on in-lake salinity and sulphate levels. However, Version 2 of the model would in the short to medium term be adequate for assessing the impact of controlled releases Witbank Dam.

3.3 Review of the latest CE-QUAL-W2 graphical user interface (GUI) software

One of early the tasks in the project was to review a number of graphical users interfaces developed to enhance the user-friendliness of the model. The objective of this task was to assess whether these interfaces could serve as the link between the catchment model and the reservoir model. The following user interfaces were reviewed and are summarized below.

W2_Post http://www.atsengineers.com/html/w2_post.html

Advanced Technology Systems Inc. developed a post processor for CE-QUAL-W2 that allows the user to view model results in animation for up to four parameters simultaneously. It also allows the user to view and compare vertical profile data to model results and view the grid in plan view, longitudinal profile and segment-by-segment sections. W2_Post is sold as a commercial product and sells for about $495 (mid 2000 price)

W2_Studio http://www.jeeai.com/w2studio.htm

W2 Studio is a suite of utilities developed by JE Edinger Associates, Inc. It consists of five modules, W2Control, W2Plot, W2Grid, W2Flow and W2Met. W2Control is an interface for editing CE-QUAL-W2 control files, launching the pre-processor and the model itself and creating the output database that is required for W2Plot. W2Plot is a module that generates 1-D and 2-D plots of simulation results with animation features. W2Grid is a tool for visualising and editing the bathymetry input file. It generates a plan view of the grid, a cross sectional view and a side view showing the layer heights and segment lengths. W2 Flow is a tool for formatting and visualising flow data published by the USGS and W2Met is a tool for processing meteorological data from various sources in the USA. W2_Studio are sold and a commercial product and individual modules can also be obtained from the developers.

AGPM http://www.loginetics.com/agpm.html

Loginetcs Inc. developed the Animation and Graphics Portfolio Manager (AGPM) post-processing software for displaying the model output from CE-QUAL-W2. AGPM lets the user build a series of plots using a WindowsTM interface for one simulation, and then efficiently reproduce all the same plots for subsequent simulations. It includes WIN2D that is a user-friendly interface for building CE-QUAL-W2 input files. Some of the plots included in AGPM are animation of distance-depth contours, vertical profiles at various times & locations, time-series at various depths and time-depth contours at a longitudinal location. AGPM is sold as a commercial software package and sells for about $895 (mid 2000 price). A copy of the AGPM program was obtained at a reduced cost and was used in the application of CE-QUAL-W2 to Witbank Dam for evaluation purposes and during the later calibration and scenario analysis phases of the project.

Witbank Dam user interface

A decision was made that the level of detailed required for this study did not justify the expense of purchasing a commercial GUI and then having to make major coding changes to customize it to serve as an interface to link the two models (if this was approved by the interface developers). Thus, it was accepted that the more effective route is to use a local programmer to develop simple graphical routines and to develop the interface with the two models. Ms J Tukker of Ninham Shand developed a prototype interface specifically for the Witbank Dam application that allows the user to run the model and to examine the models output in different formats. Many of the display options available in the commercial GUI's were incorporated in the Witbank Dam DSS but with very limited flexibility to add new simulation variables. The CE-QUAL-W2 model output is displayed as an animated time series of distance-depth contours, animated graphs of temperature and constituents for different vertical dam segments or horizontal dam layers. The interface also links the outputs from the catchment model to the inputs of the reservoir model.

3.4 Configuration of the CE-QUAL-W2 model for Witbank Dam

The CE-QUAL-W2 model was configured for Witbank Dam and it included:

- Meteorological data (wind speed/direction, air/ dew point temperature, cloud cover)
- Hydrology (inflow to reservoir, outflow, releases, and abstraction)
- Water quality (inflow, and in-dam data)
- Bathymetry of impoundment inundated area

3.4.1 Bathymetric representation

The bathymetric data is required to describe the geometry of the reservoir. The reservoir is conceptualised as a computational grid where each grid (or box) is described by its longitudinal spacing, its vertical spacing and the average cross-sectional width (Cole & Buchak, 1995).

The bathymetric data was set up using the sediment survey data and maps that was compiled by DWAF in 1983. ***Branch layout*** - Witbank Dam was configured as a single branch reservoir subdivided into a series of longitudinal segments and horizontal layers. **Figure 3.4.2(a)** shows the approximate boundaries of the segments as well as the location of the two tributaries, the Boesmankransspruit and the Noupoortspruit. Abstractions and discharges are from the dam wall. Abstractions to the Witbank water treatment works are through an abstraction tower situated at the dam wall. The tower has three outlets; the top situated at 1498.82m, the middle about 5m deeper at 1493.95m and the bottom most one about 9m deeper at 1484.81m. There is a scour outlet situated at 1481.96m through which compensation releases are made. The full supply levels for the dam is at 1502.69m and the bottom of the radial gates are at 1494.74m.

Segment layout – Witbank Dam was configured into 22 longitudinal segments (**Figure 3.4.2(a)**) that included the zero width upstream and downstream boundary segments (Segments 1 and 22). Each segment was about 1000m in length, although segments 2, 3 and 20 were about 2000m in length.

Layer configuration – The reservoir was further divided into horizontal layers at 2-meter intervals giving a total number of 22 layers that included the zero width surface and bottom boundary layers (layers 1 and 22).

Tributaries – The two tributaries were treated the same as unsimulated tributaries (point sources discharging) into segment 5 (Boesmankrans) and segment 12 (Noupoortspruit).

3.4.2 Time varying input data sets

The time varying (daily) input required to run CE-QUAL-W2 includes: temperature, quality and inflow of the main river and tributaries, starting conditions in the reservoir, meteorological data, inflow and outflow data. Complete input data sets were prepared for the period 1990 to about May 2000.

Hydrological data

A time series of inflows and outflows is required to account for the inflow and outflow of water at the upstream and downstream boundaries to the reservoir. Separate flow files were prepared for each inflow (Olifants River, Noupoortspruit and Boesmankransspruit) as well as each of the outflow components (downstream releases and spills and abstractions to the Witbank Municipal drinking water treatment plant).

Data for the inflowing and out flowing streams were obtained from the Department of Water Affairs & Forestry (**Table 3.4.2, Figure 3.4.2(a)**).

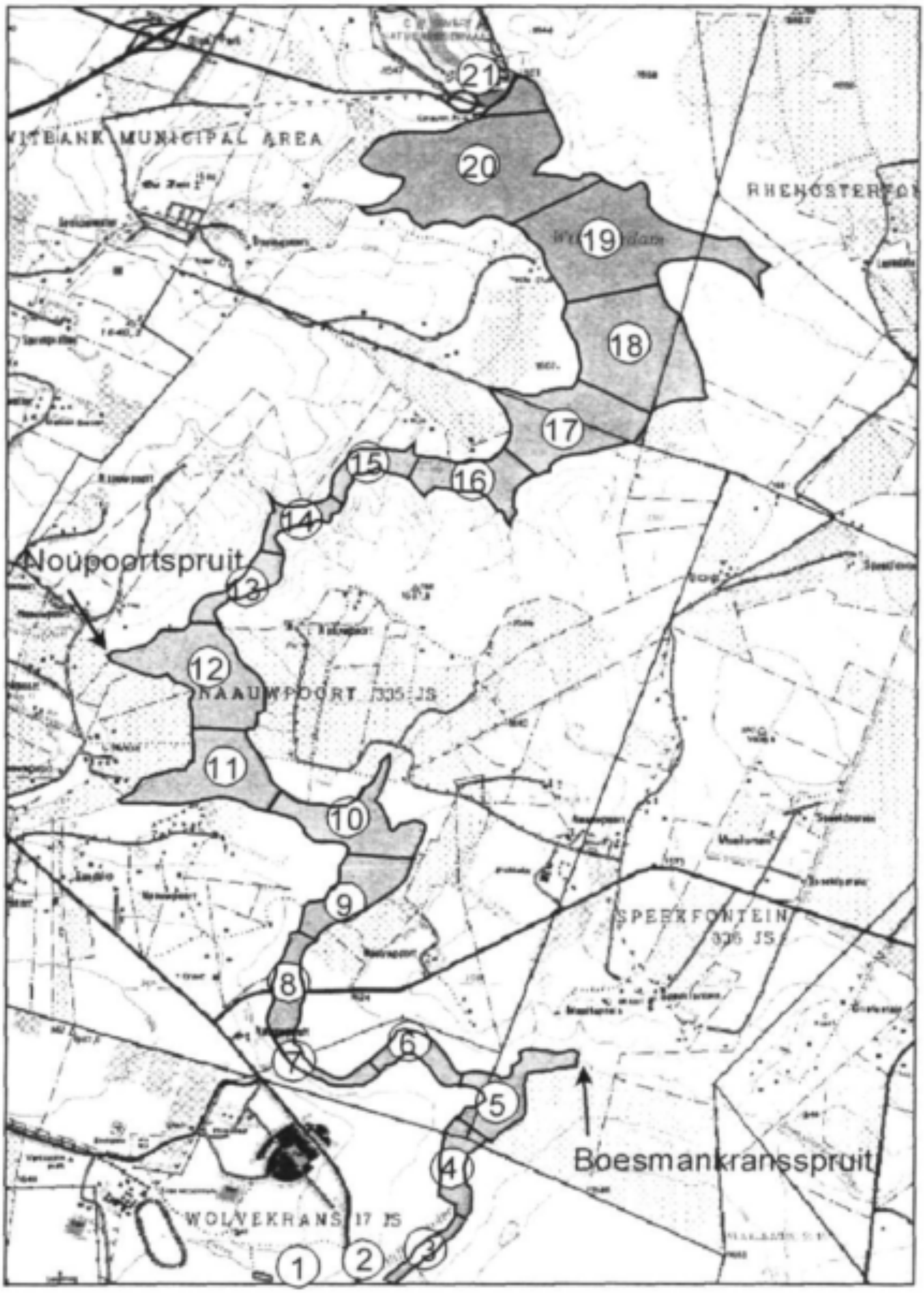

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Figure 3.4.2(a) Map of Witbank Dam showing the longitudinal segments used in the CE-QUAL-W2 reservoir model

Table 3.4.2 DWAF gauging stations used to derive the inflow and outflow time series for Witbank Dam

DWAF gauging station	Description
Inflows	
B1H005	Olifants River at Wolvekrans
B1H019	Noupoortspruit at Naauwpoort
B1H030	Boesmanskraalspruit below Middleburg mine
Outflows	
B1H007	Pipeline to the Witbank water treatment works
B1H010	Weir downstream of Witbank Dam
B1H011	Pipeline to Naauwport pump station (abstractions to the power stations were terminated in about June 1993)

Olifants River inflows - Average daily flows for the Olifants River were obtained for gauging station B1H005 (Olifants River at Wolwekrans). Little patching of the flow data was required.

Noupoort River inflows – The Noupoort is a small tributary that flows directly into Witbank Dam. In the original model application, an average daily inflow of about 0.07 m3 /s was assumed. For recent updates of the Noupoort inflow data set, flow data were obtained from DWAF for gauging station B1H019. No patching of the data was required.

Boesmanskrans River – No gauged flow data could be obtained from DWAF for the Boesmanskrans River. An average daily inflow of 0.01 m3/s was assumed.

Reservoir levels were measured at the dam wall and this data was used during the first phase of the project to compute a water balance for Witbank Dam and to verify the validity of the inflow and outflow data. The water balance showed that some of the flow gauging structures were unreliable. Where data was missing from the early 1990's data records, standard infilling techniques were used to fill in the missing flow data.

Meteorological data

Meteorological data are required to simulate the temperature in the reservoir. The model requires daily observations (or generated data) of air temperature (°C), dewpoint temperature (°C), wind speed (m s^{-1}), wind direction (radians) and cloud cover.

Meteorological data was obtained from the Weather Bureau and it included:

- Hourly wind speed and wind direction as measured at Witbank (station 05153208),
- Cloud cover and dewpoint temperatures were obtained for Pretoria (station 0513314C9),
- Air temperatures were obtained for Witbank (station 05153208).

An example of air temperatures and wind speeds measured at Witbank Dam are displayed in **Figure 3.4.2(b)** and **Figure 3.4.2(c)**.

Figure 3.4.2(b)

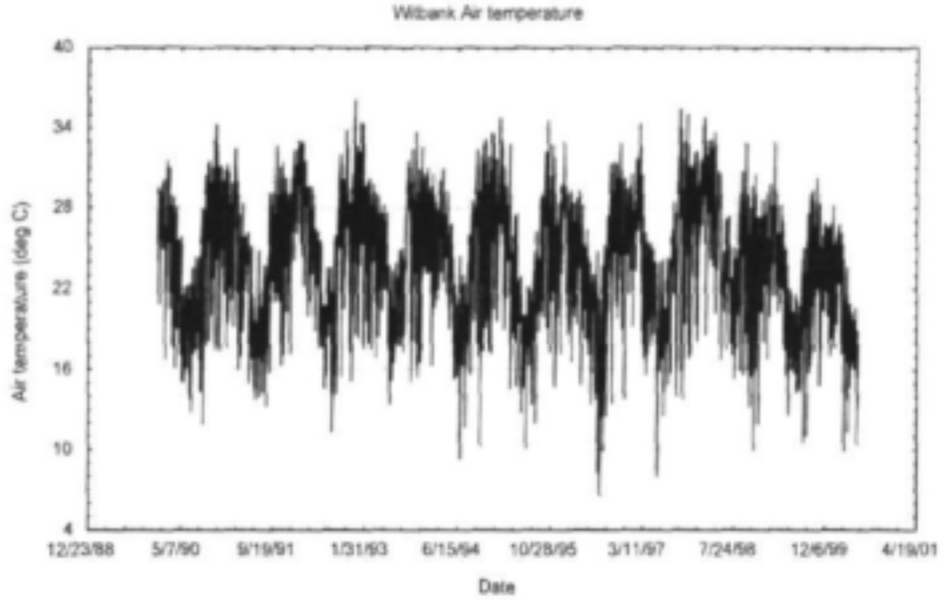

Figure 3.4.2 (c)

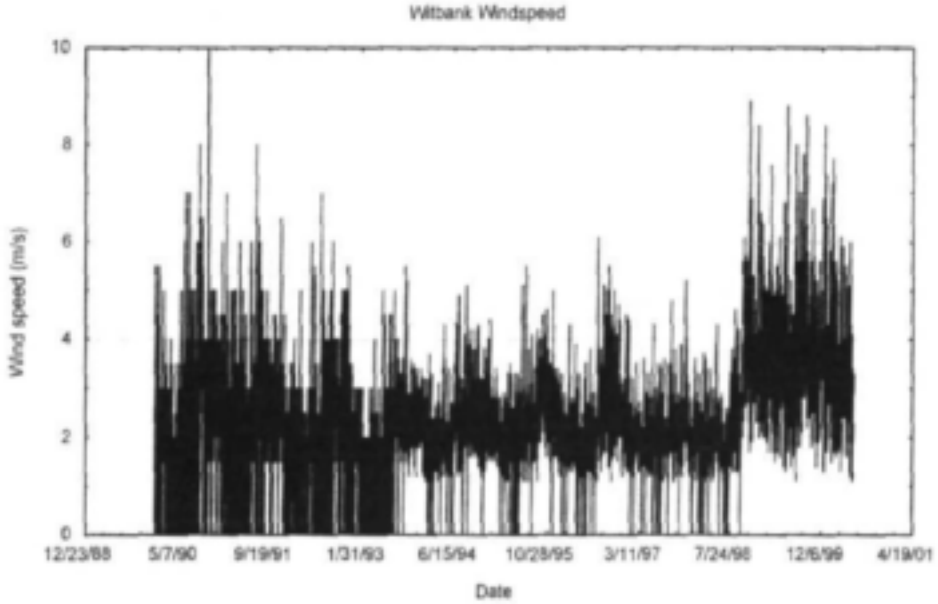

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Figure 3.4.2 Graphs of air temperatures and wind speeds used in the application of CE-QUAL-W2 to Witbank

Water Quality data

The purpose of the reservoir modelling was to describe the behaviour of Witbank Dam during high inflow periods. The water quality variables of concern were identified as total dissolved salt concentrations (TDS), sulphate concentrations (SO_4) and total suspended solid concentrations (TSS). The model requires a time series of the three variables of concern for each of the three inflowing rivers.

Olifants River – Observed TDS, SO_4 and turbidity data were obtained from DWAF for the gauging station, B1H005Q01. Missing data were in-filled using the method employed by A Bath in the Amatola Water Resources Systems Analysis study.

Noupoort River – Weekly observed TDS and SO_4 data were obtained from DWAF for the gauging station, B1H019Q01. Missing data were filled in using the same method developed by Dr A Bath for the Amatola Water Resources Systems Analysis study. No turbidity or TSS data were available and the TSS concentrations were estimated to be about equal to those observed in the Olifants River.

Boesmanskrans River – A very limited data record was available for the Boesmanskrans River and estimated concentrations were obtained from DWAF and the monitoring undertaken by Wates, Meiring & Barnard.

The Witbank Dam database was processed to create the input files for the application of CE-QUAL-W2. As a verification procedure, the individual input files are screened to check that the records correspond with the original data files.

Examples of the observed and in-filled TDS and sulphate time series for the Olifants River are displayed in **Figures 3.4.2(d)** and **Figure 3.4.2(e)**.

3.4.3 Model control file

The model control file contains the variables used to run the model. It contains information on:

- Title of a specific application
- Time control (start & end date, timestep and time interval controls etc.)
- Definition of the grid (number and identification of branches & tributaries)
- Initial conditions (location, temperatures & physical coefficients)
- Information about inflows and outflow controls (outlets & locations, abstraction points & location, location of tributaries & inflow options etc.)
- Output controls (specify outputs to different output files)
- Constituent controls (specify which constituents will be simulated)
- Kinetic coefficients (growth & decay rates and other rate coefficients)
- Input and output file names.

