RESEARCH ON BERG RIVER WATER MANAGEMENT

SUMMARY OF WATER QUALITY INFORMATION SYSTEM AND SOIL QUALITY STUDIES

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PREFACE

BACKGROUND

Impoundments and associated bulk water supply infrastructure are present in most South African river systems. Because of the disparate natural occurrence of rainfall and runoff, and its mismatch with water demand concentrations, many of these schemes have to incorporate inter-catchment transfers to meet demands in the face of inadequate local availability. Furthermore, water quality deterioration, because of human impacts through a wide range of land-uses and waste discharges, has for some time been recognised as a threat in South Africa, as it diminishes the utilisable part of the runoff in many catchments. These complexities increasingly offer challenges to water resource managers that require a response with integrative management philosophies and innovative management tools.

In recognition of the aforementioned needs, Prof André Görgens of the Department of Civil Engineering of the University of Stellenbosch, during 1997, engaged water resource managers in the Department of Water Affairs and Forestry in discussions about an appropriate research response to these management challenges. From these discussions a research proposal to the Water Research Commission (WRC) was born, whose aim would be to serve the philosophy of Integrated Water Resource Management (IWRM), through the development of an integrated information system specifically for water quality – here abbreviated to “WQIS”.

To be useful to IWRM, this WQIS was to provide diagnostic and predictive utilities to serve technical planning and operational decision-making in a river system, but, simultaneously, provide appropriate information to support water managers in communication with technical stakeholders. It was also recognised that the project would need identification of a “prototype” catchment for development of appropriate WQIS approaches and to provide a relevant database. Early candidate catchments for this purpose were the Berg River and Breede River in the Western Cape and the inter-connected Fish-Sundays river system in the Eastern Cape.

Simultaneous with the research formulation process described above, the late Prof Hulme Moolman of the Department of Soil and Water Science[1] (DSWS) at the University of Stellenbosch, started formulating a research proposal to the WRC to investigate the causes of and quantification of salinisation of the Berg River, one of the prime water sources to meet growing demands in the Greater Cape Town and West Coast Region. Both the Department of Water Affairs and Forestry and agricultural and industrial stakeholders had expressed concern about perceptions that Middle- to Lower-Berg River salt concentrations appeared to be on the increase.

Unfortunately, Prof Moolman, who at the time was engaged in salinity-related research in the neighbouring Breede River catchment and who was the leading salinity-related researcher in South Africa, fell gravely ill before the research proposal approval process was completed. As a strategy to ensure that the research process at the DSWS would continue regardless of the outcome of Prof Moolman’s illness, the WRC requested Prof Görgens, who had done salinity-related research in the past, to take over management of both his own Department’s research proposal and that of the DSWS. The result was that the two separate proposal formulation processes were merged to form a single Terms of Reference and, ultimately, a single contract between the WRC and the University, with Prof Görgens as the Project Leader. It then also made sense to select the Berg River as the prototype for the WQIS development, partly because of the accent that the DSWS research would put on salinisation processes, which is one the Berg River’s most pressing issues, and partly because the Berg contains all the general water resource management challenges and complexities referred to earlier[2].

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[1] Now called the Department of Soil Science.

[2] The combined impoundments of the Riviersonderend-Berg River (RSE-BR) system currently contribute more than 80% of the total annual water yield of 450 million m^3 available to the Greater Cape Town and West Coast Region. The current RSE-BR system comprises Theewaterskloof Dam on the RSE River, linked by tunnels to the Berg and Eerste River catchments, as well as Wemmershoek and Voëlvlei Dams (both of which are off the Berg River main-stem). Sustained growth in the water requirements of the Region necessitates expansion of the RSE-BR system in the near future. The following Berg River schemes have been under investigation for implementation: Skuifraam Dam in the Upper-Berg, Skuifraam Supplement Scheme downstream of Franschhoek and Middle-Berg Diversion Scheme to Voëlvlei Dam. Apart from supplying the bulk needs of the Region, these schemes would also serve the Government’s rural development strategy in that they will support upliftment of a number of disadvantaged communities in the Berg catchment and will make possible development of irrigation schemes for emergent farmers from these communities. Additionally, irrigation extensions by currently established farmers will be made possible. However, the implementation of these schemes would remove an additional 20% of fresh water from the Berg River main-stem and will lead to a more regulated river system between Skuifraam and the Lower Berg. The likelihood of all these developments has sparked serious concerns relating to future water quality fitness-for-use and maintenance of ecological integrity.

PROJECT AIMS

The original aims of the project as specified in the WRC contract are as follows:

i) To develop Water Quality Information Systems to support both integrated management of a water resources system, and to support communication about water quality management with stakeholders and communities in the catchments of that system.
ii) To develop an understanding of the primary water quality responses, and their causes, of the Riviersonderend-Berg River (RSE-BR) System, which would serve as a case study for the Water Quality Information System implementation.
iii) To evaluate the potential for operation of the future RSE-BR System to meet recently developed salinity guidelines for irrigation.

As the project planning unfolded, it became clear to the Steering Committee that the aims needed adjustment for two sets of reasons: On the one hand, they were too broad for the available budget and time-frame. On the other hand, parallel development of suitable approaches to community participation in IWRM, as part of DWAF's initiatives to implement the National Water Act, were forcing a change in the focus of the project. The Steering Committee, therefore, agreed that most of the research focus would fall on Aims (i) and (ii), and that (iii) should be seen as a long-term objective of salinity-based research in the Berg River catchment. Furthermore, the Steering Committee agreed that the WQIS would primarily be developed as a technical information tool aimed at supporting water resource managers and stakeholders on the technical domain, and that communication support for community participation in consultative water management processes would fall outside the ambit of the current contract.

TWO RESEARCH THEMES, TWO RESEARCH TEAMS

The background described earlier, as well as the stated objectives, imply that two related, but essentially different, research themes underlie this project:

- Theme One: Development and/or application of decision support software for general water quality management in a river system with diverse components and human impacts.
- Theme Two: Water quality-related research in the form of field-scale process studies and large-scale soils data interpretation, with a strong focus on salinisation processes.

It follows that, when the project was resourced at its initiation in July 1998, the two Research Themes, and the involvement of two different University Departments, would lead to the establishment of two separate Research Teams.

The Theme One research (water quality management decision support software) was undertaken by the Department of Civil Engineering and comprised the following researchers:

- Prof AHM Görgens – Project Leader
- N Nitsche – Hydrodynamic River Flow and Water Quality Modeller (full-time)
- W Kamish – Reservoir Modeller (part-time)
- J Tukker – Water Quality Information System Software Developer (full-time)
- MP Matji – Support Hydrologist (part-time).

The Theme Two research (field-scale-processes and large-scale mapping) was undertaken by the Department of Soil Science and comprised the following researchers:

- WP de Clercq – Senior Researcher (full-time)
- Prof MV Fey – Specialist Advisor (part-time)
- Dr F Ellis – Specialist Soil Scientist (part-time)
- H Engelbrecht – Junior Researcher (full-time)
- K Latief – Laboratory Assistant (full-time)
- K Davidse – Laboratory Assistant (part-time)
- P Basson – Technikon Internship (full-time for one year)
- M van Meirvenne – Visiting Researcher (part-time)
- G de Smet – Visiting Researcher (part-time)

Mr Willem de Clercq, appointed at the Project initiation as full-time Senior Researcher, took care of the Department of Soil Science component of the research. Prof Martin Fey was appointed as Prof Moolman's successor when about 55% of the project duration had been completed. Given the work load attached to his new position, Prof Fey preferred to act as Specialist Advisor, with Mr de Clerq continuing to lead that Department's research under this Project.

STRUCTURE OF REPORTS AND SUPPORTING OUTPUTS

Given the essentially different nature of the two sets of Research Themes described earlier, the Steering Committee decided that two free-standing sets of Reports and other deliverables would ensue from the Project – one set per Theme – as described below.

Theme One research (water quality management decision support software):

i) *Volume 1: Application of hydrodynamic water quality models for river flow and reservoir processes to the Berg River System* by N Nitsche, W Kamish and AHM Görgens.

ii) *Volume 2: Development of the WQIS (Water Quality Information System): Application to the Berg River System* by MJ Tukker and AHM Görgens.

An Extended Summary version of these two Volumes have been produced as paper documents, while the full versions of these two Volumes are presented on CD, lodged inside an envelope inside the back cover of each paper document. The reader should note that the CD also contains a demonstration version of the full WQIS as configured for the Berg River, complete with installation requirements

Theme Two research (field-scale-processes and large-scale mapping):

i) *Volume 3: Water and soil quality information for integrated water resource management: The Berg River catchment* by W.P de Clercq, F. Ellis, M.V Fey, M van Meirvenne, H Engelbrecht, G de Smet.

Volume 3 also includes a soils map with legend and Salinity Hazard map of the Berg River catchment as a free-standing program that allows viewing and printing of the maps.

An Executive summary is presented that highlights all aspects of theme two of this research. The full report is, however, presented on the accompanying CD with an interactive Acrobat version of the maps, lodged inside an envelope inside the back cover of each paper document.

CAPACITY-BUILDING

Department of Civil Engineering, University of Stellenbosch

Human resource development: The Project Team comprised four young professionals who are all members of the so-called "Designated Group" under the Employment Equity Act of 1999. These researchers are:

- Ms Nadia Nitsche (Civil Engineer and River Flow / Water Quality Modeller)
- Ms Jean Tukker (Hydrologist and Software Developer)
- Mr Wageed Kamish (Chemical Engineer and Reservoir Modeller)
- Mr Maselaganye Matji (Hydrologist and Catchment Modeller).

Three of the team members have acquired Master's degrees based on this and related research.

Technology transfer: Demonstrations of an early version of the Water Quality Information System software were given to officials of DWAF (Dept.: Water Quality Management and Dept.: Water Resource Planning) in Pretoria, DWAF Regional Office officials in Bellville and officials of the Department of Agriculture in Elsenburg. Papers on the hydrodynamic modelling of Skuifraam have been read at the SAICE Conference in May 2001 in George and at the SANCIAHS conference in Pietermaritzburg in September 2001.

Department of Soil Science, University of Stellenbosch

Human Resource Development: The following persons from the Designated Group worked on the Project as Laboratory Assistants:

- Ms Kamilla Latief
- Mr Kenneth Davidse

On each of the farms, Rooihoogte and Broodkraal, a local employee from the Designated Group was trained by the Department of Soil Science researchers to do soil moisture readings with both the neutron probe and tensiometers, and also to take and preserve water samples.

Collaboration with Technikons: Mr Pieter Basson, a final year Technikon student in Civil Engineering, worked full-time on this project for a year to meet the Technikon requirements for full-time in-service training.

Technology Transfer: On 28 August 2001 three seminars were held on the farm Rooihoogte:

- *Besproeingsgronde langs Berg Rivier met klem op Rooihoogte en Broodkraal plase*, by Freddie Ellis.
- *Sout voorkoms in besproeiingsgronde van Broodkraal en Rooihoogte*,.by Hendrik Engelbrecht
- *Die omvang van brak, bestuur daarvan en die toekoms*, by Willem de Clercq.

The following papers were presented at the Cartographic Modelling and Land Degradation Workshop, Gent, Belgium, 24-25 September 2001:

- *Mapping soil salinisation in an irrigated vineyard in South Africa*, by W de Clercq, G de Smet and M Van Meirvenne.
- *Land degradation on old land surfaces affected by termite activity in arid and semi-arid regions of South Africa*, by F Ellis.

Papers presented at congresses:

- *Contribution of termites to the formation of hardpans in soils of arid and semi-arid regions of South Africa.* Ellis, F., 2002. Paper delivered at the 17th World Congress of Soil Science, Bangkok, Thailand, August 2002.
- *Soils associated with microrelief features ("heuweltjies") occurring on an ancient land surface in the lower Berg River Valley.* Ellis, F., de Clercq, W.P. & Engelbrecht, H. Soil Sci. Soc. South Africa Congress, Pretoria, 2001.

Theses completed and in progress:

- De Smet G. (2001). Mapping soil salinity in South Africa. Land and Forest Management, Ghent University, Belgium. (Ing)
- Engelbrecht H. (2002). Modelling soil salinity in the Berg River Catchment. Department of Soil Science, University Stellenbosch. (MSc, in progress)
- De Clercq WP (2002). Defining & mapping soil salinity hazard in irrigated vineyards of S.A., Department of Soil Management, Ghent University, Belgium. (PhD, In progress).

Rural Community Interaction: Discussions about this project have been held with representatives of the Saron and Wittewater (at Moravia) communities in the Middle- to Lower-Berg River catchment.

RESEARCH ON BERG RIVER WATER MANAGEMENT

VOLUME 1

(*Summarised*)

APPLICATION OF HYDRODYNAMIC RIVER FLOW AND RESERVOIR WATER QUALITY MODELS TO THE BERG RIVER SYSTEM

by

N Nitsche, W Kamish and AHM Görgens

Departments of Civil Engineering and Soil Science,
University of Stellenbosch

Final report to the Water Research Commission on the project
A Water Quality Information System for Integrated Water Resource Management :
The Riviersonderend-Berg River System

EXECUTIVE SUMMARY
VOLUME 1

BACKGROUND

Impoundments and associated bulk water supply infrastructure are present in most South African river systems. Because of the disparate natural occurrence of rainfall and runoff, and its mismatch with water demand concentrations, many of these schemes have to incorporate inter-catchment transfers to meet demands in the face of inadequate local availability. Furthermore, water quality deterioration, because of human impacts through a wide range of land-uses and waste discharges, has for some time been recognised as a threat in South Africa, as it diminishes the utilisable part of the runoff in many catchments. These complexities increasingly offer challenges to water resource managers that require a response with integrative management philosophies and innovative management tools.

During 1997, in recognition of the aforementioned needs, the Department of Civil Engineering of the University of Stellenbosch, formulated a research proposal to the Water Research Commission (WRC) whose aim would be to serve the philosophy of Integrated Water Resource Management (IWRM), through the development of an integrated information system specifically for water quality – here abbreviated to “WQIS”. To be useful to IWRM, this WQIS was to provide diagnostic and predictive utilities to serve technical planning and operational decision-making in a river system, but, simultaneously, provide appropriate information to support water managers in communication with technical stakeholders. It was also recognised that the project would need identification of a “prototype” catchment for development of appropriate WQIS approaches and to provide a relevant data base.