Figure 3.4.2(d)

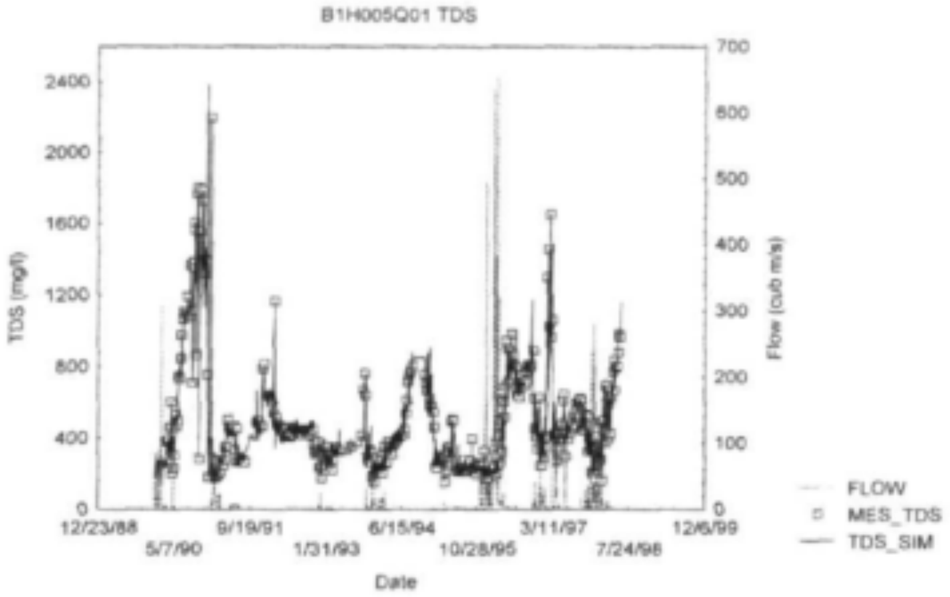

Figure 3.4.2(e)

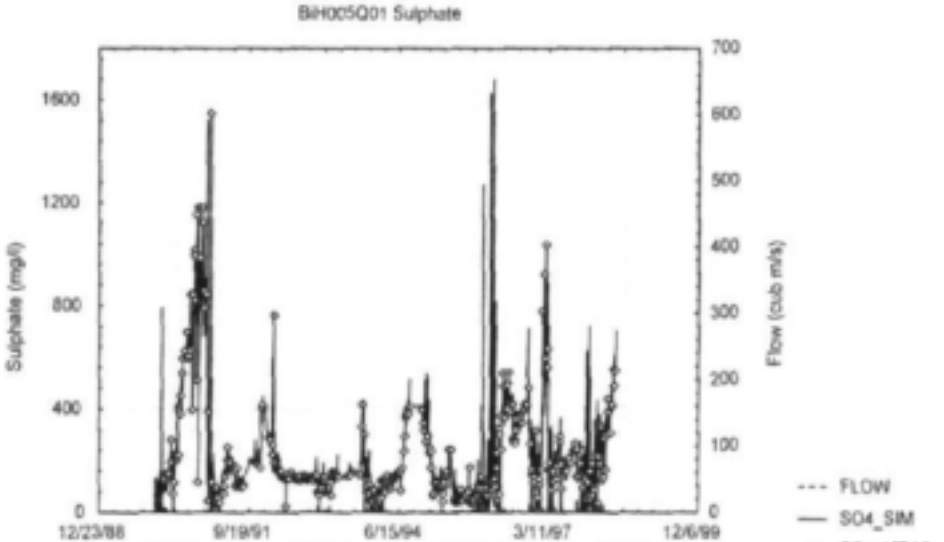

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Figure 3.4.2 Graphs of observed (MEAS) and in-filled (SIM) TDS and sulphate concentrations for the Olifants River

In discussions with the Project Team, it was agreed that the initial configuration of the impoundment model would include a long simulation sequence (1990 to 1998) to assess the overall performance of the model and to assess the hydrodynamic behaviour of Witbank Dam under different inflow and dam state scenarios.

The model was then configured for a shorter period (October 1997 to March 1998) when linked to the river model.

3.5 Confirmation of the Reservoir Model

The purpose of the model confirmation was to illustrate that the model can emulate conditions in Witbank Dam and provide some confidence in the simulation results. Any model is an approximation of the real world and simulation results are often less accurate due to uncertainties in the input data provided to the model as well as uncertainties in the modelled processes. In the case of the application to Witbank Dam where the salts and sulphate concentrations are simulated as conservative substances, uncertainties in the input data would be the overriding source differences between observed and simulated data.

The model calibration was confirmed using in-lake data collected during the period 1 October 1997 (day 274) to 31 December 1999 (day 1094).

3.5.1 Simulation of water levels (October 1997 to December 1999)

There appeared to be a moderately good correspondence between the simulated and the observed water levels in Witbank Dam (**Figure 3.5.1**). However, from about day 700 (December 1998) the model started to overestimate the water level in the dam. The model simulation is dependent on the water balance data provided as input to the model. Inflow, outflow and abstraction volumes are measured or estimated by different organisations making the estimation of an accurate water balance quite difficult because any of the observations or estimates could contain errors. The simulation results illustrate that on average, most of the inflows, outflows and abstractions were probably adequate for modelling in-lake water quality.

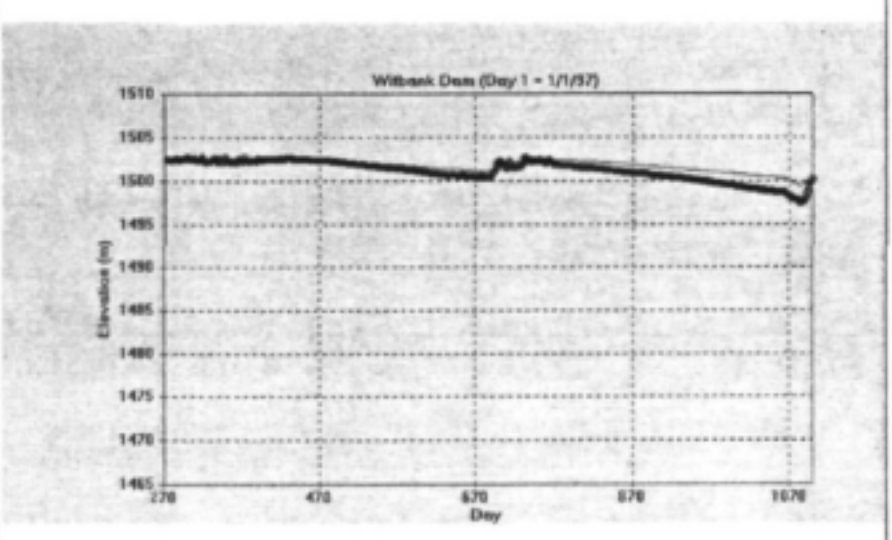

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Figure 3.5.1 Observed (circle) and simulated (line) water levels in Witbank Dam (1997 – 1999)

WRB

3.5.2 Simulation of surface water temperatures (Oct 1997 to December 1999)

Surface water temperatures were recoded at the dam wall, at the Duhva road bridge and at the Bethal road bridge. Most observations were made during the summer months and limited observations were available during the winter months. No temperature depth profiles were available for validating the temperatures of the deeper water layers. There was a moderately good correspondence between the observed and simulated surface water temperatures at the Duhva Road Bridge and the Bethal road bridge (**Figure 3.5.2**). However, at the dam wall, the surface water temperature was consistently under-estimated by about 1-2 °C. This indicates that modelling temperature in the main basin needs to be improved by more appropriate wind measurements. The model did, however, adequately simulate the seasonal changes in temperature in the reservoir.

3.5.3 Simulation of surface water TDS concentrations (Oct 1997 to December 1999)

Surface water TDS concentrations were recorded at the dam wall, at the Duhva road bridge and the Bethal road bridge. The highest sampling frequency was during the summer months and no TDS depth profiles were available to confirm the simulation of TDS concentrations in the deeper layers. There was a good correspondence between the observed and simulated TDS concentrations at the dam wall and at the Duhva road bridge as well as at the Bethal road bridge up to about day 700 (December 1998) (**Figure 3.5.3**). After that the simulated TDS concentrations were lower than what was observed at the Bethal road bridge. The model does, however, provide an adequate description of TDS concentrations in Witbank Dam.

3.5.4 Simulation of surface water sulphate concentrations (Oct 1997 to December 1999)

Surface water sulphate concentrations were recorded at the dam wall, at the Duhva road bridge and the Bethal road bridge. The highest sampling frequency was during the summer months and no SO_4 depth profiles were available to confirm the simulation of SO_4 concentrations in the deeper layers. There was a good correspondence between the observed and simulated SO_4 concentrations at the Duhva road bridge (**Figure 3.5.4**). However, the model tended to overestimate the SO_4 concentrations at the dam wall after about day 700 (December 1998). However, at the Bethal road bridge, the model tended to underestimate SO4 concentrations coming into Witbank Dam. This is also the case as well as at the Bethal road bridge up to about day 700 (December 1998) (**Figure 3.5.4**). After that the simulated TDS concentrations were lower than what was observed at the Bethal road bridge. The model probably provides an adequate description of SO_4 concentrations in Witbank Dam taking into account some of the limitations in the reservoir data set.

3.5.5 Discussion of the model confirmation

The CE-QUAL-W2 model is well suited for the purpose of simulating horizontal and vertical patterns in water quality in Witbank Dam under different flow conditions. However, the success of any simulation is dependent on the quality of the input data. Application of the model over the period October 1997 to December 1999 using flow and quality data available from various sources, illustrates this point. The inflow data for the Olifants River from about December 1998 appears to be higher than what is reflected in the dam level, leading to an overestimation of the reservoir level after that and an under estimation of TDS and SO4 concentrations close to the inflow at the Bethal road bridge. Simulations can only be improved if data quality issues are addressed, especially in the case of modelling conservative substances like TDS and SO_4.

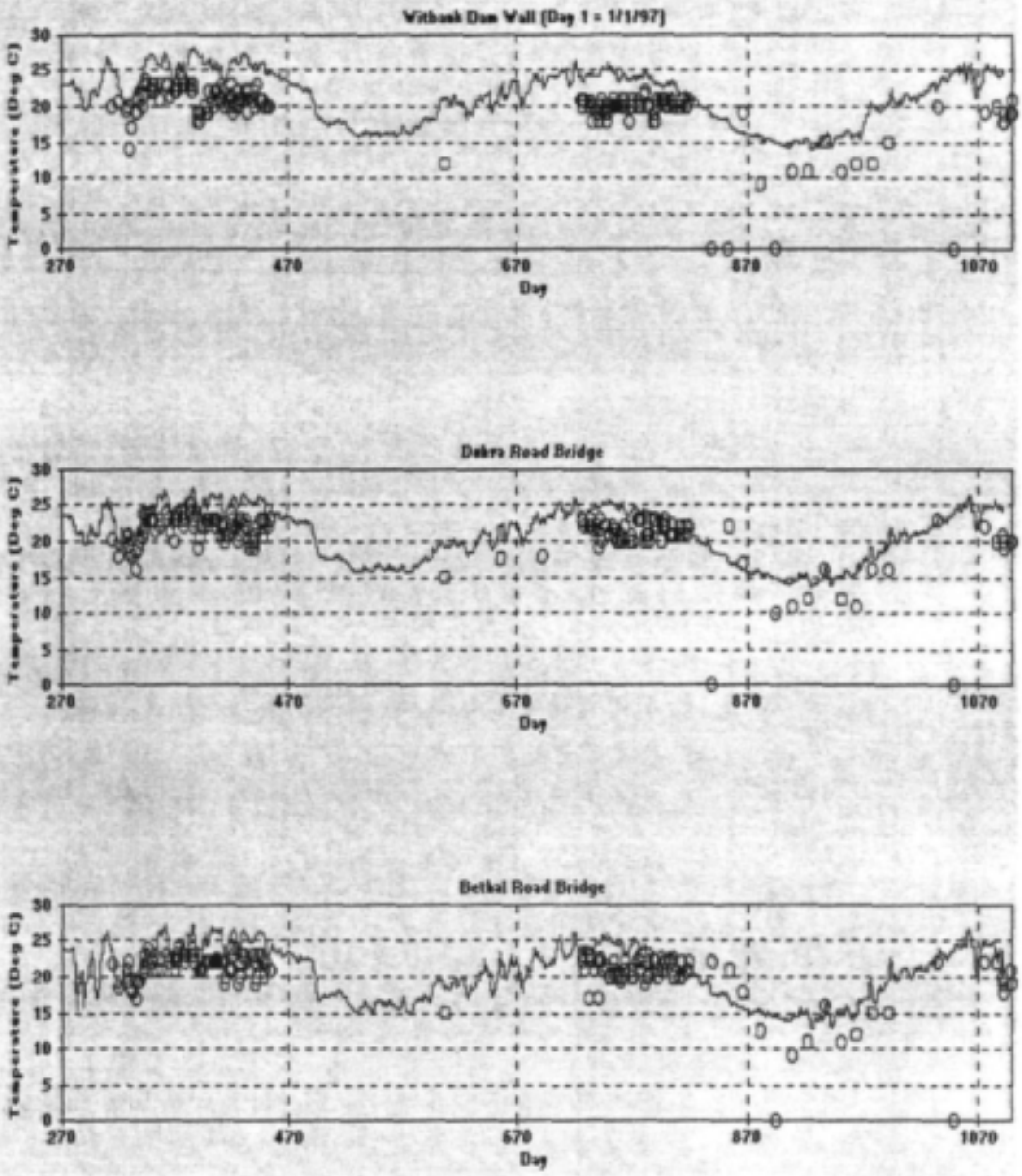

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Figure 3.5.2 Simulated (line) and observed (circle) surface water temperatures at the dam wall, Duhva bridge and Bethal road bridge.

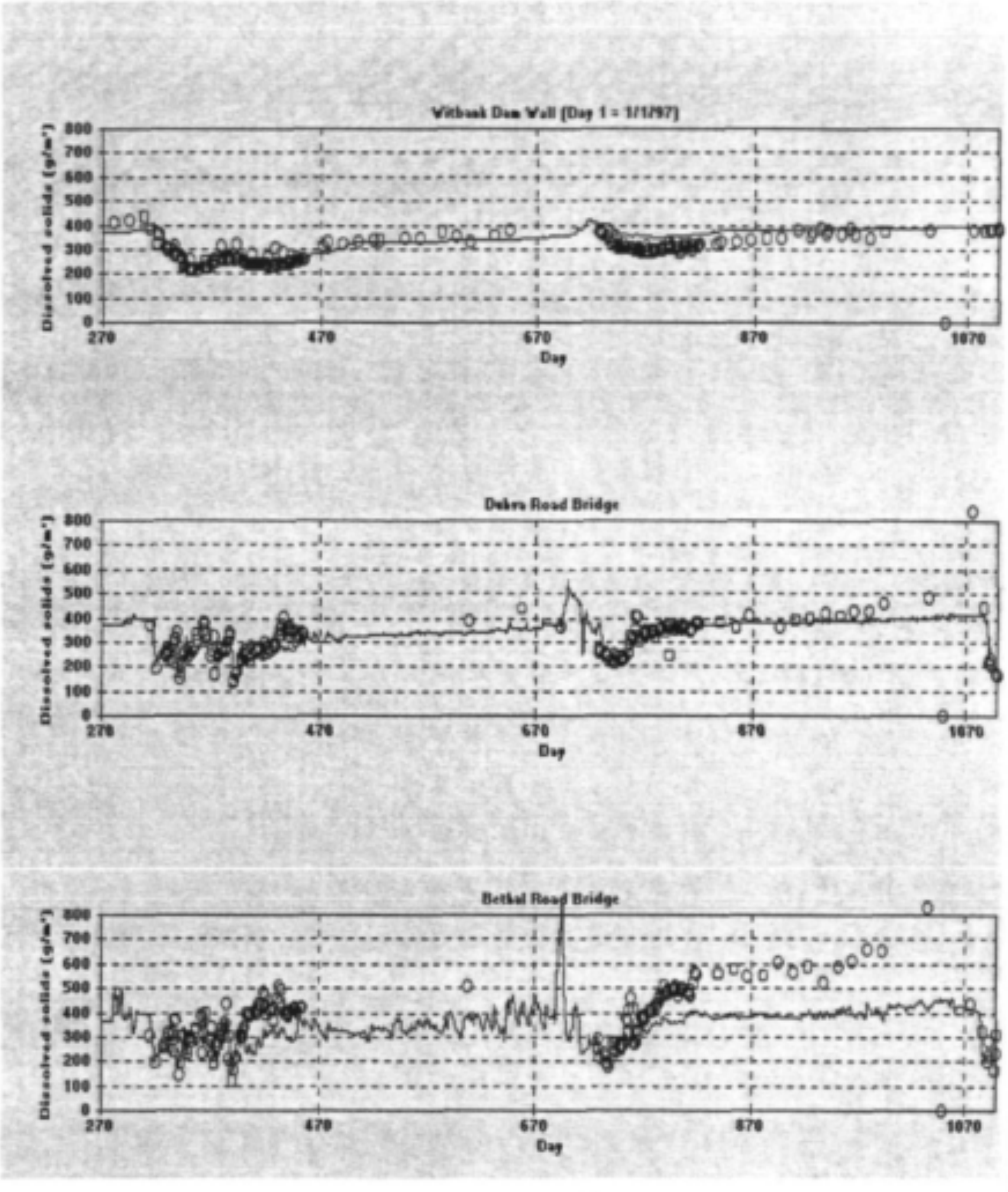

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Figure 3.5.3 Simulated (line) and observed (circle) surface water TDS concentrations at the dam wall, Duhva bridge and Bethal road bridge.