Simultaneous with the research formulation process described above, the Department of Soil and Water Science[1] (DSWS) at the University of Stellenbosch, formulated a research proposal to the WRC to investigate the causes of and quantification of apparently increasing salinisation of the Berg River, one of the prime water sources to meet growing demands in the Greater Cape Town and West Coast Region. The WRC proposed that the two separate proposals be merged to form a single Terms of Reference and, ultimately, a single contract between the WRC and the University, with Prof Görgens as the Project Leader. It then also made sense to select the Berg River as the prototype for the WQIS development, partly because of the accent that the DSWS research would put on salinisation processes, which is one of the Berg River’s most pressing issues, and partly because the Berg catchment contains all the general water resource management challenges and complexities referred to earlier

OVERALL PROJECT AIMS

The original aims of the project as specified in the WRC contract are as follows:

i) To develop Water Quality Information Systems to support both integrated management of a water resources system, and to support communication about water quality management with stakeholders and communities in the catchments of that system.
ii) To develop an understanding of the primary water quality responses, and their causes, of the Riviersonderend-Berg River (RSE-BR) System, which would serve as a case study for the Water Quality Information System implementation. (The Berg River is connected via a two-way tunnel to the Theewaterskloof Dam on the Riviersonderend River.)
iii) To evaluate the potential for operation of the future RSE-BR System to meet recently developed salinity guidelines for irrigation.

As the project planning unfolded, it became clear to the Steering Committee that the aims needed adjustment for two sets of reasons: On the one hand, they were too broad for the available budget and time-frame. On the other hand, parallel development of suitable approaches to community participation in IWRM, as part of DWAF’s initiatives to implement the National Water Act (1998), was forcing a change in the focus of the project. The Steering Committee, therefore, agreed that most of the research focus would fall on Aims (i) and (ii), and that (iii) should be seen as a long-term objective of salinity-based research in the Berg River catchment.

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Furthermore, the Steering Committee agreed that the WQIS would primarily be developed as a technical information tool aimed at supporting water resource managers and stakeholders on the technical domain, and that communication support for community participation in consultative water management processes would fall outside the ambit of the current contract.

TWO RESEARCH THEMES AND TWO SETS OF RESEARCH OUTPUTS

The background described earlier, as well as the stated objectives, imply that two related, but essentially different, research themes underlie this project:

- Theme One: Development and/or application of decision support and information management software for general water quality management in a river system with diverse components and human impacts. This Theme was the responsibility of the Department of Civil Engineering.
- Theme Two: Water quality-related research in the form of field-scale process studies and large-scale soils data interpretation and mapping, with a strong focus on salinisation processes. This Theme was the responsibility of the Department of Soil Science.

Each Theme yielded a separate set of research outputs and Reports. This document deals exclusively with the research methodology, results and findings produced by the Department of Civil Engineering under Theme One.

STUDY OBJECTIVES COVERED BY THIS REPORT

The study objectives covered by this document are as follows:

i) Application of a one-dimensional hydrodynamic river flow and water quality model, DUFLOW, to the Berg River and illustration of its utilisation to support decision-making for various water quality management scenarios.
ii) Application of a two-dimensional hydrodynamic reservoir water quality model, CE-QUAL-W2, to the proposed Skuifraam Dam in the Upper-Berg to illustrate its utilisation to support decision-making for various in-dam water quality management scenarios and to provide realistic upstream boundary conditions for DUFLOW scenario runs.
iii) Development of a WQIS that has a user-friendly GIS-based Graphical User Interface, including interfaces with DUFLOW and CE-QUAL-W2, and illustration of its utilisation in typical decision-support for water quality management in river systems, using the Berg River as prototype.

HYDRODYNAMIC RIVER FLOW AND WATER QUALITY MODEL, DUFLOW

The following steps outline the approach and essence of this component of the Study:

i) A water quality status assessment of the Berg River main-stem was completed, using readily available data from DWAF and other sources, and both spatial and temporal trends were examined and interpreted. This led to a decision that the water quality variables, Salinity, Phosphates, Oxygen and Temperature, would be a minimum set of concerns for future water resource management in the Berg River.
ii) A survey of internationally available hydrodynamic river flow and water quality models was done, and, following selection criteria that have been declared important by management-orientated user groups in South Africa and elsewhere, it was decided to select the hydrodynamic water-quality model, DUFLOW, and evaluate its adaptability for representing the Berg River with all its complexities.
iii) An exhaustive search with local authorities, DWAF and consulting civil engineers, yielded a large data base of surveyed cross-sections, while a number of cross-sections were also specially surveyed for this Project. In total, 108 cross-sections were included in the model configuration, which represented a distance of 147 km, from Flow-Gauging Station G1H004 in the Upper-Berg to Misverstand Dam in the Lower-Berg.
iv) To utilise the open-source code facility in the model, customised water quality modules for Oxygen and Temperature balance in the model were programmed.
v) After a limited sensitivity study, the model was calibrated for selected hydraulic and water quality parameters using one year of daily hydro-meteorological and water quality data for a period regarded as the most complete from a data availability point of view. As sizeable incremental

areas and tributaries of the Berg River had been ungauged, empirical estimates of daily inflows and water quality loads from those areas had to be made.

vi) The calibrated model was temporally verified for a different period of reasonable data availability, and also spatially verified, by modelling individual incremental areas independently.

vii) A range of water quality management scenarios were postulated for the Berg River and examined through customised utilities in the WQIS.

DISCUSSION AND CONCLUSIONS: DUFLOW APPLICATIONS

Flow Calculations

The finite difference approach that DUFLOW uses to calculate the St Venant equations of continuity and momentum is advanced and therefore allows the user to model complex systems. The finite difference approach allows varied space steps, which proved to be advantageous; especially in the upper Berg, where steep slopes required very small space steps for stable calculations. The lower Berg River could then be modelled in larger space steps in order to save running time and superfluous cross-sections.

Structures that were included are weirs at the specific gauging stations and bridges that are found along the main stem of the Berg River. Information was available for most of the structures, and where difficulties were experienced with computational stability, the roughness coefficient was adjusted. A trigger function used in DUFLOW for structure flow control allows modelling of multiple notches at a weir, such as is often found in South African rivers.

Water Quality Calculations

An advantage of DUFLOW is the open code structure it uses for the water quality module. This allows the user to either change the water quality algorithms according to the degree of complexity required or add additional water quality processes that need to be simulated. In future use of the configured model, water quality processes can be added or deleted. Thus, the model is very flexible. In this study, TDS, COD and Temperature algorithms were added to the EUTROF1 module, as these are variables of concern specifically in the Berg River catchment. The Phosphate algorithm had to be simplified, as most of the processes could not be modelled due to lack of in-stream data. The results of the Temperature algorithms proved to be satisfactory.

Two-weekly water quality samples were available. As the model was configured on a daily time step, the samples had to be "patched" (infilled) in order to include the variables as time series. DUFLOW has an option of entering the time series at irregular time steps, but DUFLOW linearly interpolates the values for the missing samples, which is not quite correct for the distribution of the water quality variables as they are also dependent on the flow value. A moving regression method was used to infill the TDS and soluble phosphate values, while a simple harmonic function was used for the temperature infilling.

Schematisation points were added at every location where a tributary discharges into the main stem or where a point source had been identified. A considerable number of point sources were not included, due to lack of information. It would be a pre-requisite, if the simulation model will be used as an operational tool, that all primary sources of water quality discharge into the river are identified and included in the model.

A limitation of DUFLOW is that it does not allow incoming loads to be input in a diffuse fashion along the length of the modelling reaches. It is therefore difficult to distinguish between non-point and point sources, if the model is to be used as a scenario tool, because the non-point sources have to be treated as distributed point sources.

Modelling Results

The reliability of the modelling results is mainly determined by the accuracy and availability of the input data. Errors in the water quality simulation are dependent on various factors, such as: accuracy of the infilling-method, availability of grab samples in the river, accuracy of the flow simulation, etc. The flow simulation is dependent on various factors such as cross-section data, channel roughness information, etc. The errors that are introduced at the beginning of the flow calculations (i.e. in the first reach) are carried all the way downstream to the end boundary.

The estimation of runoff from ungauged sub-catchments for the calibration of the flow module proved to be problematic. Considerable volumes of water were still missing during peak flows for most of the stations. This could be due to underestimation of the flood at the various gauging stations, which thus also leads to underestimation for the ungauged runoff. The accuracy of the simulation of the water quality loads is dependent on minimising errors resulting from the flow simulation.

Learning curve

The learning curve time to use the model efficiently is greatly reduced by the user friendly interfaces that DUFLOW offers. This is a major advantage, as it can be operated easily for configuration and scenario analyses by the user. An understanding of the underlying hydraulics and water quality processes is however needed to fully understand the system.

Limitations

- Although the finite difference approach to calculate the St. Venants equations proved to be advantageous due to the stability and the choice of unequal time and space steps, a limitation of this approach is, however, that it is very data intensive compared to other simpler flow calculation methods.
- The different network objects (i.e. weirs, abstraction points, etc.) can only be altered in the network window itself. For adjustments to the objects it would have been easier to change the specific descriptions in an additional textfile or database, especially if numerous objects are configured.
- The results are written in a textfile, which take up considerable space (about 50 Mb for the quality files). For use in other systems, such as the WQIS, a database format would have been more suitable for updating and presenting.
- Like many European or American models, DUFLOW is not able to simulate evaporation losses from the water body. Such losses can be quite significant in South Africa, and are therefore of importance. These losses had to be treated as abstraction flows at schematisation points.
- Non-point sources are not modelled as diffuse inflows by DUFLOW. These are however extremely important when considering the nutrient mass balance. From the water quality results it was evident that the agricultural runoff is significant in floods (all loads are under-simulated).
- Water Quality calculations became unstable when negative water depths were experienced for the different runs. Negative water depths are a physical impossibility, but are sometimes simulated in the low flow period, due to inaccuracies between the calculated water level and the configured cross-section’s reference level. Although the process calculations were able to be coded to overcome this problem, the transport mathematical formulations were fixed, and the negative water depths affected the calculations. Much effort went into altering the time and space steps until a stable flow calculation was achieved.

Scenario Analysis

The text files produced by DUFLOW are easily altered for different scenario runs. DUFLOW is capable of simulating different scenarios that are of interest to the user. Three scenarios were looked at: a short term effluent spill scenario, a linkage to the hydrodynamic reservoir model, which is described in Section 3 of this volume, and thirdly an operational long term management scenario. Although simulation time was long due to small calculation time steps (a calculation time step of 10 minutes proved to be stable) and the result file is large in terms of computer space, DUFLOW is capable of simulating various water quality related changes and predicting the outcomes of different water management scenarios.

RECOMMENDATIONS: DUFLOW APPLICATION

Although the information for the Berg River Catchment is probably more extensive than for many other catchments in South Africa, there is still considerable need for additional research and data if a realistic representation of the river is desired. This is especially important when the model is not only used as an analysing tool for historical data, but also used to examine management scenarios. Research into the following areas may produce results that would strengthen the models capability to represent the Berg River Catchment:

Non-point and point sources

There is considerable need to improve the monitoring system for point and non-point sources along the Berg River catchment. This would make a database available of different sources that contribute to nutrient and salt loads in the river. Although DWAF already monitors point sources that have been issued with a water quality permit, there are numerous sources that contribute to the deteriorating water quality in the Berg River. As most of the phosphorous in the river is due to runoff from agricultural land, it would be of benefit to link the hydrodynamic river model to a catchment model to estimate water quality loads from ungauged areas, rather than the ungauged runoff estimation methods used in this study.

Expansion of data/information on variables of interest in the Berg River

Oxygen is of interest in the river for ecological reasons, therefore it would be important to empirically explore the oxygen mass balance in the Berg River, by taking grab samples over a longer period and incorporating COD discharges of the point sources into the river. Different algorithms relating to oxygen should be studied and adopted according to the specific river.

The scenario analysis showed that the summer temperature in the river would change considerably (-10 degree Celsius change) if Skuifraam Dam were to be built in the upper reaches. This is obviously of concern and there is need to investigate the ecological impact of these temperature changes in the river.

Although earlier studies have been conducted on the phosphorous transport in the Berg River, the DUFLOW model has been activated in only the advection equation to analyse the phosphate concentration, as insufficient data is available on other dependent variables. By including data on the suspended solids and, therefore, the mobilisation of particulates into the river, as well as production of algae, improved results on the simulation and a better understanding of the phosphorous concentration patterns in the river can be expected.

Linkage to other models

As mentioned above, it would be beneficial for management support, if DUFLOW were to be linked to other models as this would also ensure that DUFLOW could be used in catchment-wide applications. In this research, a user-friendly interface environment was developed and implemented as a Water Quality Information System (WQIS) that provides analytical, spatial and graphical information based on the requirements of a wide spectrum of users and which integrates simulation models (river and reservoir) into the WQIS, as described below. It would be important to broaden this study and integrate a catchment model into the WQIS so that it can provide tributary inputs to DUFLOW, as well as further develop the DUFLOW model for scenario analysis to support decision making for integrated water management.

HYDRODYNAMIC RESERVOIR WATER QUALITY MODEL, CE-QUAL-W2

The following steps outline the approach and essence of this component of the Study:

i) The two-dimensional hydrodynamic water quality reservoir model, CE-QUAL-W2, was configured for the site conditions, dam wall and outlet arrangements and dam basin dimensions of the proposed Skuifraam Dam in the Upper-Berg River catchment.
ii) A four-year period of daily meteorological data for the Upper-Berg was derived from a collection of weather stations in the Region and inflow and water quality data for the Dam was assumed to be similar to that observed at G1H004, just upstream of the Dam site.
iii) Selected sensitivity studies were performed to improve understanding of the role of critical model parameters.
iv) Various water quality scenarios were formulated to demonstrate the role that the reservoir model can play in technical water resource management decisions. These range from inflow scenarios for pumping from a downstream supplement scheme, to different scenarios for transfers, and back, to Theewaterskloof Dam on the Riviersonderend River, to different release patterns for downstream environmental flow requirements.

DISCUSSION AND CONCLUSIONS: CE-QUAL-W2 APPLICATIONS

i) Two-dimensional hydrodynamic and water quality models can provide useful insight into the mixing of water and water quality variables, as well as bio-chemical processes which occur within reservoirs.
ii) Outputs from two-dimensional models are useful in assisting decision-makers in the task of determining the water quality component of the ecological reserve.
iii) Regional meteorological data has proven extremely valuable as input (driving forces) for CE-QUAL-W2 in the absence of site-specific meteorological data.
iv) Two-dimensional hydrodynamic and water quality models such as CE-QUAL-W2 require various rate constants to accurately model bio-chemical reactions. In this study, it was found that the oxygen profile within dams are particularly sensitive to the Sediment Oxygen Demand (SOD) and that this data is not readily available for this type of modelling. Availability of this type of data will greatly improve the reliability of the model outputs.
v) Water quality monitoring of inflowing streams is of utmost importance for water quality modelling. This study revealed the lack of stream temperature data, which is an important driving force for heat transfer within the reservoir.
vi) The Berg River Water Quality Information System (WQIS) is a useful tool for managers and decision-makers, bringing together various modelling tools (DUFLOW and CE-QUAL-W2) and providing post-processing which allows visualization of model outputs.

RECOMMENDATIONS: CE-QUAL-W2 APPLICATIONS

From the above conclusions the following recommendations can be made:

i) The systematic monitoring of meteorological data throughout the country should be continued and new initiatives should aim to gather site-specific meteorological data specifically for important impoundments and along important river courses, and, specifically, as a foresight undertaking for the proposed Skuifraam Dam.
ii) The systematic monitoring of water quality constituents should be continued throughout the country and special attention should be given to *temperature and nutrient* data sampling.
iii) In September 2001, Nico Rossouw and Wageed Kamish of Ninham Shand Consulting Services attended a course on the latest version of CE-QUAL-W2 (v3.1), in Portland (U.S.A) and personal contact was made with the developers and custodians of the model. It is therefore recommended that close relationships and contacts with these scientists be maintained so that modelling of this type remains relevant in South Africa.

TABLE OF CONTENTS

SECTION 1

PREFACE TO THE FULL PROJECT : WATER QUALITY INFORMATION SYSTEMS FOR INTEGRATED WATER RESOURCE MANAGEMENT : THE RIVIERSONDEREND-BERG RIVER SYSTEM

APPENDIX 1

LIST OF TABLES

SECTION 1

SECTION 2

LIST OF FIGURES

SECTION 1

SECTION 2

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WATER QUALITY INFORMATIONS SYSTEMS FOR INTEGRATED WATER RESOURCES MANAGEMENT : THE RIVIERSONDERENDBERG RIVER SYSTEMS

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

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SECTION 1

APPLICATION OF A HYDRODYNAMIC RIVER FLOW WATER QUALITY MODEL: DUFLOW :

APPLICATION TO THE BERG RIVER

CHAPTER ONE
INTRODUCTION

Impoundments and associated bulk water supply infrastructure are present in most South African river systems. Because of the disparate natural occurrence of rainfall and runoff, and its mismatch with water demand concentrations, many of these schemes have to incorporate inter-catchment transfers to meet demands in the face of inadequate local availability. Furthermore, water quality deterioration, because of human impacts through a wide range of land-uses and waste discharges, has for some time been recognised as a threat in South Africa, as it diminishes the utilisable part of the runoff in many catchments. These complexities increasingly offer challenges to water resource managers that require a response with integrative management philosophies and innovative management tools.

During 1997, in recognition of the aforementioned needs, the Department of Civil Engineering of the University of Stellenbosch, formulated a research proposal to the Water Research Commission (WRC) whose aim would be to serve the philosophy of Integrated Water Resource Management (IWRM), through the development of an integrated information system specifically for water quality – here abbreviated to “WQIS”. To be useful to IWRM, this WQIS was to provide diagnostic and predictive utilities to serve technical planning and operational decision-making in a river system, but, simultaneously, provide appropriate information to support water managers in communication with technical stakeholders. It was also recognised that the project would need identification of a “prototype” catchment for development of appropriate WQIS approaches and to provide a relevant data base.

One of the aims of this project was to develop Water Quality Information Systems (WQIS) to support both integrated management of a water resources system, and to support communication about water quality management with stakeholders and communities in the catchments of that system - In this study the Riviersonderend-Berg River (RSE-BR) System was used as the prototype catchment. To develop this WQIS, however, it was necessary to combine a suite of water quality models with a user interface so that the results of the modelling could be visually interpreted. **CE-QUAL-W2** (refer to section 3 of this report), a two-dimensional hydrodynamic and water quality model, was used to simulate the flow pattern and constituent profiles in the proposed impoundment in the system while **DUFLOW** a one-dimensional hydrodynamic river flow and water quality model was used to simulate the river. The application of the river model, DUFLOW, is discussed in the ensuing chapters.

CHAPTER TWO
CONCEPTUAL CONTEXT OF MODEL APPLICATION

2.1 INTRODUCTION

Modelling is a tool that is necessary in water quality management as it *"provides the link between the conceptual understanding of the physical catchment characteristics and the empirical quantification of the hydrological, water quality and ecological responses"* (Pegram *et al*, 1997, pg 17).

The above quotation summarises the importance of modelling in water quality management, as it is able to describe the interaction between ecology, water quality, hydrology and hydraulics and, most important, allow for *what-if* scenarios which enable the users to attain a clearer understanding of the responses of the system as a whole.

The definition of a model is given by Carstensen *et al* (1997) as: *the abstract representation of a real system by the ideas and constituents and functional relationships*. The term *model* is used in many different ways to describe any representation of the real system, such as a laboratory model, computational model or conceptual model. The term *water quality model* or *simulation model* is used in this study to describe which computational hydraulic and water quality software is being used and either *sub-models* or *algorithms*, describe the mathematical equations that represent the water quality processes.

The aim of hydrodynamic river water quality modelling is to describe and understand interactions between the hydraulics of the river and the chemical and biological water quality river constituents[1]. A model is very effective in assisting in water quality management decisions for different scenarios which would affect the river and the water users. As computers have been becoming more powerful, more complex systems and formulations of the interaction between the water quality variables have been able to be modelled and understood.

Water quality models have developed from 1920s regression relationship of water quality variables such as temperature, dissolved oxygen and biochemical oxygen demand, to current-day emphasis on fully hydrodynamic modelling of rivers, reservoir and estuary processes, with closely-coupled water quality processes, as well as on the fate and transport of toxic substances. With the advance in computer technology various models (i.e. reservoir, river and estuary) are incorporated together by interfaces and used as water quality management decision tools.

2.2 CONCEPTS IMPORTANT TO WATER QUALITY MODEL APPLICATIONS

Concepts important to water quality model applications include model constituents, attributes and concepts used in the actual model construction. There exists a wide range of terminology when describing the various aspects of models and model building. Therefore, it is important to clarify the terms that will be used in this study.

2.2.1 Model elements

In water quality simulations there are normally two primary types of model elements: variables and parameters. Examples of parameters are the kinetic coefficients of a chemical equation describing the response of a specific water body to outside or internal forces or stimuli (i.e. influenced by temperature, radiation etc.). The parameters are determined either through field studies or in the calibration process or "transferred" from other comparable applications. Examples of state variables are the water quality variables, such as concentration or loads of phosphates, chlorophyll-a, etc. that are of concern to the modeller.

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[1] A water quality constituent (also called water quality variable) is defined as a biological or chemical (organic or inorganic) substance or physical characteristic that describes the quality of a water body (DWAF (c), 1993).

2.2.2 Model attributes

The following are defined as model attributes:

Dimensions
Models may be categorized as **zero dimensional, one dimensional, two dimensional** or **three dimensional**. Rivers are normally treated as one dimensional models, where the values of flow and quality only change in the longitudinal direction; two dimensional, where both longitudinal and depth-related dynamics are simulated. With zero dimensional models the assumption is made that the water is well mixed and only the input and output changes. Three dimensional models include the vertical, longitudinal and lateral changes.

Time
The main distinction that is made among the various water quality models is between steady state and dynamic models. Steady state models assume that the variables do not change in time or in space, while dynamic models do take the variability of the variables in time and space into account and thus allow for modelling of non-point runoff and sudden increased effluent discharges.

Data
Another distinction that can be made between the different water quality models is that of deterministic and stochastic models. In deterministic models a fixed relationship between input and output is assumed. Stochastic models allow for random variation in input parameters, or random variation in process residuals.

Purpose of Model
Water quality models designed for computer solution are either simulation or optimization models. Simulation models calculate the concentration of the various variables based on the given river flow and the quantity and quality of the waste loading. Optimization models are effective in assisting management, as they include model management variables to test the impacts of certain management decisions.

Mathematical Computation
The common basis for most water quality models is the principle of continuity or mass balance. The transport as well as the chemical and biological processes are calculated in many models.

Input Data
Another distinction is made between point sources and non-point sources. Point sources refer to the concentrated discharge of contaminants from a known source (i.e. effluent discharge from a sewage treatment works). Non-point sources are spatially distributed or dispersed discharges and export of contaminants derived from the surface and subsurface drainage as well as from the atmosphere and they are often hydrometeorological driven.

2.2.3 Model Application Steps

The steps that are taken when applying a model are:

- Identification of the problem that needs to be studied
- Model Selection
- Configuration
- Sensitivity Analysis
- Model Calibration
- Model Verification
- Scenario Analysis

For any specific water quality situation studied, the appropriate model depends largely on the problem investigated and the availability of the data required. Different models place emphasis on different water quality variables or use different mathematical formulations which could be unsuitable for the specific river studied and the problem investigated. Most importantly, the model needs to be capable of configuration, calibration, verification and simulation within the limits of deadlines and budget.

2.2.4 Data considerations for model use

The resolution of data requirements is very dependent on the modelling method. The data requirements depend on the complexity of the model and the make-up of the overall uncertainties present. Uncertainty in the data result mainly from:

- quality of data
- parameter estimation

Objective Functions
Statistical indicators that determine the goodness-of-fit between measured and simulated data are called objective functions. The statistical goodness of fit tests gives the modeller information on the degree of the error between observed and simulated values.

2.3 REVIEW OF WATER QUALITY MODELS FOR RIVERS

Available models cover a range of purposes, such as combined river and reservoir models, rainfall-runoff models, catchment models, ground water models or only stream hydraulics models. A description of the main features of the available models reviewed in this study on the market can be found in the main report of Volume1. The models discussed in that document are: WQRRS, CE-QUAL-RIV1, QUAL2E, WASP, DUFLOW, ISIS and MIKE-11.

2.4 DISCUSSION

In the case of the current Berg River study the following selection criteria have been declared important by the potential management-orientated user group surveyed by the project team (DWAF, pers. comm., 1999):

1. user friendliness of model, availability and support of model
2. cost of model
3. ability to model water quality variables identified as variables of concern: salinity, oxygen, temperature and phosphates
4. applicability, or ability to adjust to South African situation
5. fine time resolution (daily)
6. should be a hydrodynamic model for modelling flow variations during floods, low flows and in tributaries in time and space
7. cost, availability and support in South Africa.

With the introduction of the new Water Act in South Africa, water resource management and planning involves various users and goals. In order to be able to execute decisions the user often does not want to rely on a complex model where extensive user expertise is necessary; but that is rather fast and reliable. If the model should be used as a management "tool", continuous support and availability is necessary. It is desirable to have a model that is flexible and can be changed according to the specific problems studied and encountered. The model should be able to cope with different time steps and also with sudden and fast releases of the proposed dam or sudden effluent spills that occur at a point source.

Using the selection criteria as a guide, it has been decided to use the DUFLOW model for this particular study. Although DUFLOW has the same limitations as say ISIS (no evaporation modelling), it is still much cheaper and has the advantage of comprising an open water quality structure where the water quality processes can either be simplified or added/removed, the model therefore is flexible to change to different water quality situations. The model allows the user to create user-friendly windows based interfaces and a graphical editor. As it is a hydrodynamic water quality model, the time and space steps can be entered as desired by the user; thus allowing fine time resolution, if needed. By inserting options for scenarios, the model could be used for management purposes.

CHAPTER THREE
DESCRIPTION OF THE BERG RIVER BASIN

3.1 GEOGRAPHY

The Berg River lies in the Western Cape and its catchment lies between latitude 23E45' and 33E50' south and longitude 18E15' and 18E55' east. The Berg River rises in the Jonkershoek and Franschhoek mountains and flows in a north westerly direction where it eventually discharges into the sea at Laaiplek. The major tributaries are the Franschhoek, Wemmers, Krom, Kompagnies, Klein Berg, Vier-en-Twintig Rivieren, Matjies, Platkloof, Boesmans and Sout Rivers. The river is about 270 km long and has a catchment of some 9000 km^2 (DWAF(b), 1993). Figure 3.1 shows the gauging stations situated in the Berg River main stem, as well as the tributaries.

3.2 TOPOGRAPHY, GEOLOGY AND CLIMATE

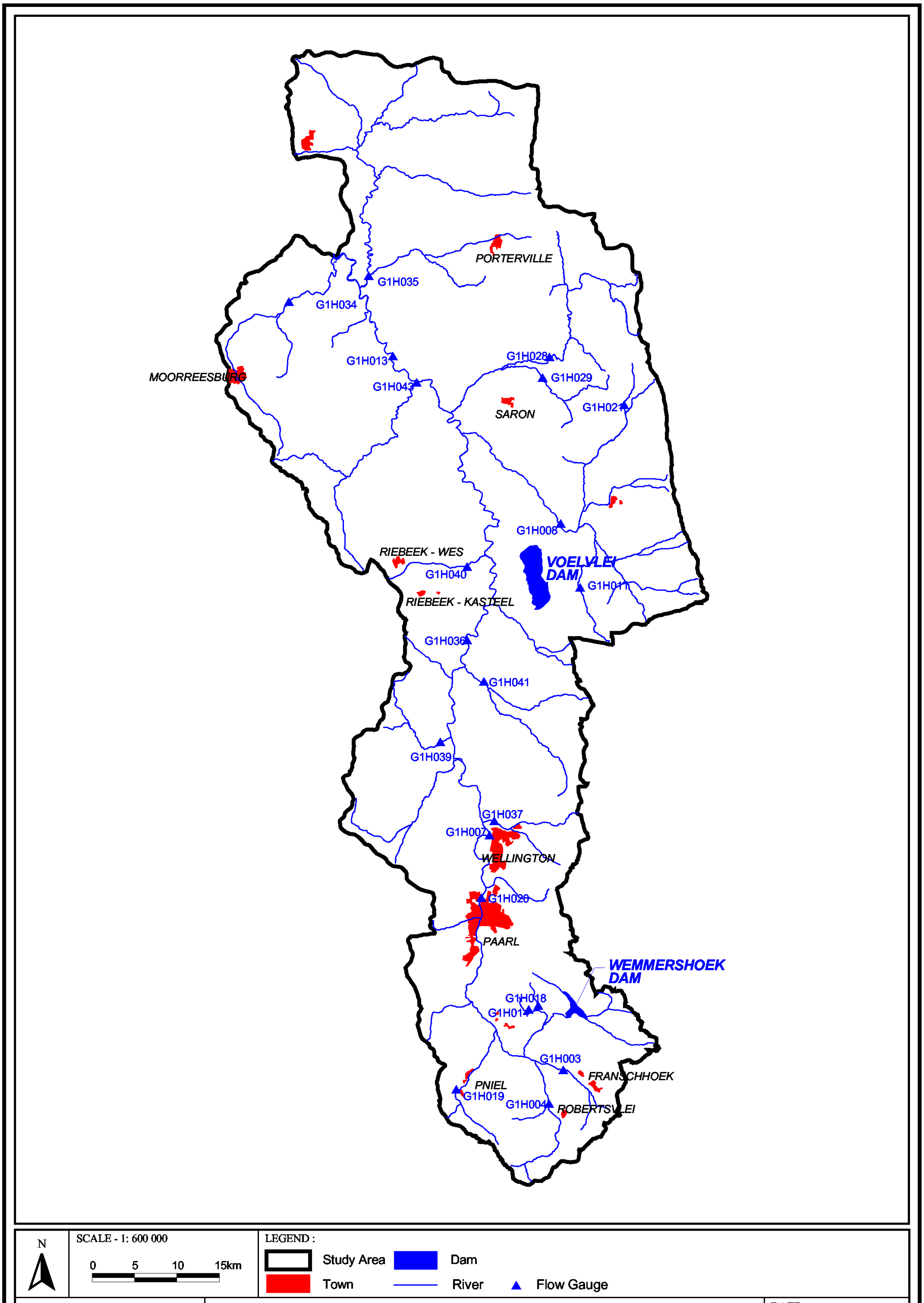
The mainstem river is about 160 km long from the headwaters to the sea and its width varies from 1 to 5 km near its headwaters to between 30 to 40 km long at the coast. (Bath, 1989). The lower reach of the river is extremely flat so that sea water intrusion pushes up nearly 100 km from the river mouth under high tide conditions (Bath, 1989). The Berg River is geologically an old river system. This can be seen firstly from the rapid fall in profile from headwaters and which then flattens out in the Paarl area, secondly from the degree of meandering of the main river channel and thirdly the existence of multiple channels separated by low lying islands in the lower reaches and the great width of the river valley (Bath, 1989). The basin of the Berg River is bounded on the eastern side by a range of mountains (RL 1500m), on the western side the basin flattens out to a hilly plain. Downstream of Paarl/Wellington sandstone formations give way to Malmesbury shales, thereafter tributaries on the eastern bank of the Berg River drain areas with Table Mountain Sandstone, while the western bank drains areas with the saline Malmesbury Shale as dominant geological formation (DWAF(e), 1993). Figure 3.2 shows the different geological formations found in the Berg River Catchment.