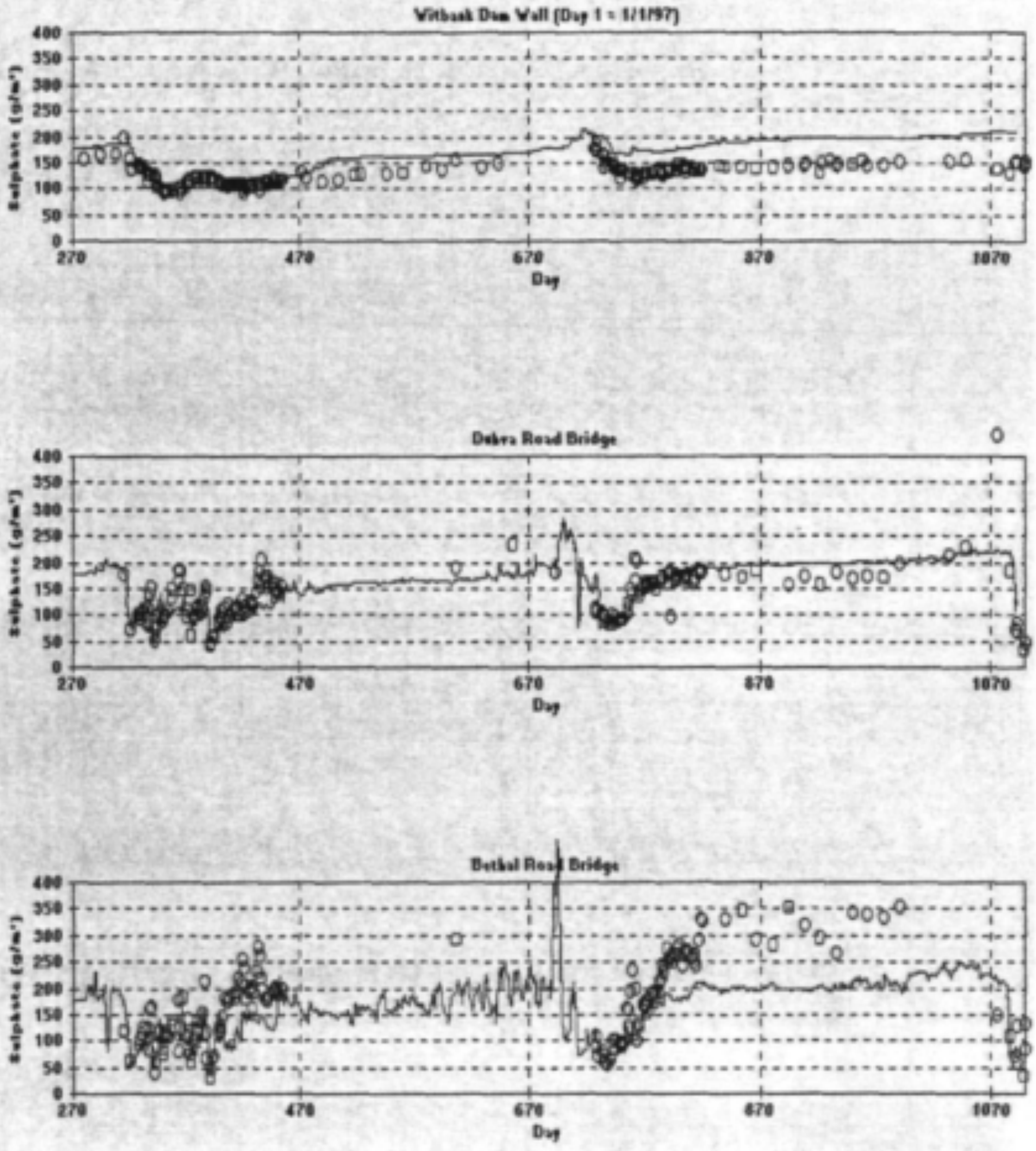

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Figure 3.5.4 Simulated (line) and observed (circle) surface water SO_4 concentrations at the dam wall, Duhva bridge and Bethal road bridge.

3.6 Selection of Reservoir Hydrodynamic Scenarios

3.6.1 An Introduction to Reservoir Hydrodynamics

The hydrodynamic state of a reservoir is constantly changing with time and space and these changes have a profound impact on the water quality status of the reservoir. The most important hydrodynamic changes that impact on water quality are thermal stratification, reservoir zonation and inflow mixing processes.

Thermal stratification

On a temporal scale, many reservoirs exhibit thermal stratification during the summer months and destratification during the winter months (Martin & McCutcheon, 1999). Stratification can have a profound effect on the tendency not to mix completely in a vertical dimension and this is also the case with Witbank Dam.

In spring and early summer, solar radiation and wind mixing heats the surface layer of the reservoir and stratifies the water column into layers with distinct differences in temperature and density. During summer thermal stratification, the warmer, less dense layer of water (epilimnion) floats on a cooler, denser water layer (hypolimnion) (**Figure 3.6.1(a)**). A zone of rapidly changing temperature, referred to as the metalimnion, separates these two layers and the point where the biggest change in temperature occurs, is referred to as the thermocline. The bigger the difference in temperature between the warm epilimnion and the colder hypolimnion, the more energy is required to mix the water column. In South Africa and in the case of a deep reservoir like Witbank Dam, summer stratification is very stable.

In autumn, the epilimnion cools and the temperature differences between the layers decrease, making mixing between the layers easier. The cooling eventually extends downward until the entire water column is mixed and homogenous. This destratification is referred to as autumn overturn. The reservoir remains in a destratified state for the remainder of winter until heating of the surface layers starts again during early spring.

In general, the following statements can be made about temperature stratification in reservoirs (Thornton *et al.*, 1990) and would also apply to Witbank Dam:

- The driving forces responsible for stratification (e.g. wind and solar radiation) act at the surface that result in minimum horizontal variations.
- There is low variability in stratification from year to year and the onset of spring stratification and autumn overturn occur at about the same time of year. Year to year variations in hypolimnetic temperatures is between 1 to 2 °C.
- The deeper the reservoir, the less kinetic energy per unit volume is available for mixing, and the stronger the stratification.

Figure 3.6.1(a)

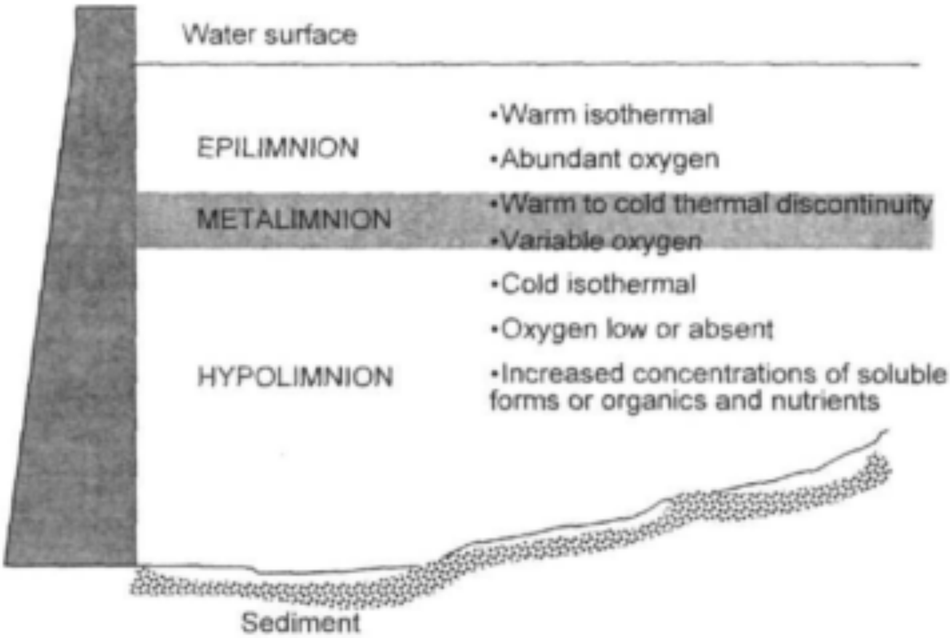

Figure 3.6.1(b)

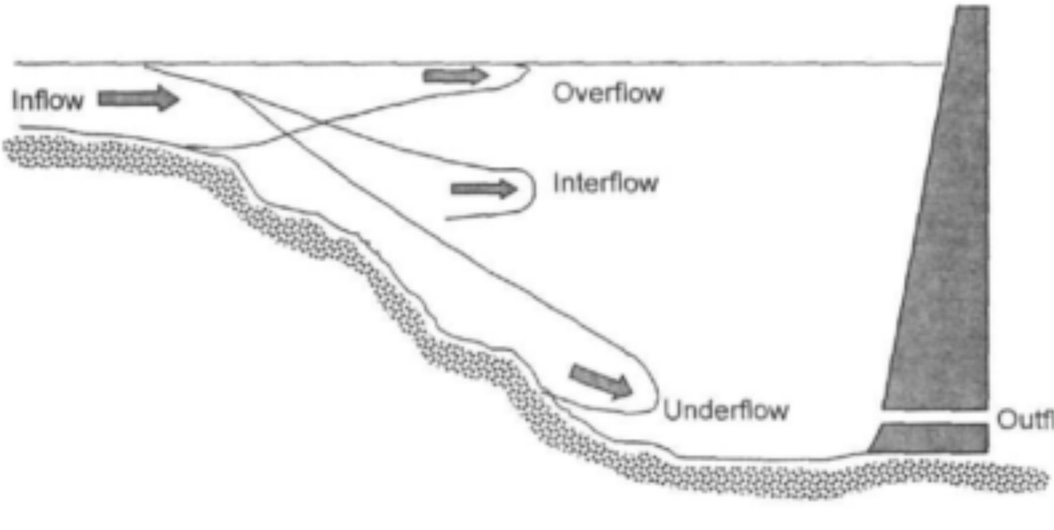

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Figure 3.6.1 Illustration of reservoir stratification (a) and the positioning of inflows (b)

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There are also vertical differences in water quality. Under summer stratified conditions, dissolved oxygen concentrations in the epilimnion are higher than in the hypolimnion. If there are large amounts of decomposing organic material present in the hypolimnion that consumes oxygen during decomposition, dissolved oxygen concentrations may disappear from the hypolimnion, leading to anoxic conditions. Under these conditions, anoxic products can form which can be harmful to aquatic organisms if hypolimnetic water is discharged into the downstream river. Common anoxic products are high concentrations of hydrogen sulphide (H_2S) and the solution of iron (Fe) and manganese (Mn) into the water.

River Zonation

On a spatial scale, distinct longitudinal zones can be identified in reservoirs. Generally, three zones can be distinguished along the longitudinal axis of the reservoir. This is probably the case with Witbank Dam as well (**Figure 3.6.1(c)**).

- The *riverine zone* is almost a lotic environment. It is characterized by higher flows, shorter water retention times, and higher levels of nutrients, suspended sediment and light extinction than the downstream sections of the reservoir.
- The *transition zone* is characterized by decreasing flow velocities; increased water residence times, sedimentation of silt and clay particles, and increased light penetration. The transition zone is often associated with a plunge point. This is the position in a reservoir where, due to density differences, the inflowing waters may enter the lacustrine zone at intermediate depths. Algal production is generally higher in the transition zone because of high nutrient availability and a favorable underwater light climate.
- The *lacustrine zone* occurs in the main basin, nearest to the dam wall. It usually has a longer water residence time, lower concentrations of suspended material, increased light penetration and transparency. Algal growth is generally limited by the availability of nutrients.

In Witbank Dam, the length of the riverine and transition zone is a function of inflow. At low baseflow conditions that typically occur during the winter months, the riverine and transition zone would be much closer to the upstream boundary of the reservoir that during the summer months when elevated inflows and floods occur.

Inflow mixing processes

A major concern of this study is the impact of inflow mixing processes on in-lake water quality. Inflows serve as the primary source of dissolved and particulate material in reservoirs. The mixing of inflows depends to a large degree on the inflow rate, and on the difference in density between the inflowing water and the water in the reservoir.

In the riverine zone, the initial momentum of the inflow pushes the in-lake water in front of it. Advective riverine processes dominate transport in this zone and the water quality is similar to the inflowing river water quality. The inflow continues until the initial momentum is substantially dissipated (Martin & McCutcheon, 1999).

In the transition zone, where the initial energy of the inflow is dissipated, the difference in density between the inflows and the ambient water starts to dominate transport processes. If the inflow is not strong enough to cause complete mixing between the inflow and in-lake waters, the inflow will flow to a layer of equivalent density and will then move along that layer.

Figure 3.6.1(c)

Lacustrine zone
- Broad, deep reservoir basin
- Little flow
- Relatively clear
- Relatively low nutrients
- Nutrients limit primary productivity
- More oligotrophic

Transitional zone
- Broader, deeper basin
- Reduced flow
- Reduced turbidity, increased light availability
- Nutrients reduced
- Primary productivity relatively high
- Intermediate

Riverine Zone
- Narrow, channelized basin
- Relative high flow
- High turbidity and low light availability
- Relative high nutrients
- Light limits primary productivity
- More eutrophic

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Figure 3.6.1(c) Figure showing the three zones that can be identified in a reservoir.

If the river water is less dense than the surface water in the reservoir, the more buoyant river water will flow over the top of the reservoir as an overflow (Martin & McCutcheon, 1999) (**Figure 3.6.1(b)**). Overflows can contribute to large variations in water quality and they deliver material directly to the more productive surface zones of the reservoir.

If the inflowing water is denser than the surface water, the negative buoyancy will cause the inflows to plunge beneath the reservoir waters becoming an underflow (**Figure 3.6.1(b)**). The higher density is generally the result of cooler temperatures or higher concentrations of dissolved or particulate matter.

If the underflows are denser that the bottom waters, they remain on the bottom of the reservoir. However, most underflows are less dense that the bottommost layers and such cases, the underflow becomes interflow as the inflowing water finds a layer of equivalent density (Martin & McCutheon, 1999) (**Figure 3.6.1(b)**).

3.7 Identification of Inflow Scenarios

The value of the long term modelling of hydrodynamic and water quality processes in Witbank Dam was that it allowed the study team to examine the behaviour of the reservoir under different inflows and dam states. An underlying objective of the study was to assess the in-lake impacts of utilising floods in the Witbank Dam catchment to mitigate the impact of saline effluents through controlled releases. The impact of floods on the in-lake water quality is a function of the size of the flood and the timing of the flood. The timing of the flood relates to the degree of stratification in Witbank Dam when the flood takes place and the temperature of the inflowing water.

Two flood scenarios were identified:

- Minor to moderate floods – these were floods where the size of a flood event was less than 25% of the full supply volume of the dam (104.018 10^6 m^3). These were floods where the total inflow volume during the event was less than 26.0 10^6 m^3
- Major to high floods – The size of a flood event was more than 25% of the full supply volume of the dam. These were floods where the total inflow volume during the event was greater than 26.0 10^6 m^3

Three timing scenarios were identified:

- Spring and early summer (weak stratification) – August to October – during this time stratification in the dam was developing, was generally weak, and could be broken down easily by wind or elevated inflow events.
- Summer (strong stratification) – November to February – during this time period stratification in the dam was strongly developed
- Autumn (stratification weakening to complete destratification) – March to May – during this time, ambient air temperatures starts to drop, stratifications starts to weaken and destratification takes place towards the end of April to early May.

The in-lake behaviour was therefore examined for six scenarios depending on the size of the flood and the time of the year during which it occurred (**Table 3.7**). An examination of the flow record in the Olifants River since 1990 (**Figure 3.7**) showed that smaller volume floods occurred throughout the rainfall season but none starting before October. High floods occurred mostly during mid summer (November to February) but high floods were recorded as late as April.

Table 3.7 Floods scenarios that were used to examine the hydrodynamic behaviour of Witbank Dam. The month during which the flood took place and the size of the flood relative to the volume of Witbank Dam (in brackets)

	Spring August – October	**Summer November – February**	**Autumn March - May**
Large		December 95 (29%) December 95 (127%) February 96 (207%) February 96 (132%)	February 90 (72%) April 97 (43%)
Small	October 93 (7.6%)	January 91 (6.5%) Jan/Feb 91 (19.6%) December 93 (10.8%) February 94 (12.5%) November 95 (24%)	May 90 (15%) March 91 (5.9%) March 91 (5.9%)

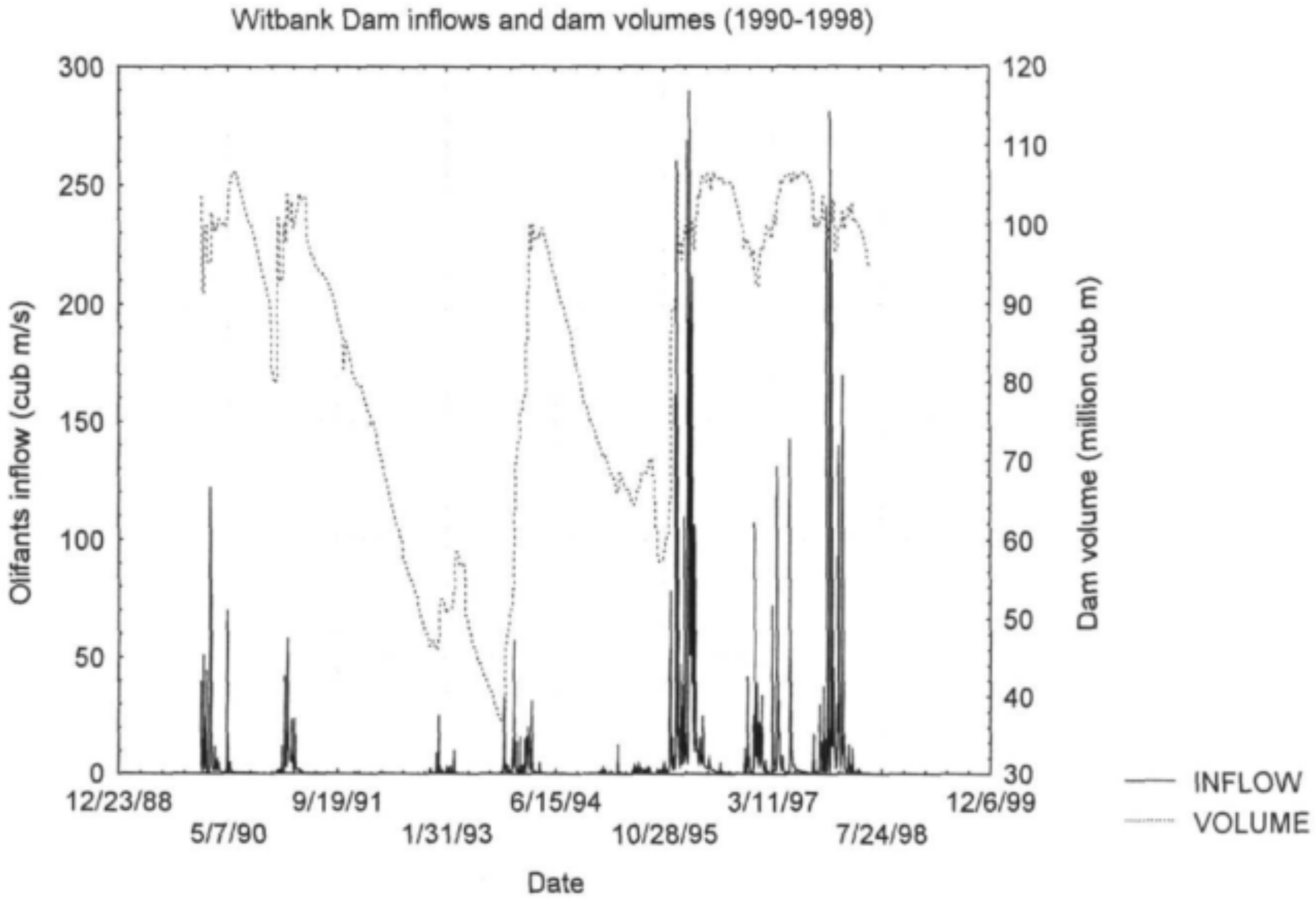

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Figure 3.7 Plot of inflows (solid line) into Witbank Dam and dam volumes (dotted line) for the period January 1990 to June 1998.

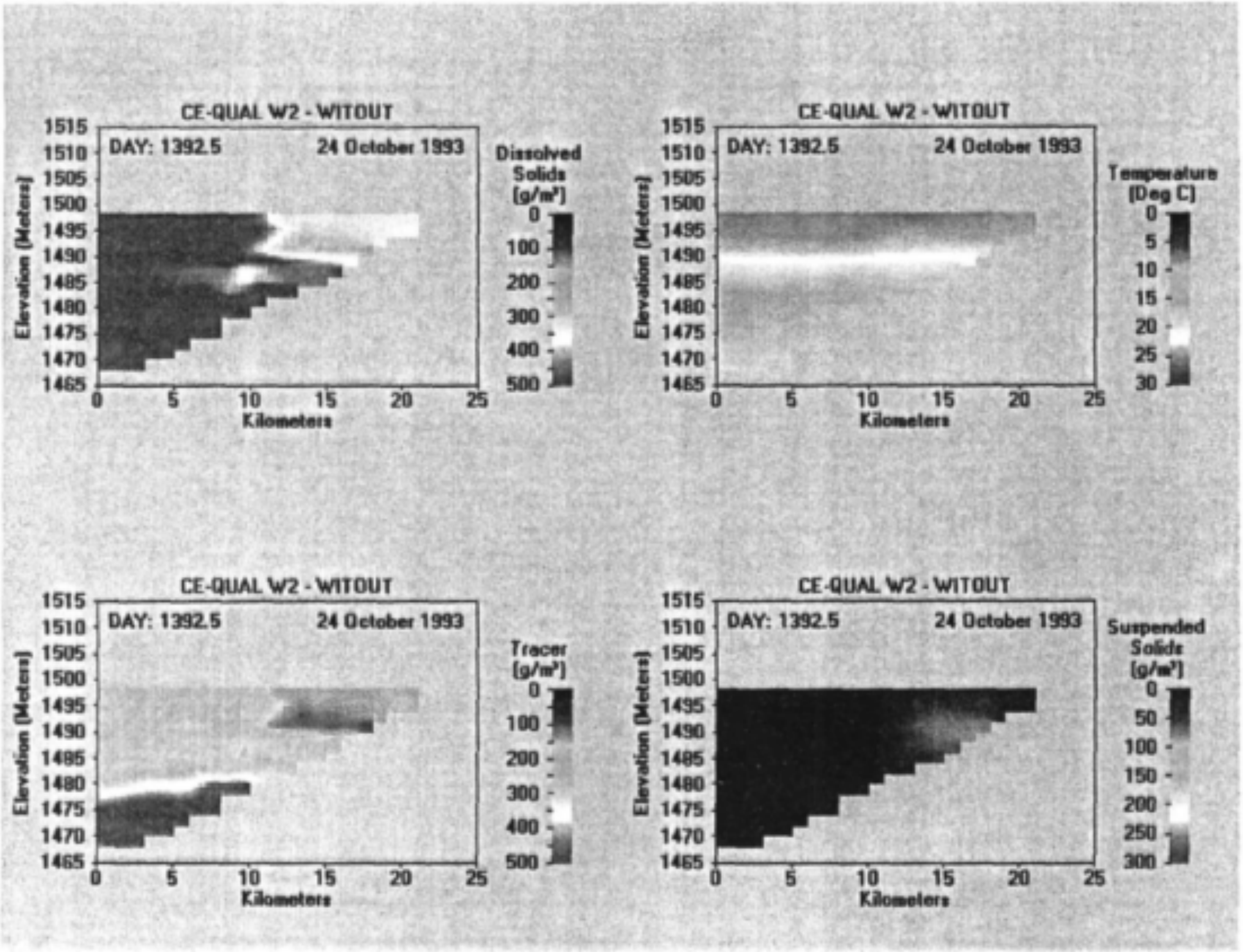

Figure 3.7.1(b) Cross section showing the effect of a small spring flood on Witbank Dam

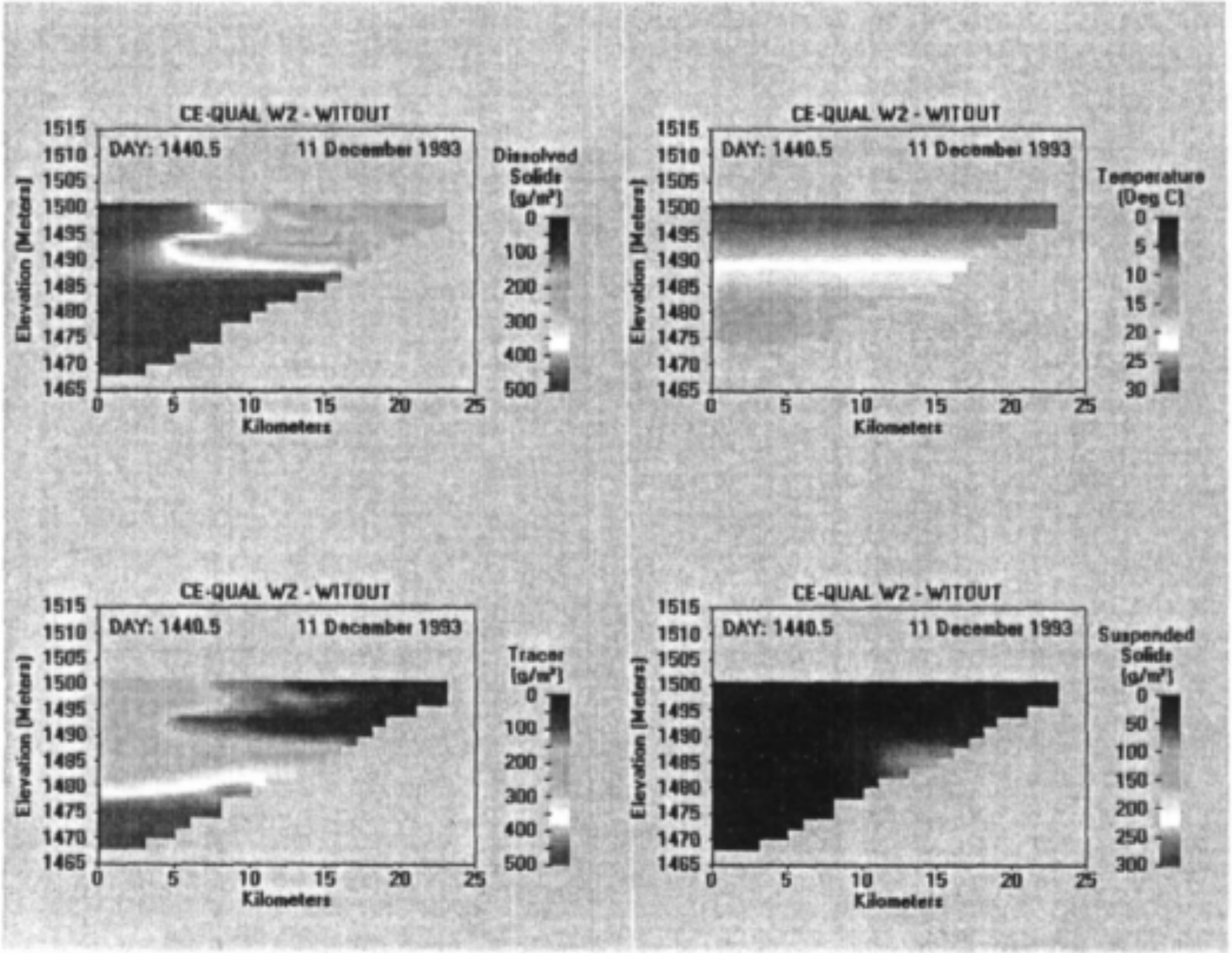

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Figure 3.7.2(a) Cross section showing the effect of a small summer ng flood on Witbank Dam

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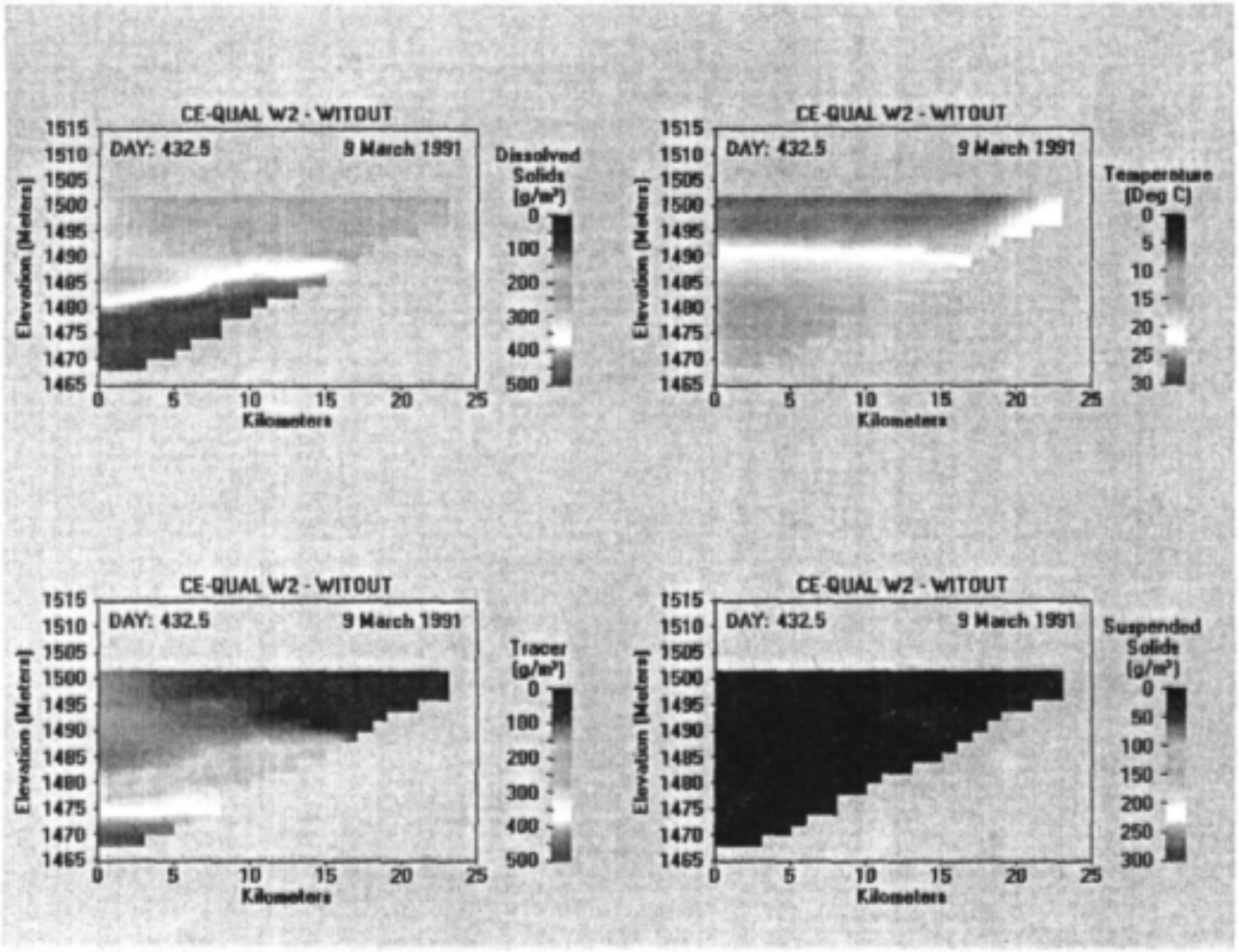

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Figure 3.7.3(a) Cross section showing the effect of a small autumn flood on Witbank Dam

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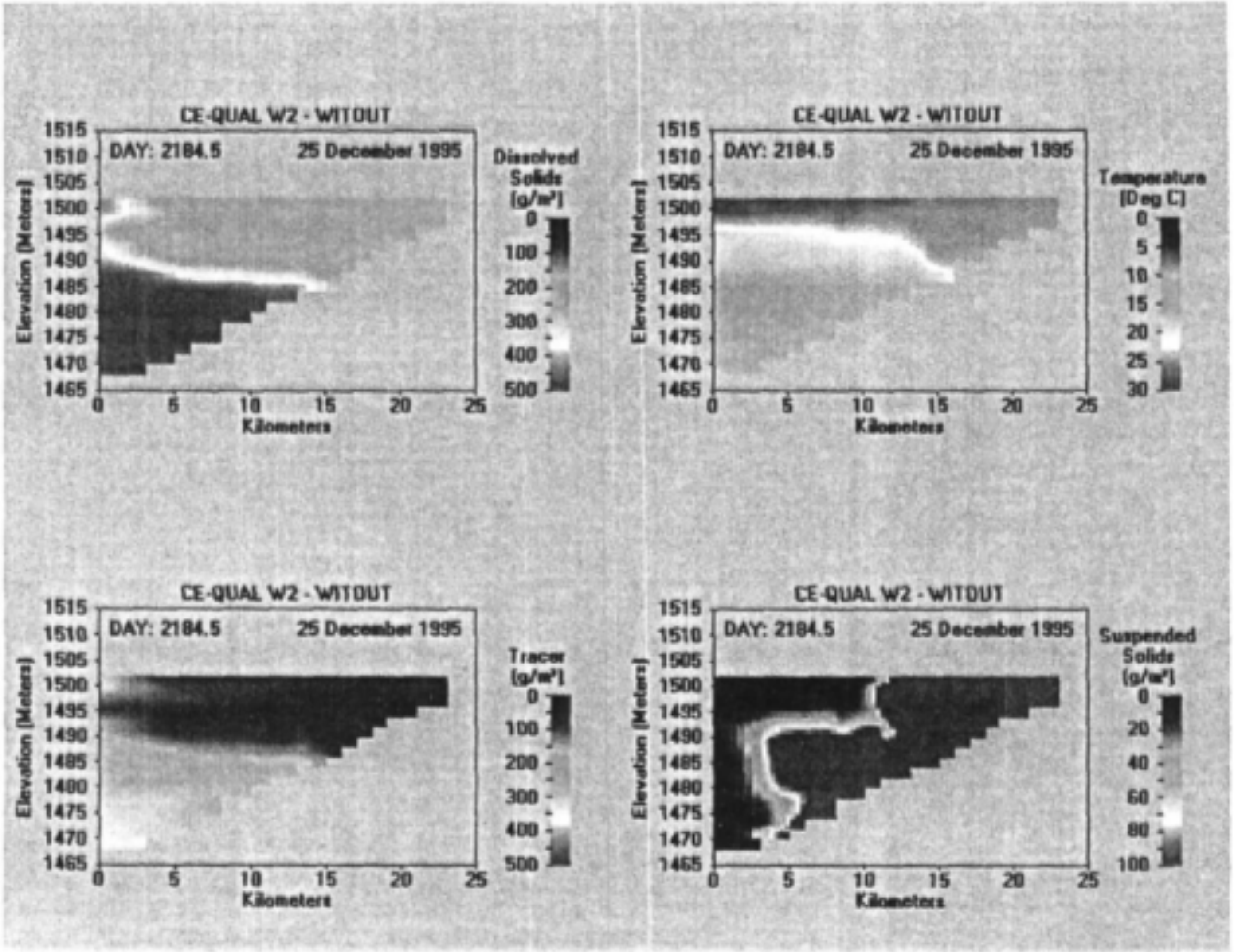

Figure 3.7.5(c) Cross section showing the effect of a large summer ng flood on Witbank Dam