The Berg River catchment lies in the Winter rainfall area of the south-western Cape, about 80% of the rainfall falls in the months of April to September. Rainfall in the mountains is about 3000mm per year (Midgley *et al*, 1994). The snow that falls on the peaks and upper slopes of the mountains during intermittent cold spells in the winter also contributes to the flows. In the adjoining valleys, rainfall varies from 900 to 1200 mm annually, but drops to between 400 and 500 mm in the hilly plain through which the river flows most of its length, and to even less when it approaches the sea (Midgley *et al*, 1994). The tributaries are perennial on the eastern side and semi-perennial on the western side.

3.3 LAND COVER

Present land covers in the Berg River catchment fall primarily into three types: agricultural, forestry and urban. Agricultural land use is further divided into irrigated, and dry land farming activities. The latter of these make up the largest proportion of the catchment (DWAF(g), 1993).

There are 9 irrigation boards in the Berg River catchment area. These are: Perdeberg, Suid Agter Paarl, Noord Agter Paarl, Riebeekkasteel, Riebeek Wes and the Berg River under the Upper Berg River Irrigation Board, Twenty Four Rivers, Klein Berg River and Lower Berg River. From the allocated amount of water, Upper Berg River Irrigation Board uses about 41%, the Twenty Four Rivers Irrigation Board and Klein Berg River area about 27% and 24% respectively, while the lower Berg River Irrigation Board uses only about 8% of the water used for irrigation (DWAF(g), 1993). A summary has been given in the Situation Analysis of the Berg River (DWAF(g), 1993) of the areas of the various crops under irrigation in the upper and middle reaches of the Berg River. The data was obtained from the irrigation boards in the Berg River catchment and from Burger *et al*, 1971. Figure 3.3 shows the land use in the Berg River catchment, the lower reaches of the Berg River dry land farming is the predominant agricultural land use.



ASSESSMENT OF A HYDRODYNAMIC WATER QUALITY MODEL, DUFLOW, FOR A WINTER RAINFALL RIVER

DATE : JULY 2000

Gauging Stations in the Berg River Region

FIGURE No. : 3.1

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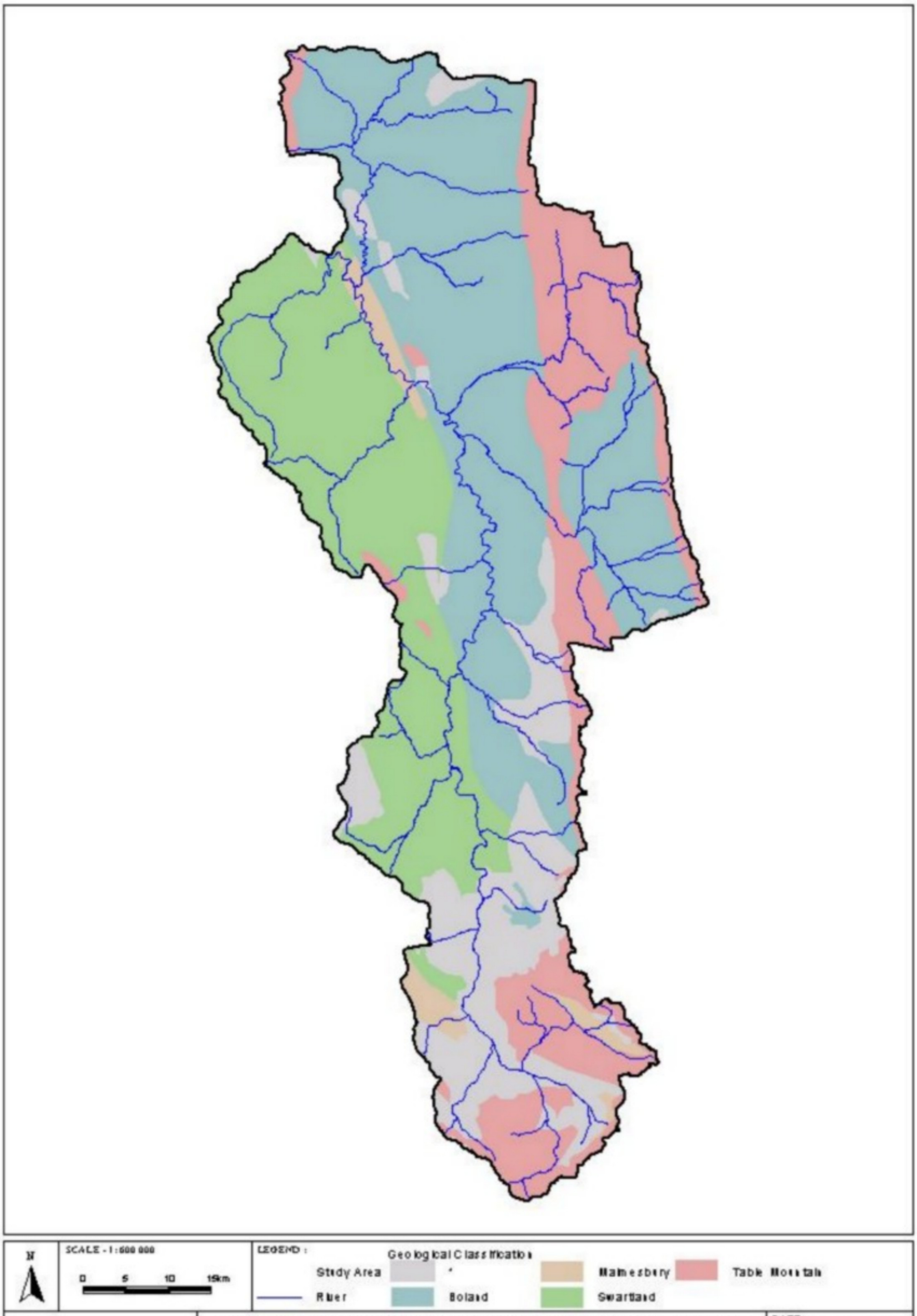
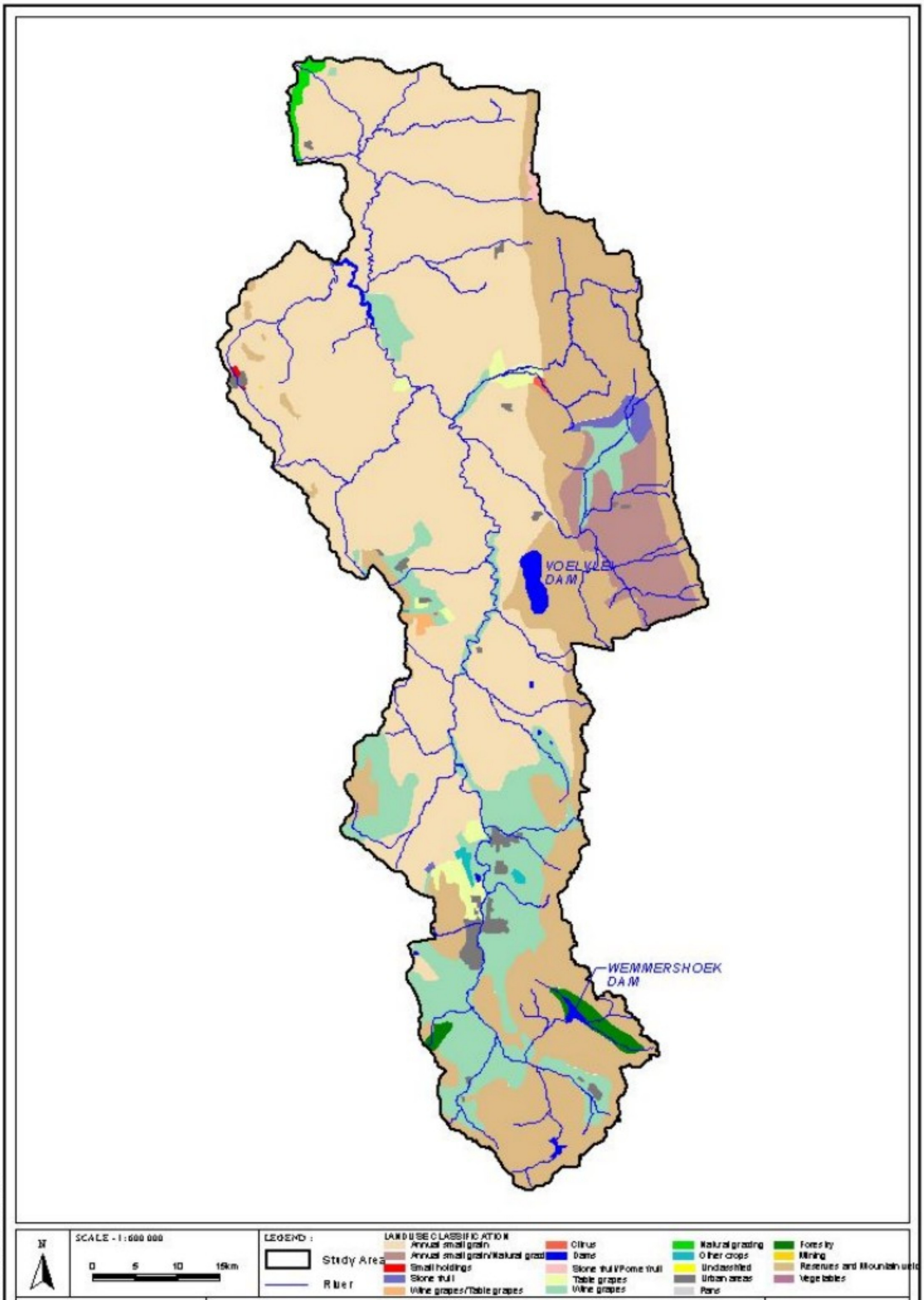


ASSESSMENT OF A HYDRODYNAMIC WATER QUALITY MODEL, DUFLOW, FOR A WINTER RAINFALL RIVER

DATE : JULY 2000

Geology in the Berg River Catchment

FIGURE No : 3.2



ASSESSMENT OF A HYDRODYNAMIC WATER QUALITY MODEL, DUFLOW, FOR A WINTER RAINFALL RIVER

DATE : JULY 2000

Landuse in the Berg River Catchment

FIGURE No : 3.3

3.4 WATER INFRASTRUCTURE DEVELOPMENTS IN THE CATCHMENT

3.4.1 Voëlvlei Dam

The Voëlvlei Dam was the first large water supply scheme that was developed in the Berg River. The first Voëlvlei scheme was completed in 1953. The natural Vogelvlei lake was impounded by building a small wall structure. As the natural vlei had a catchment of only 40 km ^{2}, additional water was diverted from the Klein Berg River, where a small weir was built, into a canal to the dam. In 1971 the dam was raised to its present full supply capacity of 172 Mm^3 (DWAF(c), 1994). The dam is currently supplied by diverted runoff from the Klein Berg River, and additionally Twenty-four Rivers and Leeu River catchments through canals. The dam supplies water to Cape Town, the Swartland Scheme and irrigation water for downstream users.

3.4.2 Wemmershoek Dam

The Wemmers River was impounded in 1957 and supplies part of Cape Town's urban demand (DWAF(a), 1992). The full supply capacity is 58.8 Mm^3 and a yield of 56 Mm^3 /a (DWAF(a), 1992). During low flow in the Berg River this scheme release compensation water to supply irrigation demands as far as the Voëlvlei canal. Since the completion of the Theewaterskloof-Riviersonderend (RSE) scheme the releases have been made from a tunnel into the upper Berg River at Robertsvlei.

3.4.3 Misverstand Dam

At Misverstand, in the lower Berg River, a weir was built across the river in 1975 to enable water to be abstracted (DWAF(c), 1994). The dam is linked to the Withoogte water treatment works via a 12.5 km pipeline, which supplies water to Moorreesburg, Vredenburg, Saldanha Bay and Langebaan. The capacity is about 6 Mm^3 (DWAF(c), 1994).