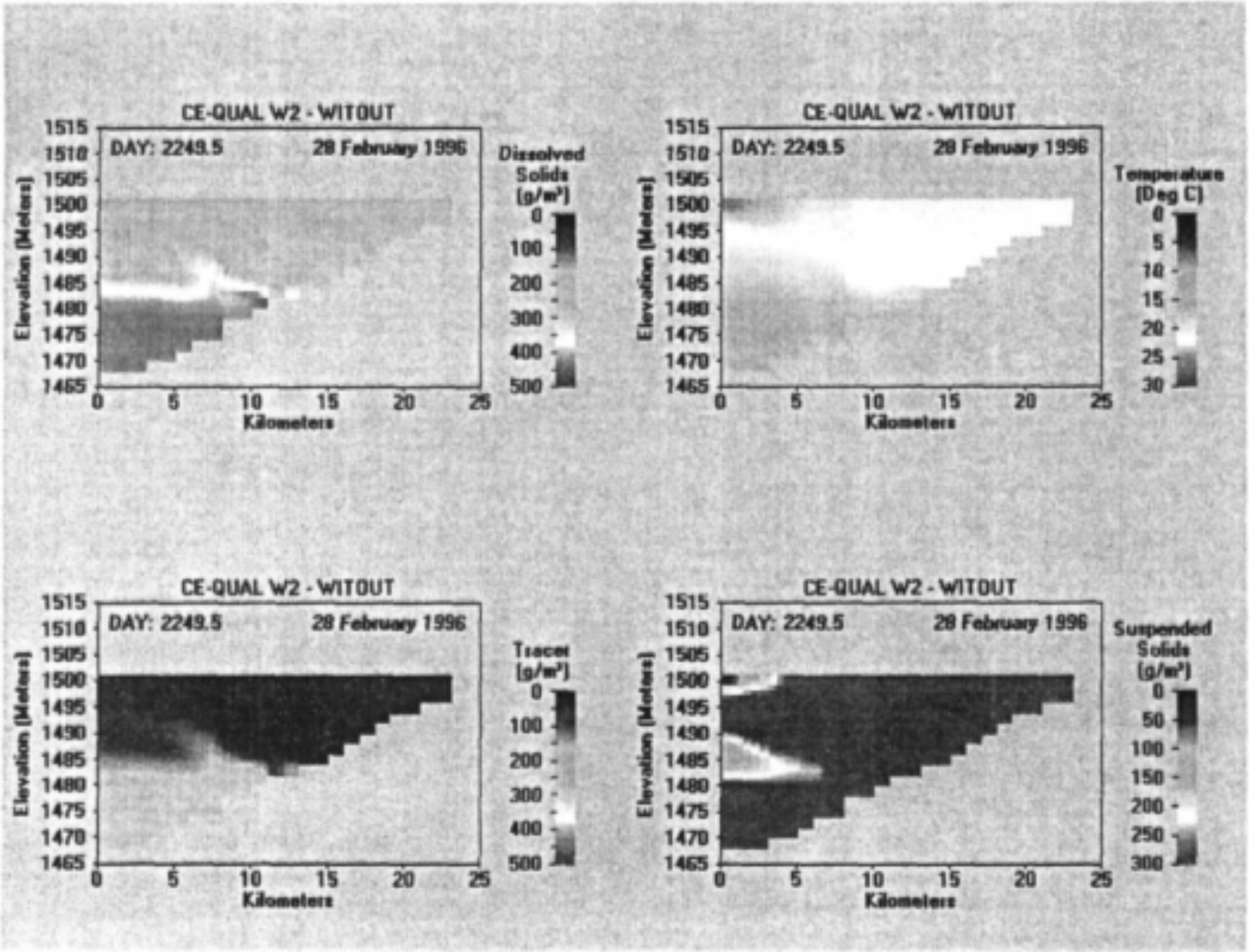

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Figure 3.7.5(d) Cross section showing the effect of a large summer ng flood on Witbank Dam

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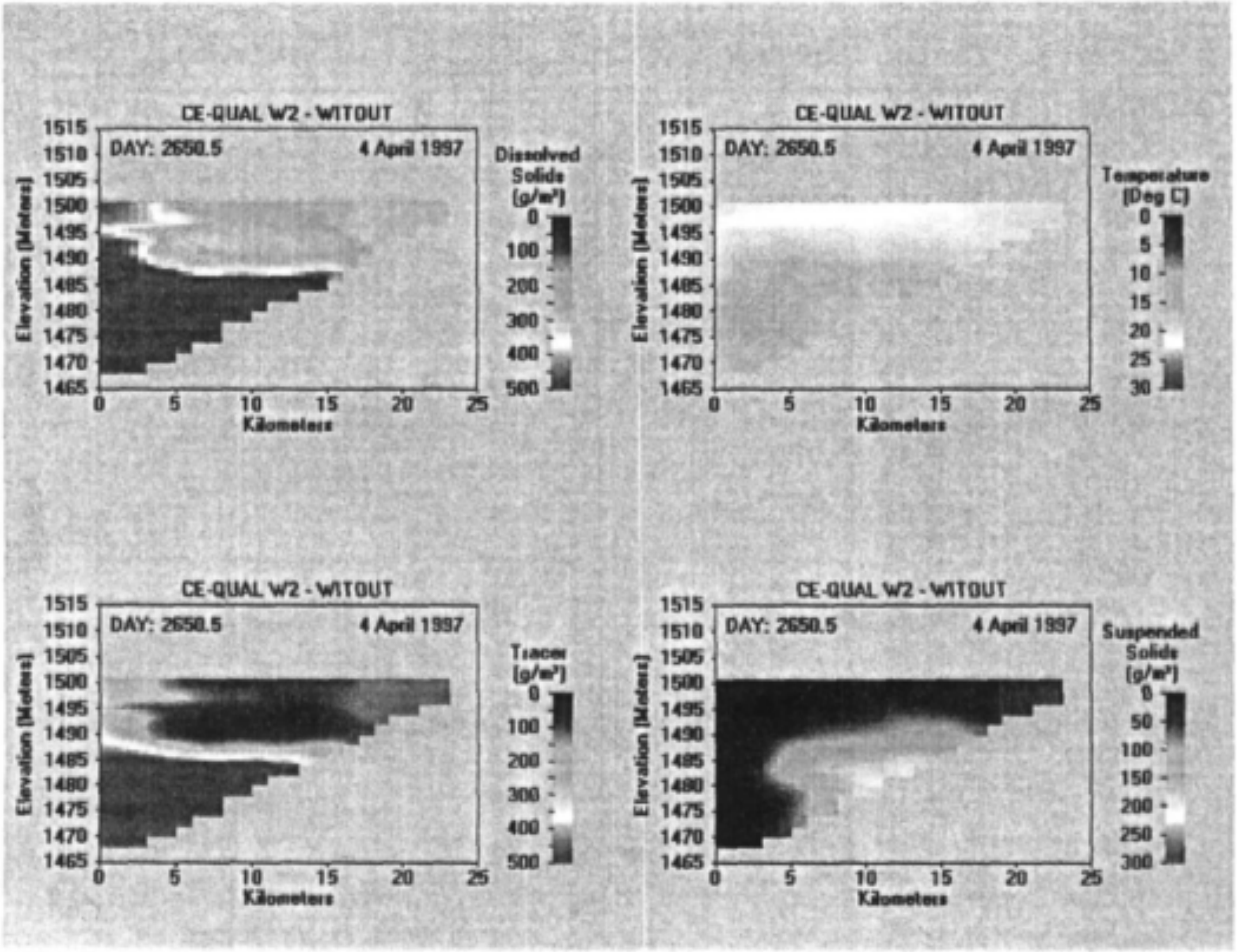

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Figure 3.7.6(a) Cross section showing the effect of a large autumn flood on Witbank Dam

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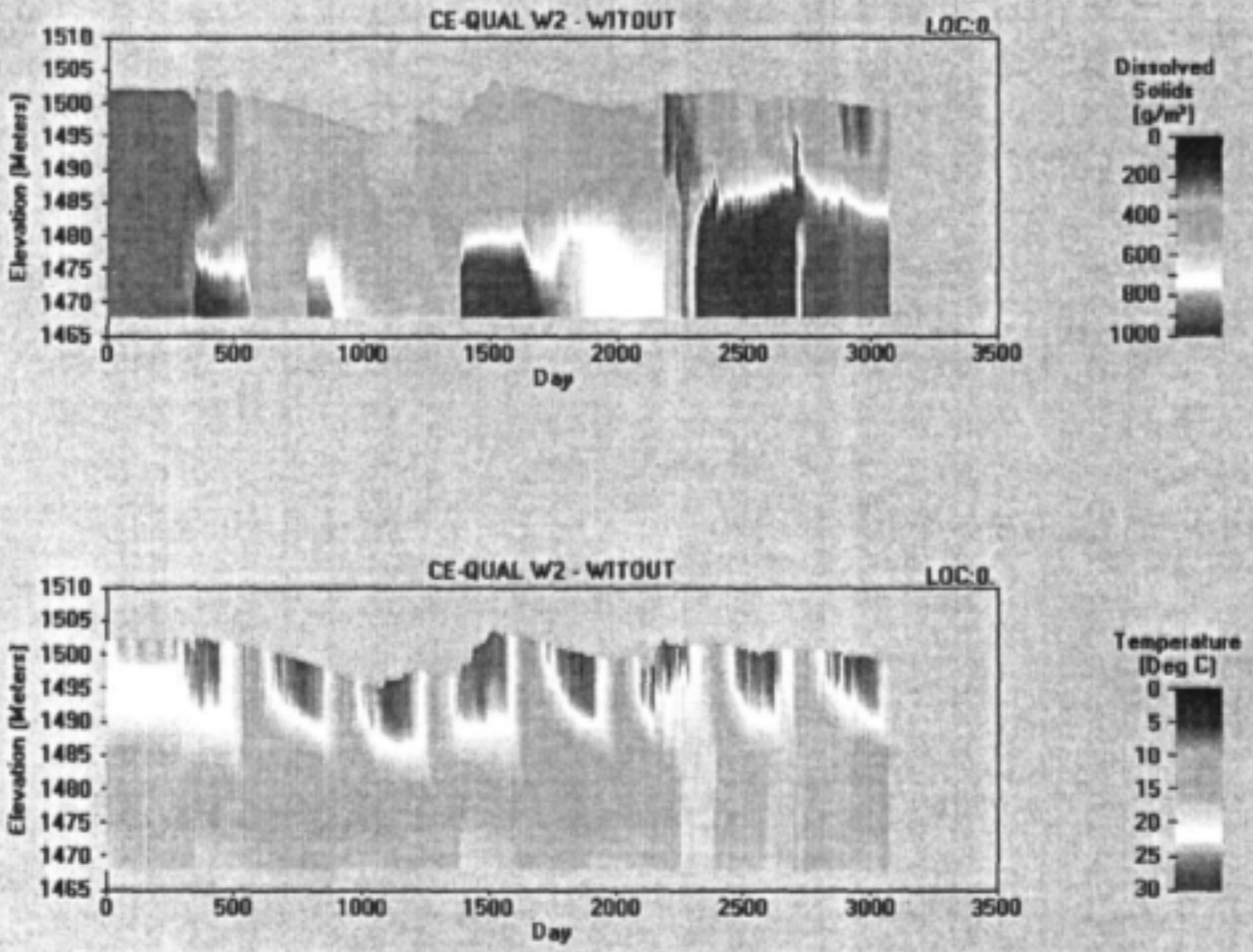

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Figure 3.7.7(a) Time-depth plot of TDS and temperatures close to the dam wall of Witbank Dam

3.8 Assessment of Witbank Dam hydrodynamics scenarios

The CE-QUAL-W2 hydrodynamic model was used to evaluate the hydrodynamic and water quality behaviour of Witbank Dam using simulated data from 1990 to 1998. Two inflows and three stratification state scenarios were evaluated (**Table 3.7**) and the impacts on the dam hydrodynamics are described below.

3.8.1 Reservoir behaviour - Small Flood – Spring

A small flood took place between 19-25 October 1993 (**Figure 3.8.1(a)**). The volume of the flood came to about 7.9 10^6 m^3 (about 7.6% of full supply volume) and the daily average inflow peaked on 21 October at about was about 33.2 m^3/s.

The impact of the flood on the dam was that most of the flow entered the main basin as interflow situated on top of the thermocline (**Figure 3.8.1(c)** 24 Oct 1993). There it dispersed into the layers above the thermocline and minor mixing took place into the layers below the thermocline. Some minor underflow also took place and followed the bottom of the dam until it dispersed in the bottom layers. Early in spring the thermocline is still weakly developed and elevated flows can break down the thermal barrier resulting in both under and interflow taking place.

3.8.2 Reservoir behaviour - Small Flood – Summer

A number of small floods took place during the summer months and examples of these small floods are shown in **Figure 3.8.1(a)** and **Figure 3.8.1(b)**. In both these examples, the dam level were allowed to increase, meaning that there were no additional releases other the supply of water to Witbank municipality and minor downstream releases. The impact of these floods could be summarised as follows.

The October flood described in **Section 3.8.1**was followed by a number of small floods in December, January and February 1993 (**Figure 3.8.1(b)**). The December and early January floods all entered the basin as interflow situated above the thermocline from where it mixed into the surface layers (**Figure 3.8.2(a)** 11 Dec 1993). There was a strong longitudinal gradient with the highest concentrations in the lower reaches of the dam and water with a lower TDS entering the dam.

A number of extended high flow events took place in February 1993 that had the effect of breaking down the thermocline and dispersing the water through most of the water column (the exception was the bottom most layers). The strong longitudinal gradient in water quality was also dispersed over the length of the reservoir. A very similar pattern was observed in early 1991 when three small floods (**Figure 3.8.1(a)**, spaced about 10 days apart, entered the reservoir. All these floods entered as interflow although there was evidence that the thermocline was being eroded away as the floods became larger. This caused a larger dispersion of flood water through the water column.

3.8.3 Reservoir behaviour - Small Flood – Autumn

A number of small floods took place during the autumn of 1990, 1991 and 1997. During these times the dam levels did not change substantially. The impacts of these smaller floods were very similar to those observed for the small floods that occurred during the summer months (**Figure 3.8.3(a)**). Winter turnover takes place in late autumn and thermal stratification may become unstable during this time. Smaller floods can have the effect of eroding the thermocline and mixing the inflow deeper into the water column than would be the case during summer months.

Figure 3.8.1(a)

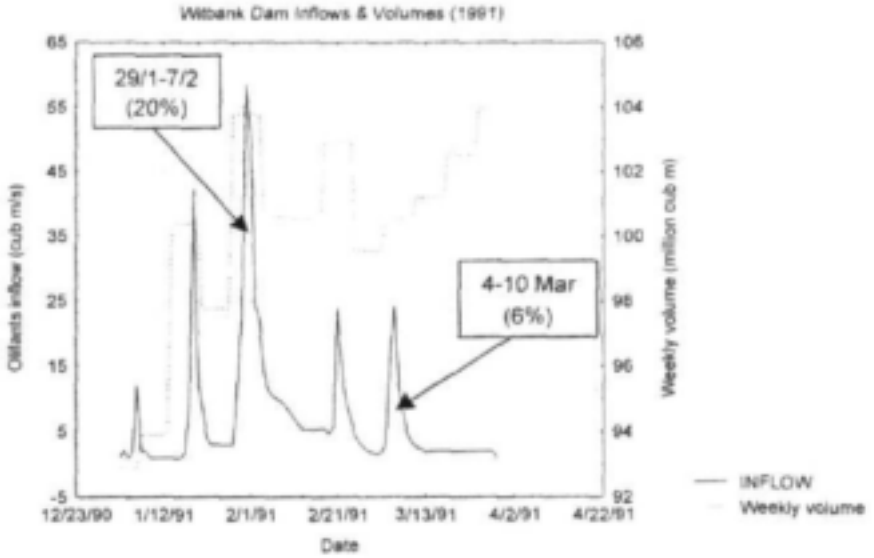

Figure 3.8.1(b)

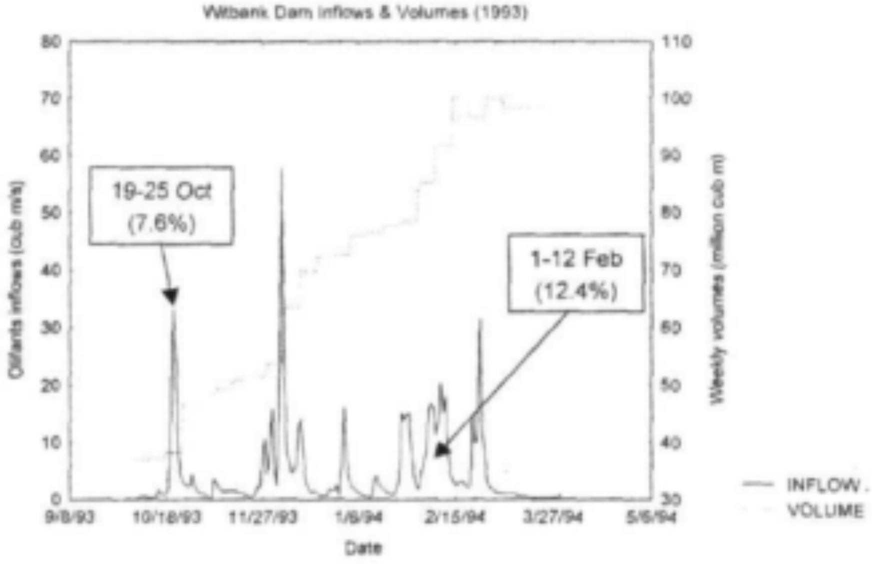

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Figure 3.8.1 Examples of small spring flood examined