3.4.4 Theewaterskloof Dam

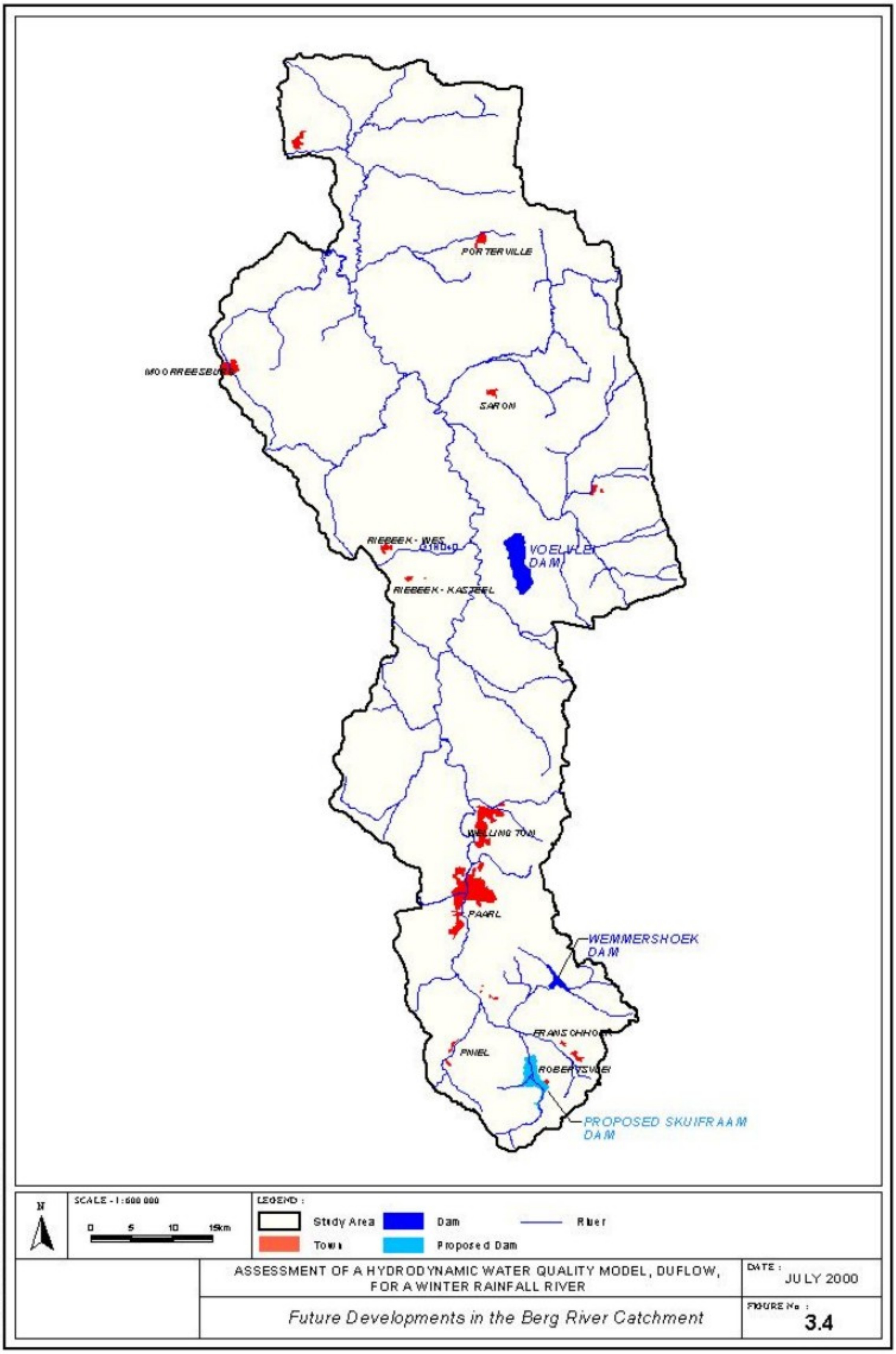
Although the Theewaterskloof Dam and the Riviersonderend scheme do not lie in the Berg River, it does supply water into the Berg River. The Theewaterskloof Dam has a capacity of about 480 Mm^3, and the system has a yield of 207 Mm^3 /a (DWAF(a), 1992).The dam was built in 1980 and is used to supply the Cape Town Municipality and irrigation in the Riviersonderend, Eerste and Berg River valleys (DWAF(b), 1994).

3.4.5 Future Developments

Due to mainly increasing population, a solution had to be found to meet Cape Town's increasing water demand. The following schemes are being investigated for imminent implementation in the Berg River: Skuifraam Dam in the Upper Berg, Skuifraam Supplement Pump Scheme downstream of Franschhoek and Lorelei Diversions to an enlarged Voëlvlei Dam in the Middle Berg (see Figure 3.4).

Skuifraam Dam:
Skuifraam Dam is proposed for the upper reaches of the upper Berg River just downstream of the confluence of the Berg and Wolwekloof Rivers. The dam would capture flood flows and transfer water to the Theewaterskloof Dam. The full supply capacity is supposed to be 168 Mm^3 and the naturalised inflow is estimated to be 115 Mm^3 (DWAF(d), 1994), the yield has been calculated to be 56 Mm^3/a.

Skuifraam Supplement Scheme:
The MAR between Skuifraam and Paarl increases by about 150 Mm^3/a (DWAF(d), 1994). Skuifraam Supplement Pumping Scheme has been proposed to abstract this potential water. The Skuifraam Supplement Scheme will have an off-channel balancing dam of about 4ha and the height of the diversion weir will be about 5m (DWAF(d), 1994). The water will be pumped at a capacity of 4m^3/s into a raised Voëlvlei Dam.


PORTERVILLE
MOORREESBURG
SARON
RIEBEEK-WES
VOELVLEI DAM
RIEBEEK-KASTEEL
WELLINGTON
PAARL
WEMMERSHOEK DAM
FRANSCHHOEK
PNIEL
ROBERTSVLEI
PROPOSED SKUIFRAAM DAM
N
SCALE - 1:600 000
0 5 10 15km
LEGEND :
Study Area
Dam
River
Town
Proposed Dam
ASSESSMENT OF A HYDRODYNAMIC WATER QUALITY MODEL, DUFLOW, FOR A WINTER RAINFALL RIVER
DATE : JULY 2000
Future Developments in the Berg River Catchment
FIGURE No : 3.4

3.4.6 Operation of the Berg River-Theewaterskloof Link

The RSE scheme includes the Theewaterskloof Dam on the Sonderend River, a tunnel through the Franschhoek mountains and an outlet in the upper Berg River which releases compensation water to supply irrigation demands in the Berg River, an tunnel in the Upper Berg River that passes under the Klein Drakenstein Mountains to a balancing dam at Kleinplaas on the Jonkershoek tributary of the Eerste River; a tunnel from the Kleinplaas Dam to an outlet near to Stellenbosch (DWAF(a), 1992). The four tunnels of the system are called the Franschhoek Tunnel/Jonkershoek Tunnel, the Stellenboschberg Tunnel and the Dasbos Tunnel which branches of the Jonkershoek Tunnel. A pipeline connects the Franschhoek/Jonkershoek Tunnel to the Wemmershoek Dam, while another pipeline connects the Kleinplaas Dam, which is situated on the Eerste River, to the Stellenboschberg Tunnel and an additional pipeline to the Blackheath water treatment works near Cape Town. Diversion works on the Banhoek and Wolwekloof Rivers (tributaries of the Berg River), allow surplus winter flows to be diverted and conveyed through the tunnel system into Theewaterskloof Dam where the water is stored. In summer it can then be released back through the tunnel system to the various outlets (DWAF(b), 1992). The releases into the Berg River include the 10 Mm^3/a which have been previously made by Wemmershoek Dam and additional releases to supply allocation made from the RSE scheme to irrigators in the Berg River. The maximum capacity of the tunnel outlet is 6.6 m^3/s (DWAF(b), 1994).

The proposed Skuifraam Dam would transfer water to the Theewaterskloof Dam or supply water direct to Cape Town via the Jonkershoek Tunnel. The transfer will be achieved by pumping water through a pipeline into the Dasbos Tunnel and from there into the Franschhoek/Jonkershoek Tunnel (DWAF(b), 1994).

CHAPTER FOUR
REVIEW OF WATER QUALITY STATUS OF BERG RIVER MAIN STEM

4.1 INTRODUCTION

To provide insight into the role a hydrodynamic model can play in the Berg River systems operations, it is necessary to assess the water quality status of the main stem of the Berg River and how it has changed through time. To give a brief background to the studies that have been done in the past of the water quality situation in the Berg River, the most important findings are summarized in the first section of this chapter. These studies have been initiated due to concerns that water users have expressed about certain water quality variables. From these studies, a minimum group of water quality variables of concern was identified, the relevant data assembled for the period of best availability; October 1992 to September 1998, and analysed for trends in comparison with the most recent source of information, i.e. the report '*Water Quality in the Berg River: A Situation Analysis' (DWAF(g), 1993)* which analysed samples taken until end of 1991. These results are discussed below in detail, showing the results in table format.

Note : For detailed explanation, results, tables and graphs the reader is referred to the main report provided in the enclosed CD.

4.2 STUDIES DONE ON THE WATER QUALITY OF THE BERG RIVER

Concerns of salinity increase in the Berg River main stem and eutrophication at the Misverstand weir has led to various research investigations in the past.

One of the first studies was in the 1950s by Harrison and Elsworth (DWAF(g), 1993). This study was initiated to determine the degree of pollution of the river. Fourie and Steer (as cited by DWAF(g), 1993) and Fourie and Görgens (1977) investigated the mineralisation of the river. It was found that the salinity increases of the river could be the result of increasing irrigation along the river. Bath (1989) studied the phosphate transport of the river and concluded that 80% of the annual phosphorous was contributed by diffuse sources. The implementation of the 1 mg/l special standard for phosphate was postponed, as it was shown that it would have an minimal effect on the phosphorous loading in the river (DWAF(g), 1993). A phosphorous transport module was developed which should assess the fate and transport of phosphorous along the river in order to be able to control it (Bath and Marais, 1991). Due to concerns that the salinity in the Berg River would increase if Skuifraam Dam would be built in the upper reaches where the good quality water would be impounded, a salinity modelling study was undertaken by Ninham Shand. (DWAF(b), 1993). This study showed that the Skuifraam Dam would have relatively small effects on the salinity of the lower reaches in the river.

4.3 VARIABLES OF CONCERN

In line with the Situation Analysis by DWAF, which identified 12 variables of concern, the following variables of concern were considered:

_ pH
_ Salinity : Total Dissolved Salts (TDS) and EC
_ Phosphate
_ Temperature
_ Oxygen

4.4 DELINEATION OF STUDY AREA

For ease of comparison we used the same division of the Berg River System as DWAF used in the Situation Analysis (DWAF(g), 1993). Water quality variables have been analysed and separated according to the river reach, one gauging station per reach representing the average expected water quality values. Additionally, the water quality data of gauging stations representing a tributary draining the Table Mountain Sandstone, and a tributary draining the Malmesbury Shales as dominant geological formation, have been evaluated. The river reaches have been divided into:

River Reach 1
The river reach 1 includes the Berg River and all the tributaries upstream of Paarl (G1H020). No large urban or industrial sites occur in this region. The river and tributaries drain areas with Table Mountain Sandstone as dominant geological formation. The water quality data of G1H004 illustrates the quality of the water one can expect in the Upper Berg River.

River Reach 2
This reach covers the part of the catchment from Dal Josafat (G1H020) to Hermon (G1H036). Paarl and Wellington lie along this reach. Tributaries on the eastern bank of the Berg River drain areas with Table Mountain Sandstone, while the western bank drains areas with the saline Malmesbury Shale as dominant geological formation (DWAF(g), 1993). Summer irrigation demands are supplied by releases from the Theewaterskloof tunnel.

River Reach 3
This reach lies from G1H036 to the old Berg River pumpstation (G1H023). Only Klein Berg River and Twenty-Four Rivers drain the Table Mountain Sandstone. The water quality is improved by the releases of the Voëlvlei Dam to supply summer irrigation demands. This reach includes the impoundment at Misverstand from where the Withoogte WTW abstracts water.

River Reach 4
This reach marks the section that is influenced by the tidal effects and is consequently characterised by higher salinity. The water quality data of G1H023 is indicative of the water quality in this reach.

4.5 WATER USERS

In the comparison of trends that follow below the division of users into municipal and raw water users in the Situation Analysis (DWAF(g),1993) was accepted for this study.

4.6 ASSESSMENT OF pH

4.6.1 Introduction

The pH of water is determined by the concentration of the hydrogen ion (H+). A pH below 7 indicates that the water is acidic in nature, while above 7 it is alkaline. The pH of natural waters influences physical, chemical and biological processes in the system. The surface waters in the upper Berg River Catchment tend to be acidic.

N.B.: In all the samples taken one can see a step of about +1 pH after 1989/1990. It should be noted that in 1989 DWAF improved the preservation of samples through a more efficient preservation method, as well as improving laboratory procedures, that prevented microbiological acidification in the sample (Dr P Kempster, IWQS: pers.comm., 1998).

4.6.2 Main Stem Sampling Stations

Spatial Pattern
It can be seen from the results that the tributaries on the eastern bank of the river tend to be more acidic than the waters of the western bank tributaries. This is because the tributaries on the eastern bank drain areas with Table Mountain Sandstone as main geological formation, which weather to acidic soils and are also low in salts. The water of the Berg River becomes more alkaline downstream with the more acidic water at the origin of the river.

Temporal Pattern

Findings in '*Water Quality in the Berg River: A Situation Analysis*'(DWAF (g), 1993)	**Trends during 1992-1998**
The pH does not seem to indicate a seasonal trend, although unusual long-term changes were observed at river reach 3. In the early 1970's the pH varied between 7 and 8 while in the term 1970 to 1980 the pH declined and ranged from 5.5 to 7 in 1980. The pH increased again, especially in 1989, 1990 and reached values ranging from 7 and 8 in 1991.	The means of the different sampling stations seem to stay constant after the increase in pH in 1989/90. Only few samples fall above a pH 8.5 and thus no actual problems should be encountered with irrigation. At all the sampling stations the range of the pHs seem to deviate less from the median than was the case in the previous years and the values are concentrated more around the median.

4.6.3 Municipal Supply

Many of the problems that are encountered by the municipal supplies occur due to the acidic nature of the water of the upper Berg River Catchment. The raw water tends to dissolve the cement lining of the water distribution networks (aggression) and thus the water needs to be treated in order to raise the pH. This increases the cost of the water treatment. The pH also influences the solubility of iron and aluminium. The concentration of these elements is quite high in waters with low pH, but as aluminium and iron are removed in the treatment process, problems would not be expected of the treated water. (DWAF(f), 1993).

Sampling Station	**Findings in '*Water Quality in the Berg River: A Situation Analysis*'(DWAF (g), 1993)**	**Trends during 1992-1998**
Wemmershoek Water Treatment Works G1R002	At Wemmershoek water treatment works the pH lies mostly below the value of 6.5. This means that 'for most of the time the water is potentially aggressive to cement structures, and that the water would require a high lime dosage to condition the final water to pH 9'. It has been observed that the alkalinity of the water is mostly low (<5mg/l as $CaCO_3$) and will thus react readily to lime addition. The pH of the water is nevertheless not considered to be a problem within the treatment works. pH does not seem to be seasonal.	Only 46 samples were taken during the period 1991 to 1998, with only 3 samples during 1993.The pH values seem to stay constant since the increase in 1989. The majority of the pH values of the samples lie between 6 and 7.
Swartland Water Treatment Works G1R001	For 35% of the time the pH of the water is below 6.5, when excess lime needs to be used. The alkalinity is low and pH conditioning should not be a problem. The pH varies from 8.9 to 4.2 with a median of about 6.7.	The pH values deviate less from their mean in the years 1993 to 1998. From 1989 to 1993 more occasional high pH values (over pH 8.5) were measured. Most values are between 6.5 and 8.5.
Withoogte Water Treatment Works G1R003	The pH seems to be seasonal, peaking in the summer months. The pH also seems to have increased over the years. The range, including the increase from 1989 to 1990, is from 5.3 to 8.8 with a median of 6.9. As most of the values lie between 6.5 and 8.5, there should not be any problems for municipal supplies.	The pH values lie mainly between pH 7 and 8. No values over pH 8.5 were observed. In the summer of 1992 some values were very low at pH 4 to 5, but thereafter the values were all above pH 6 again. The pH values seem to be seasonal but the seasonality seems not apparent in the years 1996, 1997.