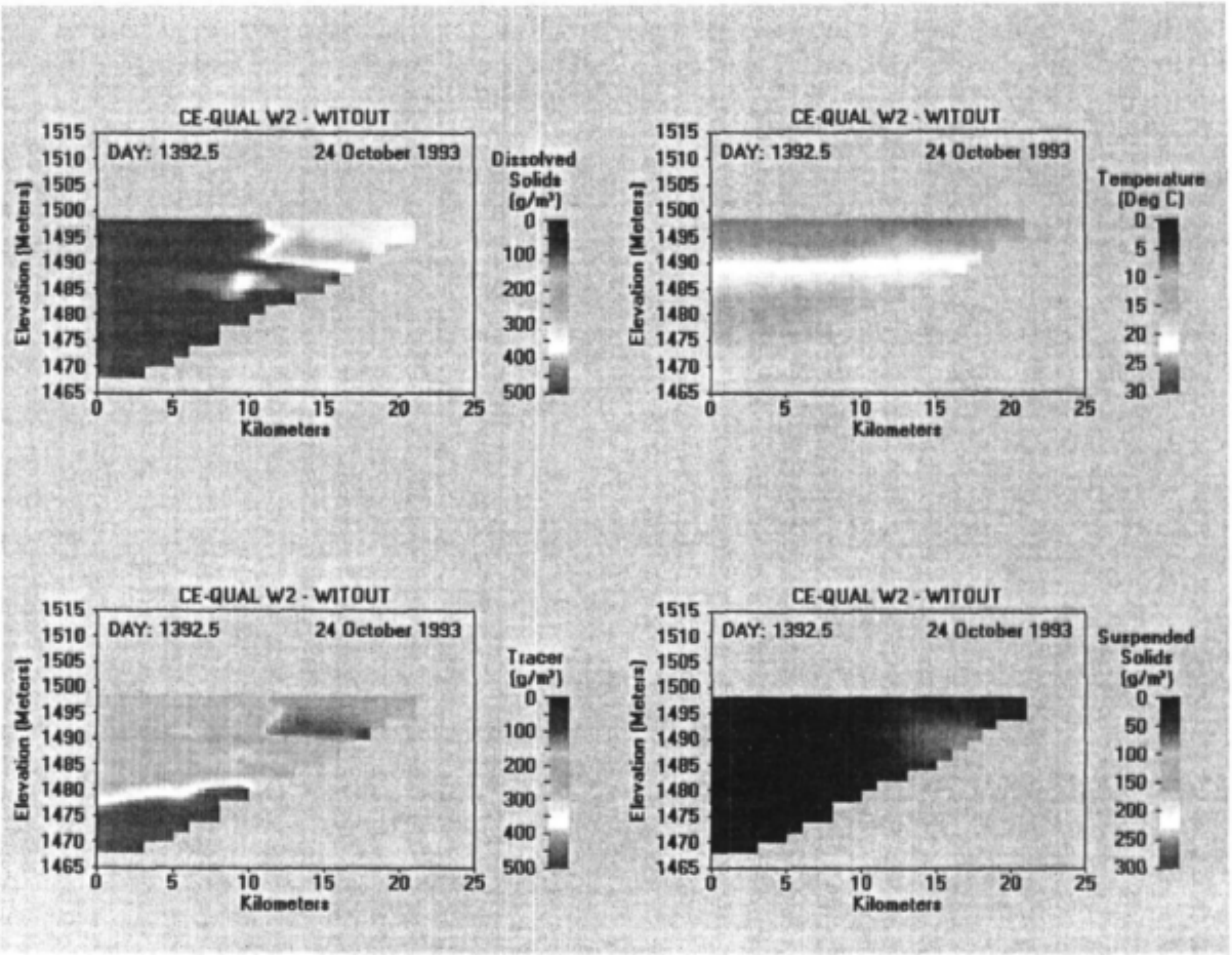

Figure 3.8.1(c) Cross section showing the effect of a small spring flood on Witbank Dam

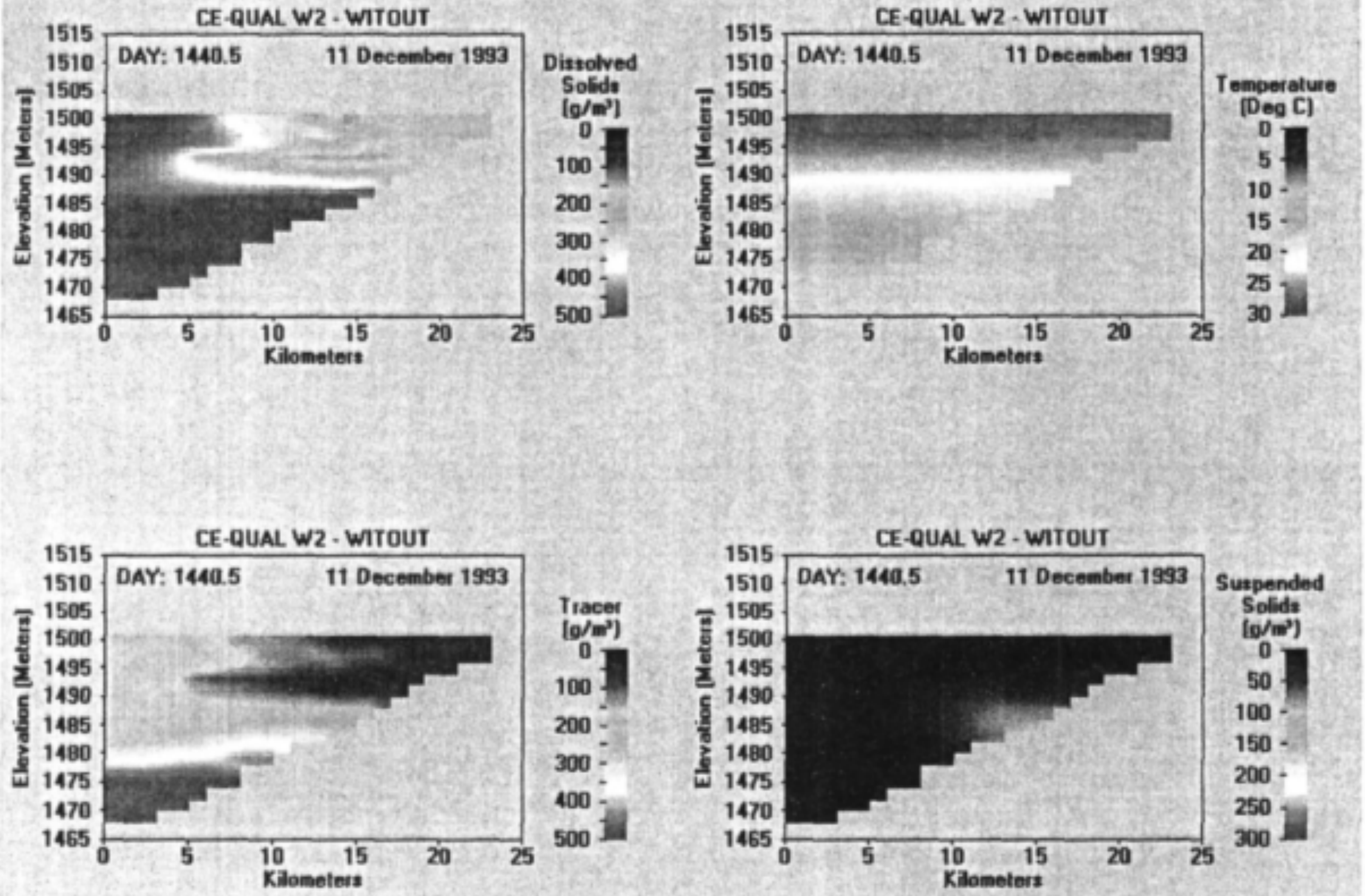

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Figure 3.8.2(a) Cross section showing the effect of a small summer ng flood on Witbank Dam

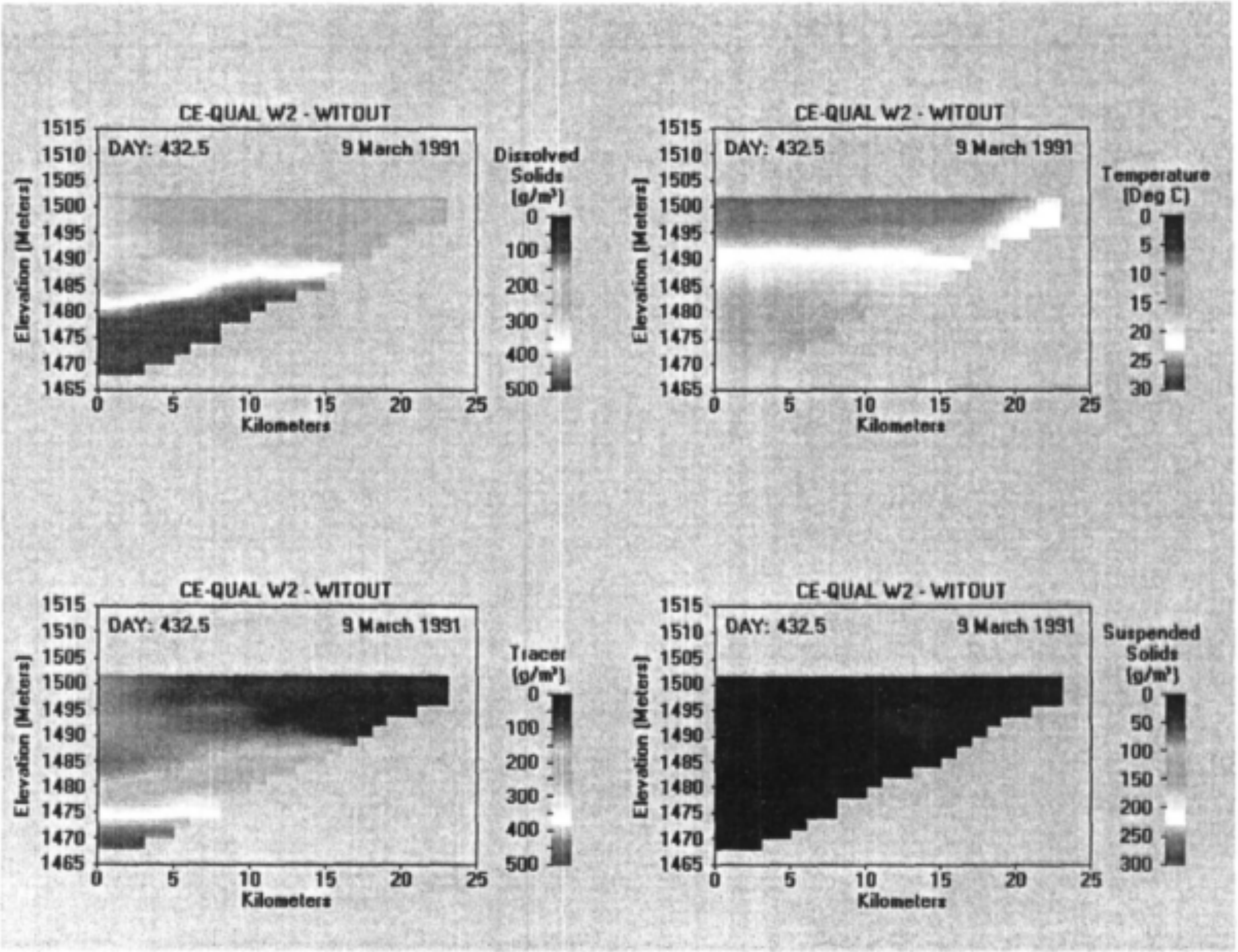

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Figure 3.8.3(a) Cross section showing the effect of a small autumn flood on Witbank Dam

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3.8.4 Reservoir behaviour - Large Floods – Spring

No large floods were recorded in the spring during the period of 1990 to 1998.

3.8.5 Reservoir behaviour - Large Floods – Summer

A number of large summer floods took place over the study period (**Figure 3.8.5 (a) & (b)**). The large floods that took place during the summer of 1995/96 were examined in greater detail.

The large flood like the one that took place in December 1995 and February 1996 had the effect of entering the reservoir as surface flow on top of the thermocline. The high velocity of the inflow had the effect of pushing the inflowing water far into the reservoir (**Figure 3.8.5 (c) & (d)** 25 Dec 1995 & 28 Feb 1996). The high inflow also had the effect of eroding the thermocline at the upper reaches of the dam. The inflow resulted in a strong water quality gradient along the length of the dam. The inflowing water had a lower TDS and SO_4 concentrations that in the reservoir. Towards the end the flood, the strong water quality gradient was reduced to a large degree and the in-lake TDS and SO_4 concentrations were reduced through dilution.

3.8.6 Large Flood - Autumn

A large flood that occurred in April 1997 was examined. The dam level was kept close to the full supply level during that time. The flood entered the reservoir largely as surface and interflow (**Figure 3.8.6(a)**). Thermal stratification was not as strongly developed as the stratification observed during the summer months. Early April is very close to winter turnover for the reservoir and thermal stratification is already unstable. The position of the thermocline therefore does not have a strong impact on determining the position of the inflowing water. Mixing of the inflow is therefore deeper into the water column. A large autumn flood has the potential of breaking down thermal stratification to a large degree before winter turnover can take place. However, large autumn floods do not occur every year and is the exception rather than the rule.

3.8.7 Conclusions about flood events and its impact on water quality in Witbank Dam

There are a number of factors that determine what happens to flood inflow into a reservoir like Witbank Dam.

Timing of the flood – timing of the flood is related to the degree of stratification in the reservoir. Early in summer, the thermocline is shallow and weakly developed. A small flood can erode the thermocline and result in good mixing of the inflowing water. During summer, the reservoir is generally strongly stratified and inflowing floods tend to enter the reservoir as surface and interflow. Mixing tend to be in the surface layers. It was seen that very large floods can erode the thermocline, especially in the upper reaches of the dam and this results in deeper mixing of the inflowing floodwaters. Floods that occur in autumn tended to enter on top of the thermocline but the later the flood, the easier it was to erode and break down the thermal stratification resulting in deeper mixing if the inflowing flood waters. Most winter inflows was colder that the water in the dam and entered the dam as underflow, following the bottom contours and accumulating in the bottom layers of the dam.

Magnitude of the flood – the magnitude of the flood (and through flow) determined how far the inflowing water extended into the dam and how deep it mixed into the water column. Smaller floods did not extend very far into the dam before it became well mixed with the surrounding water. Larger floods extended far into the dam in some cases, it eroded the thermocline to such a degree that it mixed with the deeper layers of the dam. This was especially evident in the upper reaches of the dam.

Figure 3.8.5(a)

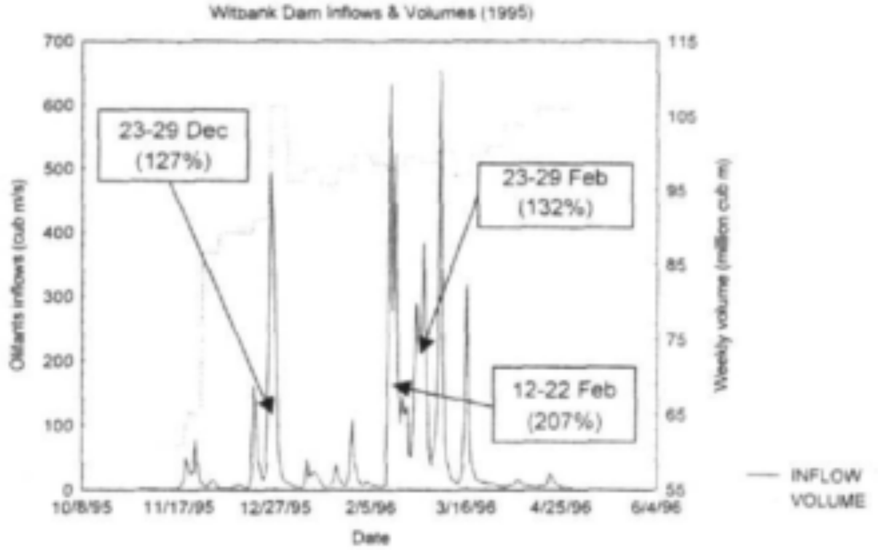

Figure 3.8.5(b)

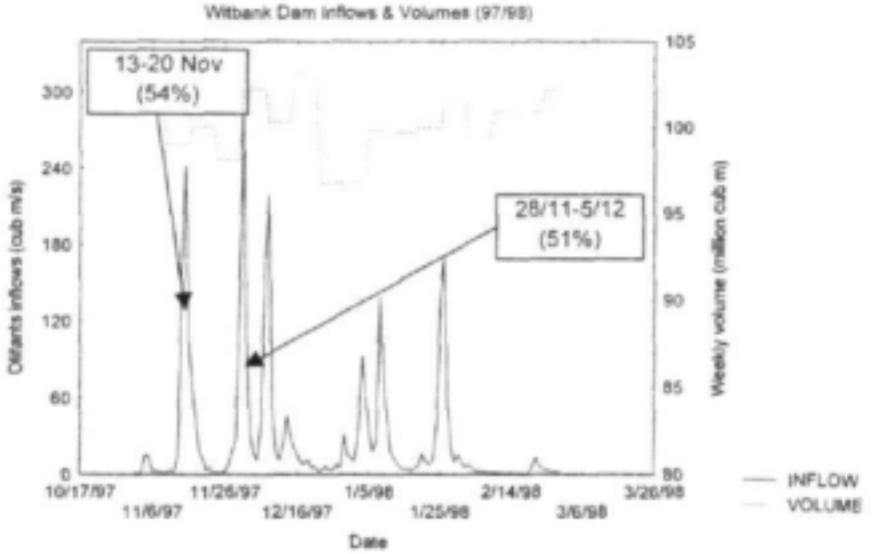

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Figure 3.8.5 Examples of large summer floods examined

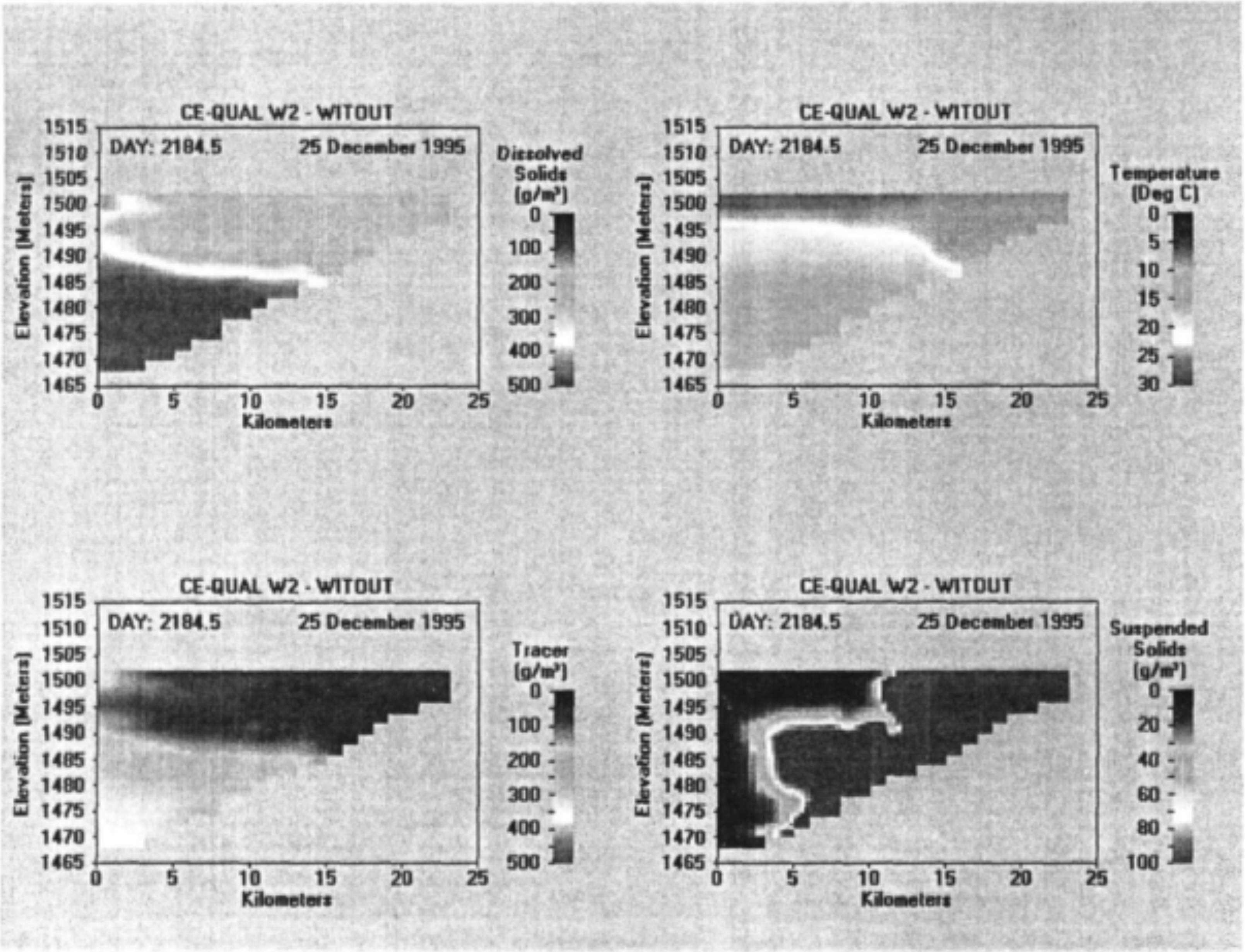

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Figure 3.8.5(c) Cross section showing the effect of a large summer ng flood on Witbank Dam

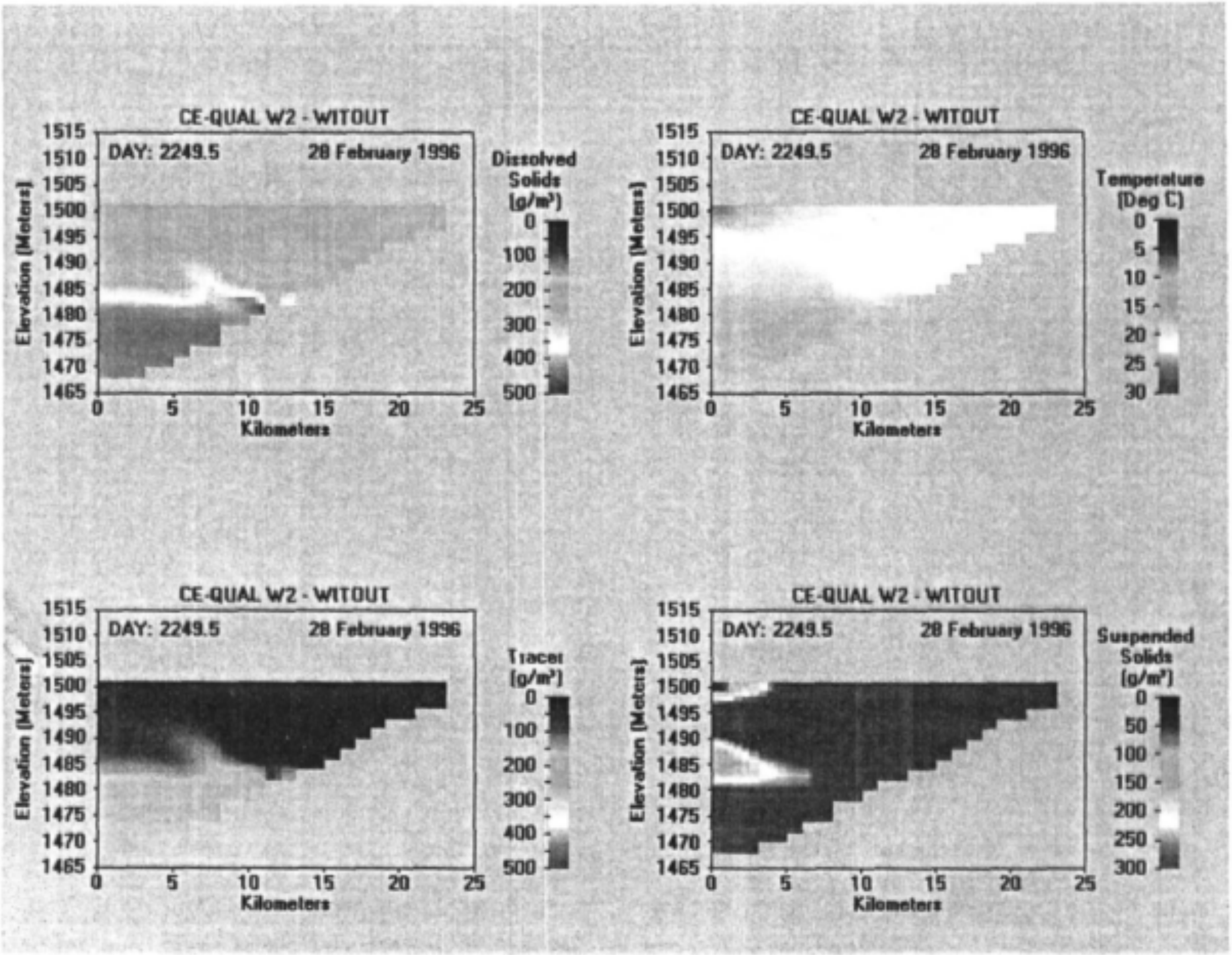

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Figure 3.8.5(d) Cross section showing the effect of a large summer ng flood on Witbank Dam

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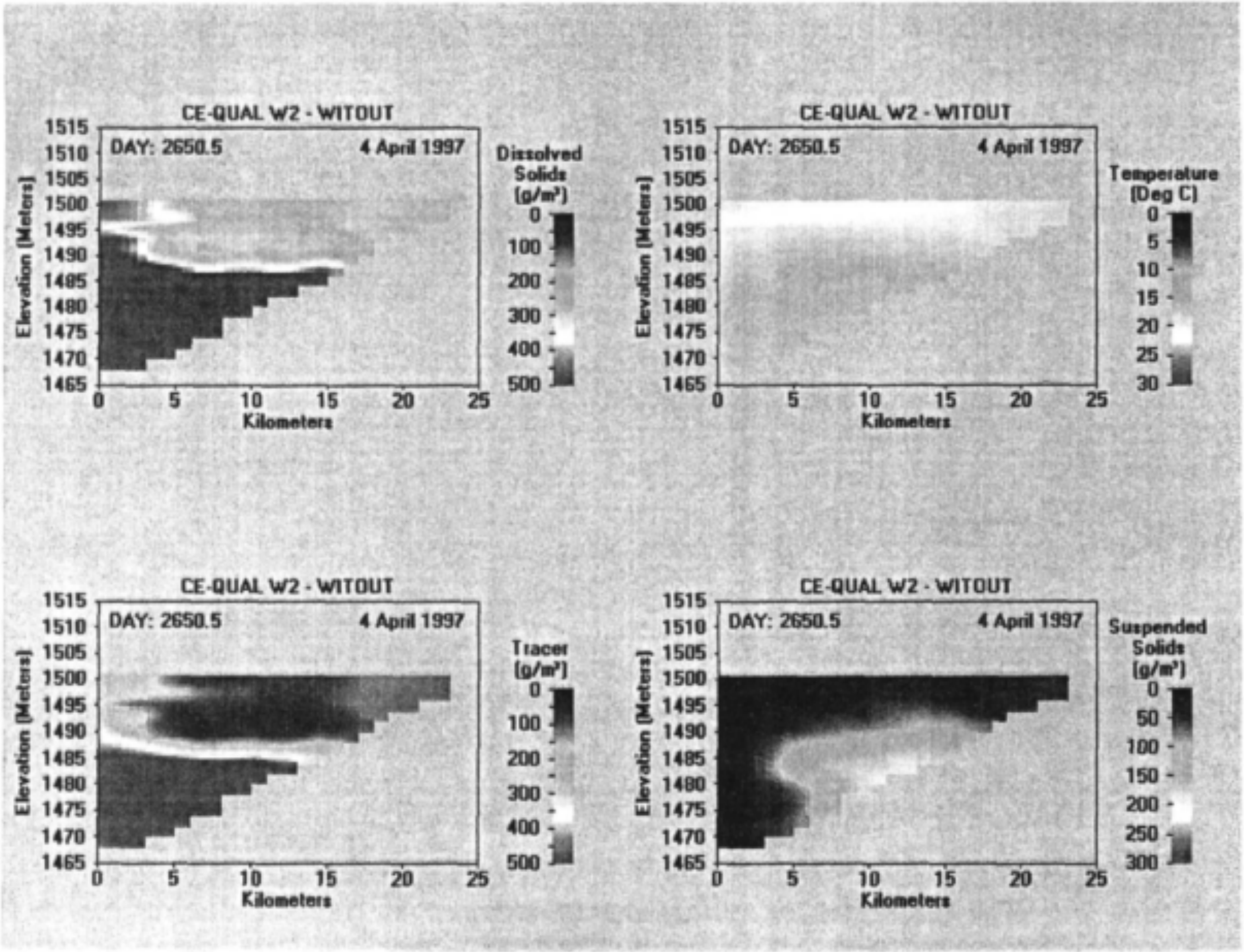

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Figure 3.8.6(a) Cross section showing the effect of a large autumn flood on Witbank Dam

It is clear that the reservoir cannot be regarded as fully mixed, i.e. no or little changes in water quality along its length or depth. **Figure 3.8.7 (a)** shows a depth profile at the dam wall for TDS and for temperature.

The temperature profile shows the annual change in stratification, starting with the warming of the surface water in spring, the deepening of the epilimnion during summer and then breakdown of thermal stratification when winter turnover occurs in late autumn.

The TDS profile shows that there is a build-up of high TDS water in the bottom layers of the reservoir. The TDS in the bottom layers can only be removed if a large through flow of water occurs. It can be seen that allowing the dam to fill, (like happened early in 1993 (day 1100-1500)) resulted in a build-up of TDS in the lower layers of the dam because very little water was let out during that time other than the normal releases to Witbank Municipality and meeting other minor demands. However, that was followed by a period during which the flow of water through the reservoir increased and the TDS concentrations in the lower layers of the dam gradually decreased.

It can be concluded that, in order to utilise floods for the controlled release of saline effluents, the flow through the reservoir should be carefully considered so that saline water is not allowed to accumulate in the bottom layers for extended periods of time.

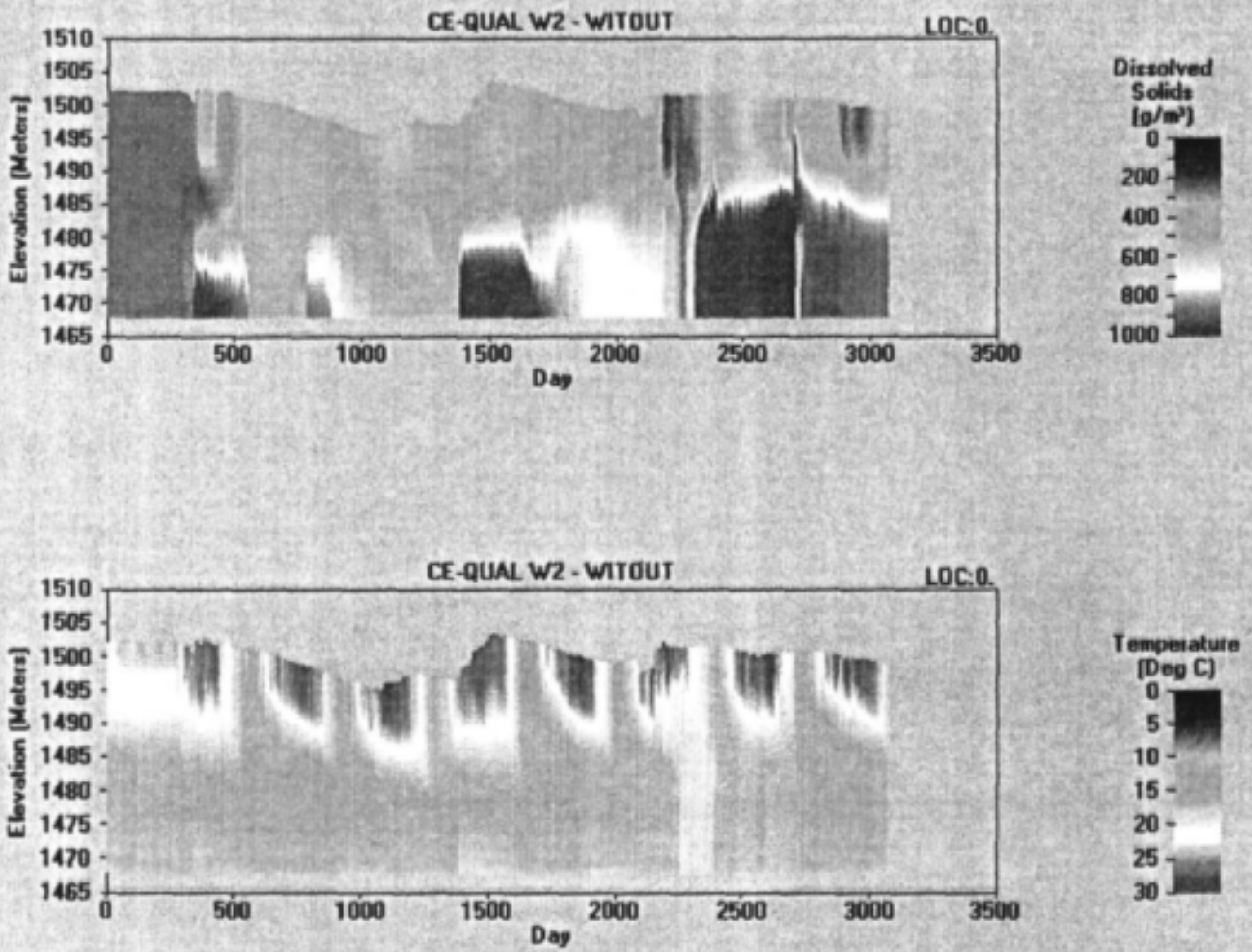

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Figure 3.8.7(a) Time-depth plot of TDS and temperatures close to the dam wall of Witbank Dam

4 LINKAGE OF MODELS

4.1 Introduction

In this section, the linkage between the catchment and dam models is described as well as the general operation of the program. The dam model consists of the compiled source code, text data input and output files and a program to display the simulation results. The output program was developed by Ninham Shand and is written in Delphi. The catchment model consists of Visual Basic code with the input and output from the model stored in an Access database. The challenge in developing the model is to get the different programs to communicate with each other. The approach adopted is described in **Section 4.2**.

The software required to operate a controlled release scheme needs to be able to address the daily operation of a scheme and to be able to look at possible future scenarios that could occur in the Witbank Dam. The two modes that were identified and that have been incorporated in the model are an operational and a scenario mode. Details of the two modes are given in **Section 4.3**.

4.2 Description of Model Structure

The model consists of the following components:

- Catchment Model
- Catchment Model, input and output programs
- Dam Model
- Dam Model output program
- Dam Model input and output files
- Access Database
- Translator

The structure linking the different components listed above is shown schematically in **Figure 4.2(a)**.

4.2.1 Catchment Model

The catchment model consists of the flow and pollution routing algorithms described in **Section 2**. The connectivity of the different channel reaches making up the system is built into the program. The details of each of the reaches such as slope, length and cross sectional shape are stored in the database and are automatically accessed from the model. The results of a run are stored in the database. The results are the routed flows and sulphate concentrations at the control points in the system.

4.2.2 Catchment Model, input and output programs

The input program for the catchment model enables the daily flows and sulphate concentrations measured at the control points in the field to be input into the database as well as the data on the releases made by the mines. The results of the catchment model runs can be viewed using the output program for the catchments.

4.2.3 Dam Model

The dam model is the CE-QUAL-W2 model. The model uses text files to store its input and output data.

4.2.4 Dam Model output program

The output program developed by Ninham Shand is used to display the results of the model runs. Plots of the sulphate concentration at different elevations and cross sections in the dam can be displayed. The model allows the user to step through the time series and view the concentration changes on the computer screen.

4.2.5 Dam Model Input and Output files

These fields are used to store the input and output data for the Dam model. The files are in text format specific for the CE-QUAL-W2 model.