4.7 ASSESSMENT OF EC AND TDS

4.7.1 Introduction

Electrical Conductivity represents the ability of the water to conduct an electrical current. It is a measure of the concentration of dissolved salts and hence the salinity and total dissolved salts (TDS) contents of the water. Taste, hardness and corrosion are affected by the components of TDS, including chlorides, sulphates, magnesium, calcium and carbonates.

The South African Water Quality Guidelines expresses the target range in conductivity (mS/m) and lists the corresponding value for total dissolved solids in milligrams per litre (mg/l). In the South

African Guidelines the relationship between Total Dissolved Salts (TDS) and Electrical Conductivity (EC) is specified as:
EC (mS/m) * 6.5 = TDS (mg/l), but in reality it varies, depending on the nature and concentration of the solutes present, their degree of dissociation into ions, the amount of electrical charge on each ion, the mobility of the ions and the temperature of the solution (DWAF (e), 1993).

To be able to compare the samples of the period 1980-1990 that were analysed for the Situation Analysis (DWAF(g), 1993) with the samples of 1991-1998, EC was taken as the measure of salinity.

4.7.2 Main Stem Sampling Stations

Spatial Pattern
High salinity occurs in the rivers draining the Malmesbury Shales (Doring, Fish, Sand, Matjies, Sout and Morreesburg Rivers). This makes the water of these rivers highly unsuitable for irrigation and yield losses should be expected. The tributaries draining the Table Mountain series as dominant geological formation show a low TDS concentration. The water of the Berg River becomes more saline further downstream due to the runoff from the Malmesbury Shales.

Temporal Pattern

Findings in ‘*Water Quality in the Berg River: A Situation Analysis*’(DWAF (g), 1993*)*	***Trends during 1992-1998***
It was detected in the analysis by DWAF that positive trends exist in the years 1980 to 1992 at all the points analysed for EC. It was implied that this increase in salinity is because of increases predominantly in the sodium and chloride concentrations.	Comparing the percentage of values falling in a certain range (see Table 1.1.6) one could say that the salinity has increased slightly over the years in the lower reaches, although this increase is not very high. One can see clearly that the EC has a seasonal pattern. The seasonal variation in conductivity for G1H020 and G1H036 is probably caused by saline irrigation return flow entering the river during the low flow summer months. (DWAF (d), 1993).

4.7.3 Municipal Supply

Sampling Station	**Findings in >*Water Quality in the Berg River: A Situation Analysis*=(DWAF (g), 1993*)***	**Trends during 1992-1998**
Wemmershoek Water Treatment Works G1R002	The EC of the water supplied to Wemmershoek water treatment works remains steadily below 4 mS/m, except for an outlier on the 7th August 1986: EC = 88mS/m, TDS value is 595 mg/l.	There does not seem to be an increase in EC values. Most of the samples taken fall below 5 mS/m.
Swartland Water Treatment Works G1R001	The EC of the water ranges from 8 to 14 mS/m and problems should not be encountered.	All samples taken are below 25mS/m. There seemed to be an increase in salinity from the years 1992 to 1994, but thereafter it seems to decrease again and most samples are just above 11 mS/m.
Withoogte Water Treatment Works G1R003	At Misverstand Weir the EC does not seem to be seasonal, but it has been perceived that the EC is higher in the wetter months in the year. It has been suggested that rainfall washoff is responsible for the higher salt concentrations and that long term trends in the salinity are likely to follow the trends of the rainfall cycles. The range is from 13 to 95 mS/m with a median at about 37.2 mS/m.	There does not seem to be an increase in EC values at Misverstand weir.

4.8 ASSESSMENT OF PHOSPHATES

4.8.1 Introduction

Eutrophication refers to water, particularly in lakes and reservoirs, which is high in nutrients and hence has excessive plant and algae growth, rendering the water less fit for use. DWAF assessed the trophic status of the Berg River by examining the chlorophyll a concentration. For economy of efficiency it was decided to focus in this study on phosphates as indicator of the nutrient status.

4.8.2 Main Stem Sampling Stations

Findings in ‘Water Quality in the Berg River: A Situation Analysis’(DWAF(g), 1993)	*Trends during 1992-1998*
It has been observed by studying the chlorophyll a concentrations that the concentrations still fall within the South African target guideline range.	An increase in phosphate concentrations at all stations can be clearly seen. In the years 1980-1990 there seems to be more occasional outliers in the concentrations.

4.8.3 Municipal Supply

Sampling Station	*Findings in >Water Quality in the Berg River: A Situation Analysis= (DWAF(g), 1993)*	*Trends during 1992-1998*
Wemmershoek Water Treatment Works G1R002	From the analysis of the chlorophyll-a concentrations it was suggested that at Wemmershoek WTW, Voëlvlei and Swartland WTWs no serious problems are expected with regard to the chlorophyll a concentrations.	At Wemmershoek water treatment works (G1R002) only few samples were taken and it is difficult to see any pattern to be able to compare it to the previous years. The samples taken show still a low phosphate concentration and thus there should be minimum algal growth
Swartland Water Treatment Works G1R001	From the analysis of the chlorophyll a concentrations it was suggested that at Wemmershoek WTW, Voëlvlei and Swartland WTW no serious problems are expected with regard to the chlorophyll a concentrations.	At the Swartland water treatment works the range of phosphorus lies between 0 to 0.04 with most values between 0.01 and 0.03, where previously the values mostly fell below 0.02 mg/l. Here also the concentration of phosphate is still relatively low.
Withoogte Water Treatment Works G1R003	"Nutrient concentrations in Misverstand weir are more than sufficient to sustain a large algae population, but the number of algae in this water body are held in check by the high turbidity of the system. Elevated turbidity reduces the amount of light available to the algae and hence inhibits their growth. However in the Misverstand weir the physical and chemical conditions are such that they promote the development of a type of algae which creates taste and odour problems at very low concentrations." (DWAF(g), 1993). At Misverstand weir the chlorophyll-a concentrations are much higher and the water needs to be treated accordingly. The chlorophyll a concentrations seem strongly seasonal with peak concentrations in summer.	From the graphs of Withoogte (Misverstand weir) and at Swartland water treatment works one can very clearly see that the phosphate concentrations have increased from 1991 onwards. The phosphate concentration ranges from 0.01 to 0.06 with most values at 0.025 mg/l as PO_4

4.9 ADDITIONAL WATER QUALITY SAMPLES TAKEN IN THE BERG RIVER MAIN STEM

Additional water quality samples have been taken in the Berg River main stem weekly over a two month period. The water quality variables sampled were EC, pH, Oxygen and Temperature. The location the samples were taken are at:

- Bien Donne : lies upstream of Paarl, wine and fruit farm
- Picardi: lies in Paarl just upstream of railway bridge, samples were taken at the effluent discharge and just downstream of effluent discharge
- Wellington: samples were taken downstream of Krom River confluence at Sanddrift downstream of Leather factory in Wellington

Table 4.1 Summary of water quality samples taken in the Berg River

	pH	EC (mS/m)	O_2 (mg/l)	Temp (EC)
Bien Donne	6.7	7.2	9.6	19.3
Picardi (ds of effl.)	6.8	8.4	/	/
Picardi (at effl.)	6.7	24.4	/	/
Wellington	6.9	17.2	7.7	18.4

It can be seen that the EC values measured upstream of Dal Josafat (G1H020) are below the mean of 10.6 mS/m at G1H020. At Wellington the EC value measured is 6.6 mS/m higher than the mean measured at G1H020. These measured values indicate that the EC in the river increases rapidly downstream of Paarl, which could be the result of the industrial effluent discharging into the river.

The pH samples measured just upstream of G1H020 (Bien Donne and Picardi) are below the average pH of 7.3 calculated for the historical grab samples taken at G1H020. The pH measurements taken at Wellington are also below the average at G1H020.

As no other oxygen samples have been taken in the Berg River no comparison to other samples can be made.

The temperature samples lie below 20EC.

4.10 CONCLUSIONS

Assessment of pH
After the change in preservation of samples (1989,1990) the pH concentration seems to be more consistent and deviates less around the mean. Problems that could occur for the municipal water users stem from the low pH of the upper Berg River and the acidic runoff from the Table Mountain Sandstone areas.

Assessment of salinity
No significant increase in salinity during the period 1992-1998 is evident and should therefore at this time not be necessarily a cause of concern. The lower part of the Berg River is much more saline than the upper reaches (which could create problems for the municipal supply and irrigation) and care should be taken that these reaches do not increase in salinity over the years.

Assessment of phosphate

At all stations a definite increasing trend in phosphates over the years can be seen. At the water treatment works the phosphate concentrations have increased during the years, although they still show low concentrations. It can therefore be assumed that most of the increase in phosphate is due to increasing land use and irrigation. In the years 1980-1990 there seems to be more occasional outliers in the concentrations.

CHAPTER FIVE
SOFTWARE STRUCTURE AND MATHEMATICAL BACKGROUND TO DUFLOW WATER QUALITY MODEL

5.1 INTRODUCTION

On the basis of the review of available water quality models, it was decided to use DUFLOW to model the Berg River because of the appropriateness of its scientific content, its user friendliness, the graphical interface and inexpensiveness compared to the various other packages that are on the market. DUFLOW is jointly owned by the Faculty of Civil Engineering at Delft University of Technology and the Public Works Department (Rijkswaterstaat), International Institute for Hydraulic and Environmental Engineering (IHE), the Agricultural University of Wageningen and STOWA.

In this Chapter a short description is given of the software structure of DUFLOW. Additionally an outline is given, firstly, to the basic hydrodynamic equations and, secondly, to the water quality processes, as well as the numerical method that DUFLOW uses to solve these equations.

Note : For detailed explanation, results, tables and graphs the reader is referred to the main report provided in the enclosed CD.

5.2 DESCRIPTION OF THE DUFLOW MODEL SOFTWARE STRUCTURE

5.2.1 Features of the Interface

The user interface consists of the following components:

- Menus
- Toolbars
- Status Bar
- Scenario Manager window
- Working space with the Network window and Results windows
- Output windows

The Network editor is a graphical editor that enables the user to draw the network schematization in a very user-friendly way.

5.2.2 Calculation Options

Type of calculations possible:'

- *Flow* : Only flow can be calculated
- *Flow and Quality*: Flow and quality are calculated simultaneously
- *Quality* : (This option can only be used if an intermediate flow result file was generated in a flow calculation.)
- *Box* : The calculations for the water quality only takes the processes into consideration.

5.2.3 Import and Export of Data

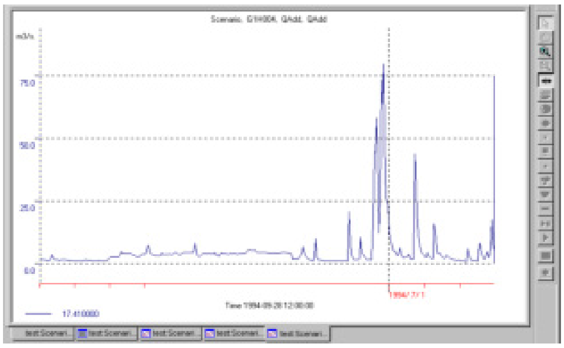
Time Series that are used as boundary conditions and discharge points can be imported from and exported to external files in ASCII format. Results in text form can also be exported in the text form to be used in spreadsheets for statistical analyses.

5.2.4 Presentation of Results

The results of a calculation can be displayed in three different ways:

- A Time Related Graph,
- A Space Related Graph (the user can define the route that should be plotted)
- Results as Text in a table as a function of time (makes it possible to export the results into spreadsheets).

A result window can contain the output of more than one variable or the output from different scenarios.



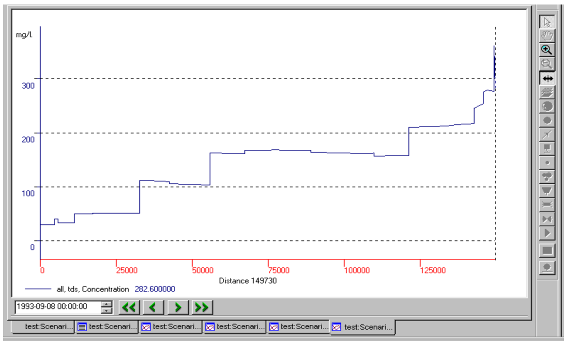


Figure 5.2: Time Related Graph

Figure 5.3: Space Related Graph

5.2.5 Configuration of the Model

Network Schematization
The configuration of the model occurs through the network window. One can create the model easily by using different methods, i.e. the mouse, etc. Variables can be added in the network window or through text files.

Calculation Settings
In the calculation settings dialog box the start calculation time and time step need to be selected. The type of calculation also needs to be specified. When the flow calculation is verified, a quality model can be added.

Scenarios
The programme consists of a Scenario Manager with which the user can define several different scenarios, without changing the base scenario. This gives the user the ability to see the result of different scenarios, such as pollution spills or sudden rainfall storms.

5.3 HYDRODYNAMIC MATHEMATICAL BACKGROUND

5.3.1 Introduction

DUFLOW can represent riverflow as non-uniform and unsteady. This is the most complex flow type as it requires the solution of the St. Venant equations through time and distance.

5.3.2 Unsteady Flow Equations

The equations used to analyse unsteady flow in an open channel are the continuity equation and the momentum equation, known as the St. Venant equations. The variables that have to be entered are: resistance, velocity correction factor and the advection term.

The solution to the St. Venant equations is complex and therefore a number of numerical methods have been developed to get a solution to the equations. It has to be recognized that although the St. Venant equations are capable of calculating supercritical flow, the numerical solution is not able to do so. Therefore, DUFLOW is unable to calculate supercritical flow.

5.3.3 Numerical Solutions to Unsteady Flow

Three principal types of numerical methods can be used to calculate open channel flow: method of characteristics, finite differences and finite elements. DUFLOW discretises the St Venant equations by using an implicit finite difference scheme, the four-point implicit Preissmann scheme.

5.3.4 Boundary and Initial Conditions

A unique solution to the St. Venant equations requires two initial and two boundary conditions. In DUFLOW the boundary conditions are user defined and may be specified as levels, discharges or a relation between the two.

The initial conditions are specified at every node and schematization point as flow conditions at the initial time step.

5.3.5 Cross-sections

For modelling purposes, cross-sections are often assumed trapezoidal, rectangular or of parabolic shape. DUFLOW gives the option to enter the cross-section as any of the three. The cross-section is entered as a function of depth, as can be seen in Figure 5.4. Therefore, storage areas and flow areas can be entered at different depths.

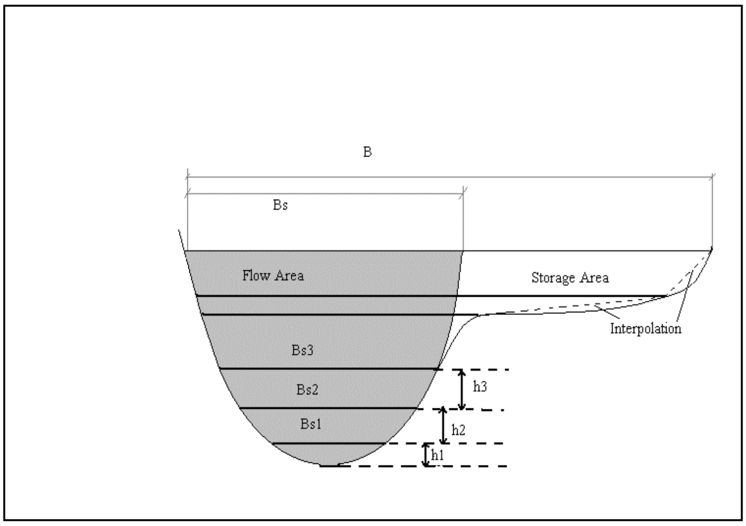


Figure 5.4: Schematization of cross-sections

5.3.6 Structures

Various types of control structures can be defined in DUFLOW. Discharges and levels can be modified and controlled by so-called trigger conditions at structures: depending on flow conditions, parameters such as the width of a weir, etc. can be adjusted during the computation to reflect structural changes during this period.

5.4 WATER QUALITY

5.4.1 Introduction

Water quality models predict changes in water quality variables due to loading, transport and reactions within the water body. The basic theory describing these changes is the conservation of mass. *Sources* specify all the chemical reactions that contribute to an increase of mass of the constituent, while the *sinks* are responsible for the decrease of mass.

5.4.2 Transport

A differentiation needs to be made between a conservative and a non-conservative constituent, a non-conservative quantity has a continuously decaying mass due to the biological or chemical reactions, even if no transport or diffusion takes place. A conservative constituent does not undergo any changing processes except for being transported and diffused. Therefore, the production term P would only apply to non-conservative variables.

The equation used, is the mass balance equation, which states that the accumulation of a water quality variable is equal to the production rate minus the transport gradient.

One Dimensional Dispersion
The value of D (longitudinal dispersion coefficient) will vary along the channel, depending on the geometry of the channel. A dispersion coefficient needs to be specified at every node and discharge point, this allows the user to model the influence of different coefficients, as the dispersion coefficient varies along the river stretch.

5.4.3 Discretization of Mass Transport Equations

In the flow calculations the discharges were expressed as a set of linear equations as functions of water levels.

5.4.4 Initial and Boundary Conditions

The user has the option of entering the water quality data as loads or as concentration. At the physical boundaries, a concentration boundary for every defined dissolved substance is compulsory.

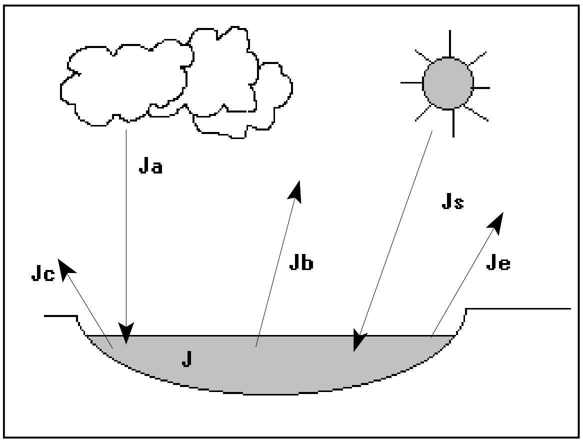
5.4.5 Water Quality Processes

The mass of water quality variables can be changed by a variety of chemical and biochemical reactions. In DUFLOW the mathematical formulations describing the processes can be supplied by the user. These are supplied in a file which can be created or modified by using the user interface. A special description language DUPROL has been developed to allow this. DUFLOW comes with EUTROF1 and EUTROF2, which are two predefined eutrophication models. EUTROF1 was used in the Berg River study; as it contains simpler algorithms describing the water quality processes, therefore, less data and parameter intensive than EUTROF2. For this study alterations have been made to the model to allow additional modelling of TDS and temperature, as these variables are of great concern in the Berg River study.

Temperature
The temperature of a water body is of particular significance as:

(a) temperature influences all biological and most chemical reactions,
(b) the discharge of municipal or industrial effluent may affect the aquatic ecosystem due to different temperatures than the receiving water, and
(c) variations in temperature affect the density of water and hence the transport of water.

<u>Temperature Model developed for this study:</u>
The temperature of a given water body depends on the sources and losses of heat in a water body. These have to be therefore estimated as accurately as possible in order to assess the heat balance. Thomann and Mueller (1987) summarize the sources and sinks as follows:



Sources:

- Shortwave solar radiation
- Longwave atmospheric radiation
- Conduction of heat from atmosphere to water
- Direct heat inputs from municipal and industrial activities.

Sinks (losses):

- Longwave radiation emitted by water.
- Evaporation
- Conduction from water to atmosphere.

Figure 5.5: Sinks and Sources of Temperature Model

The heat balance in a small volume of the river will be:
Rate of change of temperature = heat in - heat out -+ net heat exchange

The EUTROF1 and the EUTROF2 models do not allow the user to model the temperature in the particular water body, but only take the effect of temperature on the kinetic reactions into account. Thus, for this study, a temperature sub-model has been developed and incorporated into the EUTROF1 model by using the Compiler.

The components of the introduced equation will be explained briefly below.

Net solar shortwave radiation (Js):
Solar radiation is dependent on various factors such as the solar altitude, scattering of radiation by clouds and adsorption by atmospheric gases, reflection, as well as shading of the streams. Many algorithms have been developed to calculate the solar radiation. Solar radiation is often measured by meteorological stations around the country and these measurements can be used directly in the equation.

Atmospheric longwave radiation (Ja):
The atmospheric longwave radiation takes the Stefann Boltzmann law into account, the atmospheric attenuation which represents the difference between the emittance value for the earth's surface and the effective emittance for the atmosphere, and the reflection of the water body. These terms are explained below:

Back Radiation of water (Jb):
The back radiation (J/m^{2}day) from the water surface can also be represented by the Stefann Boltzmann law.

Conduction (Jc):
With conduction the heat transfer is dependent on the water, as the heat is transferred from one molecule to another when the molecules of different temperatures come into contact. This occurs normally at the air-water interface. Conduction plays a more substantial role in the heat transfer in lakes than rivers as the air-water interface is larger.

Evaporation (Je):
The heat lost due to evaporation is determined by the rate of mass transfer from the water to the atmosphere times the latent heat of vaporization.

Nutrients as Phosphorous
The major nutrients that contribute to eutrophication are phosphorus as phosphate ions ($PO_4{}^{3-}$) and nitrogen as nitrate ($NO_3{}^-$), nitrite ($NO_2{}^-$) and ammonium (NH_4^+) ions. Plants normally use the

nutrients in inorganic form. The reduction of algal growth rate depends on the most limiting factor, which means that the growth of a phytoplankton is limited by the nutrient that is available in low levels in the water body. Several studies show that phosphorus is often the limiting nutrient to phytoplankton growth in rivers (Chapra, 1997).

Although DUFLOW can simulate changes in nitrates, ammonia and phosphates, only the impact of phosphates will be modelled in the Berg River. The main sources of phosphate are human activities, in the form of non-point sources from agricultural and urban land and point sources as wastewater effluents. There are many ways to characterise phosphates. Chapra(1997) summarized these forms of phosphate found in a body of water as follows:

- *Soluble reactive phosphorous* (H2PO4 - ,HPO42-, PO43-)
  This form of phosphorous is available for plants. It is also called orthophosphates.

- *Particulate organic phosphorous*
  This form consists of living plants, bacteria as well as organic detritus.

- *Non-particulate organic phosphorous*
  Dissolved or colloidal organic compounds containing phosphorous. primary origin is decomposition of particulate organic P.

- *Particulate inorganic phosphorous*
  These are the phosphate minerals sorbed onto sediment such as clays or complexed with solid matter (e.g. .calcium carbonates or iron hydroxydes).

- *Non-particulate inorganic phosphorous*
  These are condensed phosphates.

The differentiation into particulate and non-particulate is classified for measurement purposes. The particulate is removed by settlement and can then be measured. The division into available phosphorous is created especially for modelling purposes as this is the only form of phosphorus that is available for phytoplankton growth. The inorganic and organic form is often not mentioned in the literature or in water quality models but rather lumped into particulate and non-particulate unavailable phosphates. In DUFLOW a distinction is only made between organic phosphorous and inorganic phosphorous, the organic particulate phosphates are modelled separately as the phytoplankton group.

The inorganic dissolved phosphorous (orthophosphate) is only available for algae growth and thus normally of interest. DUFLOW calculates the amount by multiplying it by a factor which allows for the fraction of inorganic phosphates that have been sorbed onto sediments. No suspended solids data was available for the years that have been studied, thus the assumption has been made that SS=0. This means, that all the inorganic phosphate is measurable as orthophosphates.

Dissolved Oxygen (DO)
Dissolved Oxygen in the water body shows clearly the impact effluent has on the water and thus is ecologically of much interest. In an unpolluted river, the oxygen level will normally be near to the saturation level. The dissolved oxygen becomes depleted when effluents enter the river, because heterotrophic organisms (organisms that live on organic matter) deplete the oxygen in the process of breaking down the organic matter.

In the water body, the sources of oxygen are:

- Re-aeration from the atmosphere
- Photosynthetic oxygen production
- DO in incoming tributaries or effluents.

The sinks of DO are:

- Oxidation of carbonaceous waste material.

- Oxidation of nitrogeneous waste material
- Oxygen demands of sediments.
- Use of oxygen for respiration for aquatic plants.

The equation in Duflow only models the re-aeration. Additional terms are included in DUFLOW in the equation describing oxygen, but have been omitted here as they will not be modelled in this particular study.

Oxygen saturation concentration:
The oxygen saturation concentration is a fixed level of oxygen that is reached in the water body for a given temperature (Thomann and Mueller, 1987). This oxygen saturation level is dependent on the temperature, salinity and pressure due to elevation.

Dissolved oxygen deficit:
The DO deficit is introduced as the difference between oxygen saturation concentration (C_s) and oxygen. The re-aeration coeffcient determines the time it takes for the DO in the water body to recover to the equilibrium value.

Re-aeration Rate:
Re-aeration is the process of oxygen absorption from the atmosphere to the water. This is one of the main sources of oxygen in water. As the depth increases, the re-aeration coefficient approaches zero in the algorithm; this is in reality not the case and therefore an additional minimum value of oxygen transfer coefficient is introduced.

COD:
At most South African wastewater treatment plants the effluent will be tested for the Chemical Oxygen Demand (COD) rather than that the Bio-chemical Oxygen Demand (BOD) as in Europe. As DUFLOW only measures BOD_5 (5 day carbon BOD), another adjustment had to be made to allow the user to enter the COD data.

Total Dissolved Salts
EUTROF1 models no conservative substances, thus as with the additional coding of temperature and COD, TDS has been included as an additional variable. TDS is only dependent on the mass transport.

Parameters used in water quality reactions
The parameters used in the reaction processes are the parameters that can also be adjusted by calibration.

5.5 ACCURACY AND STABILITY OF NUMERICAL MODELS

An accumulation of errors in the finite difference scheme is called *instability* (Grijsen, 1986). An implicit scheme is much more stable than an explicit scheme, because all the equations occur simultaneously and errors are not brought forward from one point to the following and then accumulate, such as is the case in an explicit scheme.

The *accuracy* of the finite difference solution depends on the differential equation. *Accuracy* refers to the difference between the exact solution to the algorithms and the finite difference solution.

5.6 TIME AND SPACE STEP

The space step can be defined by the user as a maximum length. The hydraulic characteristics between the space steps are interpolated. The time step is also defined by the user. Normally, smaller values are used as the solution then becomes more accurate.

5.7 CONCLUSION

Hydrodynamic Model:
It has to be remembered that DUFLOW is unable to calculate supercritical flow, although the St Venant equations are able to do so. The implicit scheme shows some advantages to the explicit scheme especially with regard to schematization and calculation time. The implicit scheme is advantageous for this particular study, as it is unconditionally stable. This was of value when configuring the upper Berg River(as is explained in Chapter 6), where the slope of the river is very steep and small calculation steps are necessary.

Water Quality Model:
A limitation to the predefined eutrophication model EUTROF1 is, that no temperature, nor conservative variables such as TDS are not modelled. Nevertheless, DUFLOW allows (by having an open structure) that the user can adjust the water quality model corresponding to the particular problem that needs to be studied. The water quality model should be altered to adjust the various algorithms for South African situations.

Time and Space:
As the hydrodynamic and water quality model do not necessarily need to have the same time step, the computation time can be greatly reduced by allowing the water quality time step to be higher than the hydrodynamic model. The benefit of allowing the user to define a time step is to analyse the water quality variables in the required time the chemical and biochemical processes take place. If at a later stage more data should become available, the model could run at an even finer resolution. As the numerical scheme is implicit it has major advantages regarding the space step. The user can define unequal space steps according to the problem and the output required. Also, the stability of the calculations is improved by using an implicit scheme.

CHAPTER SIX
DATA PREPARATION AND CONFIGURATION OF THE MODEL

6.1 INTRODUCTION

This chapter presents the preparation of data and the configuration of the Berg River in the DUFLOW Modelling System (DMS). The first stage of developing the model was the data gathering and the preparation of the data according to the format that DUFLOW requires, these include the geometrical profile of the river, the boundary conditions (i.e. the flow hydrographs). The chapter is divided into two main sections, the first section describing the configuration and data preparation for the hydraulic calculations, while the second section reports on the water quality data preparation and configuration.

Note : For detailed explanation, results, tables and graphs the reader is referred to the main report provided in the enclosed CD.

6.2 HYDRODYNAMIC SCHEMATIZATION

6.2.1 Flow Data Preparation

The daily flow data was obtained from DWAF and modified into a format which is required by DUFLOW. Only the recent flow data was considered, i.e. measurements made from 1990 to 1998.

6.2.2 Nodes and Boundary Conditions

The two external nodes are upstream at upper Berg (G1H004) and downstream at Misverstand Dam (G1R003). Three internal nodes were also included in the schematization at the gauging stations G1H020 (Dal Josafat), G1H036 (Hermon) and G1H013 (Drie Heuwels). The total length of the river is approximately 149 km. The river length between the two external boundaries was divided into four reaches, which can be seen in Table 6.1.

Table 6.1 Reaches of the main stem Berg River

Reach	Beginning node	End node	Length (km)	Average Slope (%)
1	G1H004	G1H020	31	0.35
2	G1H020	G1H036	41	0.095
3	G1H036	G1H013	57	0.055
4	G1H013	G1R003	20.5	0.05

One boundary condition is needed at each end point of the network schematization. The upstream boundary condition at G1H004 is the inflow hydrograph, while at G1R003 a stage-discharge rating curve has been specified as the end boundary condition. The rating curves for all the weirs were obtained from DWAF.