4.2.6 Access Database

The Access database is used to store the flow and water quality data collected at the control points in the catchment, the mine release information and the results of the model runs in the form of time series graphs of flow and sulphate concentration can be viewed on the screen.

4.2.7 Translator

The translator has been written to convert the flow and water quality data into the format required by CE-QUAL-W2. The Translator is therefore the communication software between the Access database and the text input and output files for CE-QUAL-W2.

4.3 Modes of Operation

4.3.1 Scenario Mode

There are two ways in which the model can be run in scenario mode. The first way is to merely view the historic flow, dam capacities and water quality information at the control points and in the Witbank Dam. The method of viewing is through the catchment and dam output programs. The output is in the form of time series plots of flow and water quality at the control points and in the dam.

The other approach that can be used in scenario mode is to be able to predict what the sulphate concentration in the Witbank Dam could be sometime in the future. This capacity is useful for predicting possible conditions in the dam at the end of winter when the next year's controlled release scheme is due to begin. The methodology employed is based on a set of start conditions being selected from the historic records for the Witbank Dam and the control points. Then any time series of flows and qualities can be selected from the historic records at the inflow points to the dam and run through the catchment and dam model to predict the concentrations that could occur in the dam at the end of the specified time period.

4.3.2 Operation Mode

Under the operational mode, the model can be used to predict the impact of flood releases into Witbank Dam. The system is designed to predict the state of the dam two to four weeks in advance of the current state. The catchment model provides the inflow volume and water quality to the reservoir model. The system then performs a water balance for the dam; it helps with the selection of a meteorological condition for the next two weeks and then estimates the state of the dam for the next two to four weeks. The user can then examine the state of the dam to assess whether any of the water quality objectives set for the dam will be violated during that period. If so, the model can be rerun with new starting conditions.

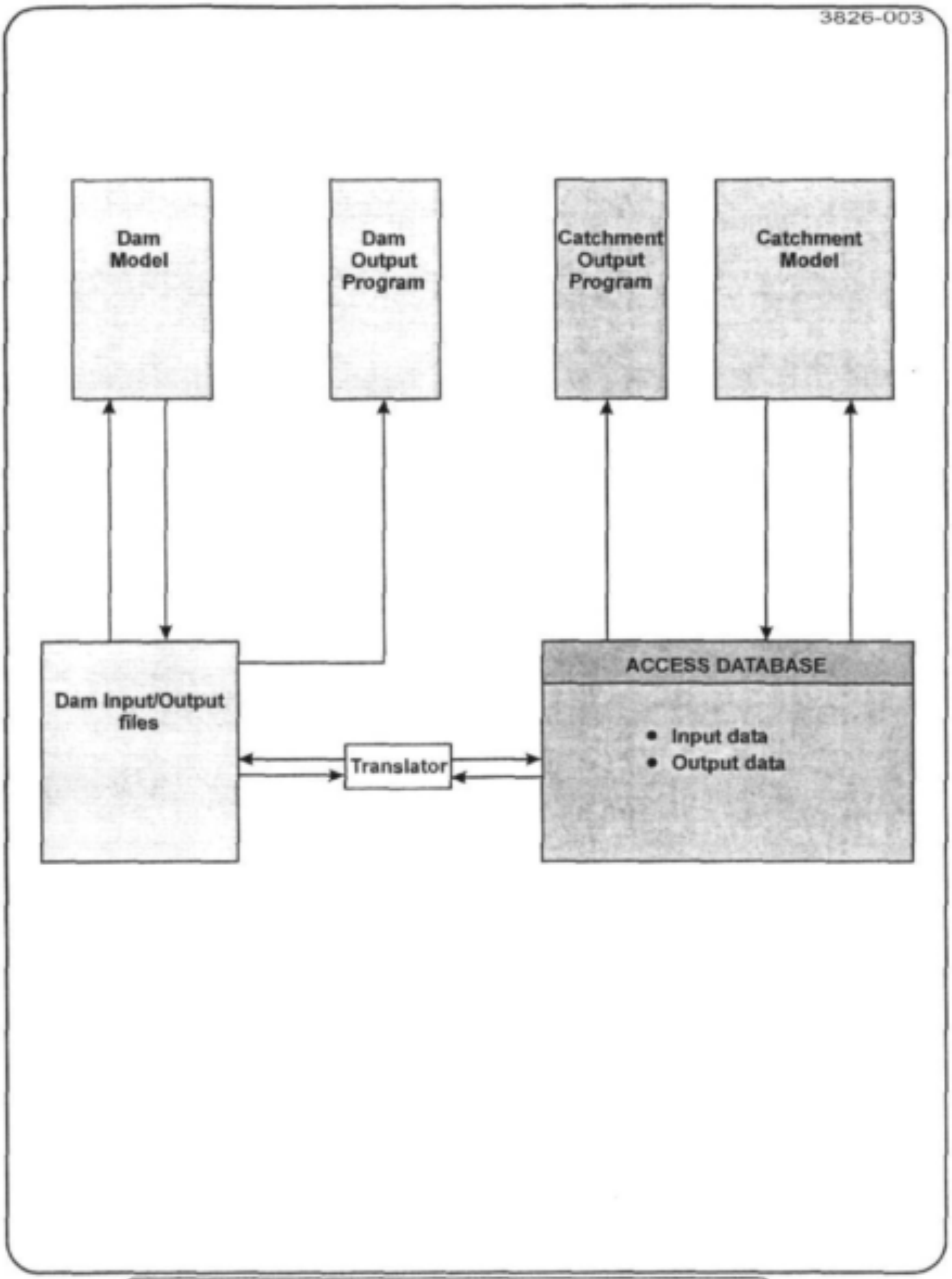

Figure 4.2 (a) : Structure of Program

5 APPLICATION OF DECISION SUPPORT SYSTEM

5.1 Introduction

The purpose of this Chapter of the report is :

- To give an indication of the usefulness and possible applications of the research;
- To provide an example of the application of the Decision Support System (DSS) to the Witbank Dam;

Section 5.2 deals with the application of the research while the example of the application of the model is described in **Section 5.3**.

5.2 Application of the research

The application of controlled release as a method for the management of water containing waste is relatively new in South Africa. In particular the application of this approach on a regional basis involving a number of role players sharing the available assimilative capacity. The requirements for the use of this type of scheme are not widely understood or appreciated. The contribution that this research makes can be divided into general insights and guidance and specifics related to the DSS for the Witbank Dam.

The research described in this report provides insight and guidance to the following aspects of controlled release schemes as a means of managing water containing waste:

- The application of controlled release schemes on a regional basis is relatively new in South Africa. There are a number of issues that have to be considered at the feasibility and implementation stages of this type of approach to the management of water containing waste. The factors that were considered in setting up the Witbank Dam catchment scheme are discussed in **Section 1** of this report. These elements will have to be considered wherever a scheme of this type is to be applied;
- The type of pollutant, flood routing and dam pollutant modelling methodology best suited to a controlled release scheme are discussed;
- The extent and level of the management system needed is highlighted. In particular the intensive flow and quality monitoring programs required;

In terms of the DSS, the project has resulted in a system that can be used to better run the existing controlled release scheme. The system, although "hard wired" for the Witbank Dam catchment, can be applied to other catchments and dam systems. This is shown in the following sections of this chapter with the application of the DSS in scenario and operational modes.

5.3 Application of the DSS

5.3.1 Introduction

The DSS can be applied in two modes viz the scenario and operation modes. The scenario mode is used to predict the changes in the sulphate concentration in the Witbank Dam some time in the future. The current storage and sulphate concentrations in the dam are used as the start conditions. A number of possible future inflow time series of sulphate concentrations and volumes are input to the model of Witbank Dam to predict possible time series of sulphate concentrations in the dam. These runs are typically done for dry, median or wet flow sequences into the dam. This gives the planners and the scheme participants an indication of the likelihood of releases during the next rainfall season.

The operations mode is the day to day running of the scheme. To demonstrate the application of this mode, the DSS system is run for a particular inflow event during which releases could be made. The process followed in determining the available assimilative capacity using the system is demonstrated.

5.3.2 Scenario Mode

Two three year sequences of inflow and sulphate concentrations measured at the Boesmankransspruit, Noupoortspruit and on the Olifants River (Wolwekrans weir) were input to the model of the Witbank Dam. The sequences were representative of dry and typical or median flow conditions in the catchment. Plots showing the variation in the sulphate concentration at the dam wall predicted by the model for the two sequences are given in **Figure 5.3.2(a)**.

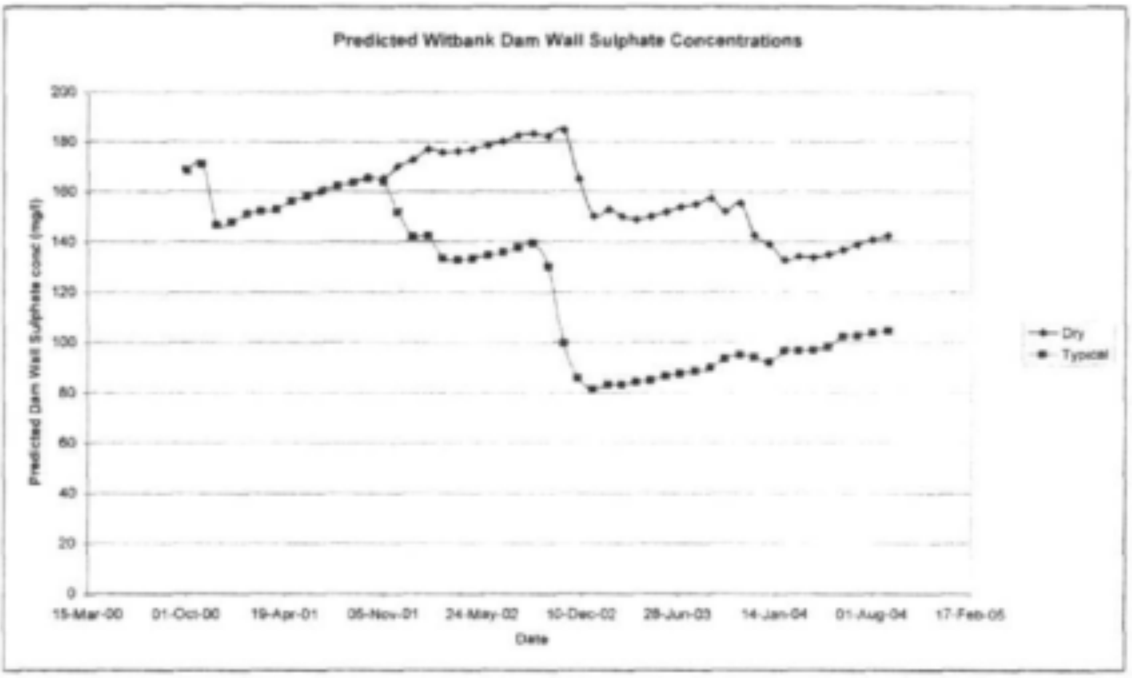

Figure 5.3.2(a) : Predicted sulphate concentrations at the dam wall for dry and typical inflow sequences

The sulphate concentrations in the dam in November 2001 were used as the start conditions for the modelling. The current abstractions from the dam were assumed to be constant over the three year simulation period. Seasonal averages of the required meteorological input parameters to the dam model were estimated from the historic records and used for the modelling.

The results show that for a dry flow sequence, releases are unlikely for a target of 155 mg/ℓ during the first year of the sequence. Release can only be considered during the second year. However, for the more typical flow sequence, releases will be able to be made in the first year.

5.3.3 Operations Mode

The aim of using the DSS in operations made are:

- To determine the releases that can be made while maintaining the target concentration at the control points in the catchment.

- To calculate the available assimilate capacity in the dam.

The approach used to determine the releases that can be made is summarised as follows:

- Assume that the current flow rates and sulphate concentrations at the control points will be constant over the next 24 hours. This includes the mine release rates and qualities.
- Route the flow and sulphate concentrations from the upstream control points to predict a hydrograph and pollutograph at Wolwekrans weir for the current releases.
- Adjust the mine release rates and re-route the flows and qualities until the target concentrations are met at the control points.
- The process is repeated once the next days flow and quality readings are available.

The above procedure is shown graphically in **Figure 5.3.3(a)** for the Wolwekrans weir

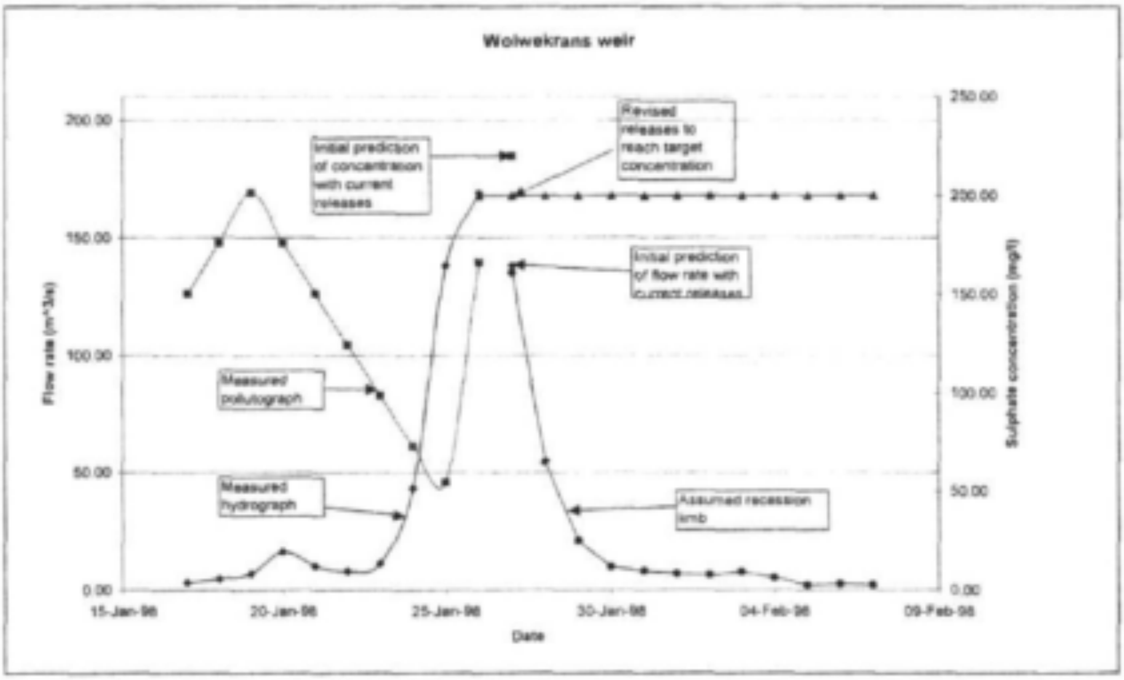

Figure 5.3.3(a) : Graphical representation of the DSS process at Wolwekrans weir

During the operations mode, the dam model is run to check that the releases made do not result in the dam exceeding the target concentrations. A point is fixed in time at which the start conditions in the dams are known. The model is run from the start point with the measured inflows up until the latest set of readings. As the dam takes 2 to 4 weeks to respond to changes in the inputs, the existing hydrographs and pollutographs on the three main influent streams are extended using typical curves for the recession limb and base flow sulphate concentrations. The extended hydrographs and pollutographs are routed through the dam model to check on the impacts of the releases on the dam sulphate concentrations. If necessary, the release loads are reduced if the concentrations are going to exceed the targets.

6 CONCLUSIONS

The following conclusions and recommendations can be made as a result of this study.

- The ISIS and HSPF models could both be used for a controlled release scheme. However, the linking of the data stored in the database of the ISIS and HSPF models to the CE-QUAL-W2 model would be too onerous. The flow and pollutant routing algorithms in the WITSKM/WITQUAL package were used in developing the Decision Support System.
- Considering the accuracy of the available information, a reasonable calibration of the flow and pollutant routing methods was achieved at Wolwekrans weir.
- The time step at which data is collected determines the accuracy of the hydrograph and pollutograph. The longer the monitoring time step, the less accurate the representation of the event.
- The choice of a suitable monitoring time step depends on the variability of the flow. The more variable, the smaller the time step has to be to adequately capture the flow and quality information.
- The performance of a controlled release scheme is sensitive to the decision making time step. The longer the time step the poorer the performance of the scheme. In the case of the Witbank Dam catchment, a factor of safety is built into the waste load while the scheme is operating at a 24 hour time step. Flow projection techniques on the recession limb of the hydrograph should be considered to reduce the number of target concentration exceedances.
- The CE-QUAL-W2 model runs showed that Witbank Dam cannot be considered as completely mixed during the summer months. The data records and the modelling indicate that there is both a vertical and a longitudinal variation in salinity and sulphate concentrations during the summer months.
- The application of the reservoir water quality model showed that the smaller autumn floods tended to enter on top of the thermocline resulting in little mixing with deeper water layers. However, the later the flood occurred in autumn, the easier the thermal stratification is to break down and the deeper the mixing.

7 RECOMMENDATIONS

- Consideration should be given to managing the flow through the reservoir to prevent the build up of saline water in the bottom layers during summer stratification. A monitoring program should be implemented on the dam to determine salinity depth profiles to verify the dam behaviour and to implement management if needed.
- The depth profiles should also be used to verify the model predictions and to improve the calibration if necessary.
- Controlled release has a future as a management method. A set of guidelines should be developed detailing monitoring and instrumentation requirements, feasibility level studies needed, modelling requirements, management systems and legal requirements.
- The impact that the principles to be used in determining waste discharge charges could have on a controlled release scheme should be assessed.

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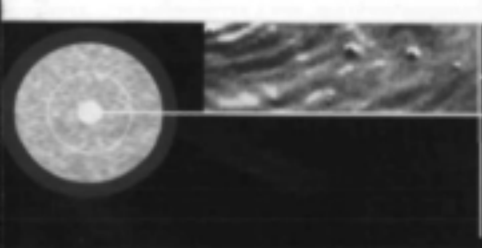

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