6.2.3 Cross-sections

A total of 108 cross-sections were used for configuration of the model. Some of the cross-sections were not surveyed beyond the banks and information on the characteristics of the floodplain was obtained from orthophotos (1:10 000). The cross-sections were represented in DUFLOW with the width as a function of height. A minimum of one cross-section has to be defined per reach and an unlimited number of cross-sections may be inserted between two nodes. Detailed cross-sections were sourced from DWAF, Ninham Shand, Paarl Municipality, Robin Pharaoh & Associates, SATMAP Solutions CC and Photosurveys.

6.2.4 Structures

Weirs
Details for the weirs were obtained from plans which were made available by DWAF (Western Cape Regional Office). The weirs that have been included in the model are at gauging stations G1H004, G1H020, G1H036 and G1H013.

Bridges
A total of 13 bridges were identified along the main stem of the Berg River for the river reach modelled. The information on the various bridges was available from Department of Road Transport and Paarl Municipality. From the 13 bridges identified, only 7 could be modelled. For some of the bridges no information was available, while the Dal Josafat, Hermon and Jim Fouche Bridges caused persistent numerical instabilities in the model. The effect of these problematic bridges was approximately retained by increasing the roughness coefficient in the specific reach.

6.2.5 Tributaries

The tributaries were entered at schematization point, that allow the user to insert the hydrographs as time series.

6.2.6 Roughness Coefficient

The roughness can be expressed as the inverse of the Manning roughness coefficient ‘n’ or by the Chezy coefficient C. DUFLOW gives the user the option to change the roughness at every cross-section and also at every point defined in the cross-section at the relevant sides of the section. This allows the section to have changing roughness. The initial roughness coefficients were based on the relationship between the absolute roughness and the hydraulic radius in Figure 3.8 in the NTC Road Drainage Manual (Rooseboom *et. al*., 1983) and adjusted during calibration.

6.2.7 Abstractions and Return Flows

Paarl Abstractions
The Municipality of Paarl receives water mainly from the Wemmershoek Dam, but additional water is abstracted from the river as the water from Wemmershoek Dam is costly (Pers. Com. A. Kowalewski, Paarl Municipality). The abstraction data were made available as monthly average flows. It has been identified that there is a 100% decrease in the winter months from the period before 1990 to 1999, while abstractions in the summer months has increased (310% in November). It has been assumed that the abstractions have increased linearly in the years and the calculated figures for 1993/1994 have been inserted into the model.

Other Industrial Abstractions
Water Quality in the Berg River: A Situation Analysis’ (DWAF(g), 1993) describes industries which utilise water from the Berg River with little or no pre-treatment. None of these industries, occur in the reach considered for this study and therefore the industrial abstractions have no effect on the flow modelled.

Irrigation
There are currently eight Irrigation Boards which are permitted to abstract water from the river. For the irrigation boards where no information was available, a rate of 7500m^3/ha/annum was applied to the scheduled areas. The monthly distribution of water abstracted was adjusted by following the seasonal distribution of the evaporation rate. The irrigation demand was calculated as follows:

> monthly crop factor * mean monthly A-Pan evaporation - effective rain/total rain ratio (0.7) * mean monthly precipitation

The total volume of abstractions was calculated to be 42 Mm^3/a. This present figure shows a rising trend when compared to the abstraction value of 35 Mm^3/a calculated for the WCSA in 1995 (DWAF(b), 1995). This rising trend is further illustrated by the ‘*Water Quality in the Berg River: A Situation Analysis’* (DWAF(g), 1993) that calculated abstractions to be 21.7 Mm^3/a from G1H004 to Sonkwasdrift.

Return Flows:
Sewage Return Flows from Paarl are monitored by the Paarl Municipality. The Paarl Sewage Treatment Works (STW) is the most significant effluent producer in the whole of the Berg River catchment (10.8 Mm^3/a).

Sewage return flows from Wellington are not monitored, as the water is discharged into evaporation pans.

6.2.8 Evaporation Losses

Records of average daily evaporation were made available by Western Cape Department of Agriculture, Elsenburg. As no function is incorporated in the DUFLOW model to calculate the evaporation loss rate relative to the function of surface area at each time increment, the average evaporation loss was modelled as abstraction points. The loss rate was calculated as:

$$\text{Loss } (m^3/s) = \text{average width (m)} * \text{length between sections (m)} * \text{evaporation loss rate (m/s)}$$

The evaporation rate was divided into several abstraction points in relative proportion to the surface areas that each abstraction/schematization point represented, in order to achieve even distribution of the evaporation along the river. This also ensured that a smoother concentration profile was calculated; thus the impact of the evaporation on the water quality was shown fairly realistically. The evaporation rates of four meteorological stations were applied to the Berg River model.

6.3 WATER QUALITY CONFIGURATION

6.3.1 Water Quality Data Preparation

DUFLOW needs daily concentrations for the variables of concern in the form of continuous time series. As the water quality data obtained by DWAF is measured mostly on a one- or two weekly basis, the daily sequences have to be developed by 'infilling'. Table 6.2 shows the infilling techniques that have finally been used to turn the grab sample water quality time series into a daily series.

Table 6.2: Infilling of water quality variables

Parameter with missing data	Parameter used for infilling	Infilling technique
Log TDS	Log Flow	Moving-Regression
Log PO_4	Log Flow	Moving-Regression
Water Temperature	Date	Harmonic Function

TDS and PO_4 Infilling
Two methods were investigated for this study, before deciding on a certain infilling method:

- The program **FLUX** (Walker, 1987)
- A **moving-regression** method (DWAF, 1998)

Flux
Flux interprets water quality information and flow information from grab samples over the complete flow record between two dates. There are five different equations that can be used to calculate the concentrations. Flux has an option to divide the flow and concentration data into different data groups (stratification) and calculate loadings for the different groups using the calculation method chosen. The groups can be defined based upon flow, time or any other variable that seems to influence the load dynamics.

Discussion:
Flux seemed suitable for calculating monthly and yearly loads. The results were not satisfactory as the daily concentrations would remain consistent over a certain period, as it is stratified according to flow. The method seemed to calculate a single concentration for the range of flows entered and thus the concentrations do not differ for every single value of flow, but rather displayed five different concentration values for the five ranges of flow stratified.

Moving-Regression
The relationship between concentration and flow can be described with a moving regression. Studies of the relationship between flow and the concentration constituent have revealed that a single prescribed value for each of the regression coefficients a and b does not adequately describe the relationship between concentration and flow over the full range of most flow regimes in South Africa (DWAF, 1998). The regression coefficients vary because of different factors that influence the relationship between flow and the concentration such as variable loadings from point sources, or whether the sample has been taken during a rising (more surface runoff) or a falling hydrograph (more groundwater). A moving regression method was developed for the Amatole Water Resource System Analysis (DWAF, 1998), which takes these variations into account.

Discussion:
When the intervals between observed values are long (>14 days), the regression does not show satisfactory results. This is due to the strong seasonality of the concentration variables. These water quality variables were infilled for all the catchments where flow and water quality data was available.

Results of Infilling Method
TDS
The moving regression works well for the TDS infilling. For zero flows the regression is interrupted and produces zero concentrations. From the statistics it is illustrated that the difference in means of the observed and calculated values are low (all below 10%). Table 6.4 shows the results.

Phosphate as PO_4
Table 6.5 shows that a similar pattern occurs for PO_4 at low flow as for TDS infilling. Some stations show a better relationship between flow and phosphates.

It has to be borne in mind that only about eight grab samples values are included in the regression at a time. If the variance is higher between the grab samples, the difference between the estimated values and the grab sample will be greater. As the method is based on a regression equation, the concentration maxima and minima may be over or underestimated.

Temperature Infilling
Temperature was also measured on a two weekly basis. Three methods were examined in order to determine the best suited function for the infilling of temperature: Regression with air temperature, Fourier series and a simple harmonic function. The simple harmonic function seemed to be sufficient to predict the temperatures reasonably accurately. Table 6.3 summarizes the coefficient of determination (R^2) and the errors for every year infilled for the various stations.

Table 6.3: Statistics of Temperature Infilling

Station	Summer Mean Infilled (Oct-March)	Winter Mean Infilled (Apr-Sept)	Summer Mean Measured (Oct-March)	Winter Mean Measured (Apr-Sept)	Summer Mean Error	Winter Mean Error	(R^2)
G1H004	20.19	12.87	20.23	13.33	-0.19	-3.45	0.75
G1H003	21.67	14.52	20.58	14.1	5.3	2.98	0.67
G1H019	17.21	14.17	17.17	14.24	0.2	-0.5	0.7
G1H036	23.31	13.66	22.48	14.55	3.7	-6.1	0.63
G1H008	21.13	12.78	20.57	13.77	2.7	-7.2	0
G1H039	22.3	15.17	23.04	15.24	-3.2	-0.5	0.75
G1H041	22.23	14.15	21.69	14.44	2.5	-2	0.75
G1H013	23.4	15.3	23.6	14.6	-0.85	4.8	0.72

Oxygen Infilling
No oxygen data is available for the Berg River, but as oxygen is also temperature-dependent, the saturated oxygen concentration may be used as an upper limit reference value, assuming that no oxygen has been lost for any chemical process.

Incorporation of observed grab samples in infilled time series
The measured grab samples are not included in the generated time series. The infilled time series were used initially in the configuration, as it follows a “smoother” trend without the measured data. A sensitivity analysis was completed with and without the grab samples incorporated into the infilled time series. The grab samples were included in the time series by interpolating the two values before and after each grab sample in order to smoothen the impact it might have on the time series.

6.3.2 Water Quality Variables

The water quality concentrations of interest have been entered as non-uniform time series, which has been infilled according to Section 6.3.1.

6.3.3 Abstractions

There are two possibilities for DUFLOW to calculate water quality loads at points where the water flows out of the system.

- If no water quality boundary condition is specified at a point, the concentration of the outflowing water volume is treated as zero concentration. This option has been used at the evaporation points.
- At irrigation and water abstraction points, a water quality boundary condition had to be defined. The outflowing concentration is then calculated relative to the volume of the outflowing water.

Table 6.4: Statistics of TDS Infilling

Gauging Station	No of Samples	Mean Concentration (infilled)	Mean Concentration (Grab Samples)	% error in mean	Std. Dev (infilled)	Std. Dev (grab samples)	% differ. in std deviation	R^2 (Loads)
Main Stream:								
G1H004	174	32	33	-2.8	6.9	10.3	-33	0.93
G1H020	303	59	61	-4	9.54	18.6	-49	0.98
G1H036	251	127	128	-1.1	23.4	35	-33	0.87
G1H013	271	151	153	-1	34.7	48.5	-28	0.89
G1R003	333	211	217	-2.8	65.2	78.5	-17	0.93
Tributaries:								
G1H003	163	82	83	-1	24.9	28.54	-13	0.98
G1R002	34	25	25	-1.4	1.59	4.14	-62	0.99
G1H019	277	39	40	-2.3	7.8	10.5	-26	0.93
G1H037	65	95	101	-5.5	26.4	31.4	-16	0.95
G1H039	130	2648	2712	-2.4	735	897.5	-18	0.97
G1H041	234	160	175	-8.5	51.5	88	-41	0.97
G1H008	300	113	118	-4	29.4	40.4	-27	0.99
G1H065	491	67	67	-0.2	8.4	10.2	-18	0.99
G1H043	106	4639	4665	-0.57	1263	1341	-6	0.99
G1H035	168	1637	1681	-2.6	648.7	840.5	-23	0.91
G1H034	315	6310	6253	0.9	2220	2297	-3	0.91

Table 6.5: Statistics of Phosphate as PO_4 Infilling

Gauging Station	No of Samples	Mean Concentration (infilled)	Mean Concentration (Grab Samples)	% error in mean	Std. Dev (infilled)	Std. Dev (grab samples)	% differ. in std deviation	R^2 (Loads)
Main Stream:								
G1H004	174	0.019	0.02	-9	0.0077	0.012	-35.8	0.8
G1H020	302	0.023	0.027	-16	0.013	0.047	-72.3	0.84
G1H036	252	0.053	0.059	-10	0.03	0.049	-38.8	0.88
G1H013	297	0.023	0.025	-7	0.016	0.021	-23.8	0.89
G1R003	354	0.024	0.025	-5.5	0.012	0.017	-29.4	0.92
Tributaries:								
G1H003	160	0.025	0.034	-25	0.0164	0.071	-77	0.79
G1R002	34	0.009	0.01	-10.8	0.003	0.008	-62.5	0.97
G1H019	267	0.012	0.013	-8.3	0.005	0.008	-37.5	0.9
G1H037	72	0.027	0.0277	-3.5	0.01	0.015	-33.3	0.87
G1H039	128	0.3	0.33	-9.7	0.16	0.212	-24.5	0.96
G1H041	234	0.02	0.024	-15	0.0099	0.023	-56.9	0.91
G1H008	294	0.016	0.017	-6.8	0.0087	0.011	-20.9	0.96
G1H065	506	0.013	0.014	-5.4	0.0057	0.0078	-26.9	0.86
G1H043	101	0.033	0.036	-7.8	0.012	0.019	-36.8	0.84
G1H035	164	0.038	0.046	-17	0.026	0.043	-39.5	0.95
G1H034	317	0.147	0.176	-16.5	0.15	0.18	-16.6	0.62

6.3.4 External Variables

External variables, such as solar radiation, evaporation rates and air temperature have been imported into DUFLOW. External parameters can be defined at every schematization point or node. This allows for more flexibility, as the external variables can be adjusted corresponding to their location.

6.3.5 Parameters

Default values for the parameters are used in the first simulation runs and are then adjusted at the calibration.

6.4 PROBLEMS ENCOUNTERED

The accuracy and stability of the calculations depend on the implicity factor θ, as well as the time step and the space step (refer to section 5.6). Most of the stability problems were encountered in the upper reach as the slope is very steep (0.35%) and >negative= water depths resulted at some sections.

- Difficulties were experienced especially in the first reach from G1H004 to G1H020. Downstream of G1H020, the flow calculations were fairly stable. This is because the slope of the river is quite steep in the first reach and DUFLOW does not handle supercritical flow or near supercritical flow well.

- Negative water depths were calculated at some sections in the river, which resulted in instabilities.
- In a longitudinal graph the concentrations would be shown as very strong A toothed @ graphs. This is due to instability in the transport, which occurs when the Peclet number becomes too high (Pe>2).
- As initial conditions are user defined, a constant flow corresponding to the first date of simulation was taken as the upstream boundary value. The simulation was run until the longitudinal graph as well as the time series showed a stable calculation. The levels and the discharge calculated were then used as the initial value. Normally, the initial values should not create any problems as any error would cancel out after a few time steps, but as the calculations start at a very steep slope (average slope of 0.35% in reach 1, G1H004 to G1H020), negative water depths are calculated from the very beginning and the errors then accumulate.

All the above problems mentioned have been overcome by implementing very small space steps and by adding schematization points (points where a level and discharge can be defined as initial values at very small distances. These distances depend on the problem area; for the first reach the schematization points were spaced at about 100m, while further downstream, where the slope is milder, the space steps were increased to about 2 km. This lets the computation proceed, but still does not change the fact that the configuration is unstable and any change, like an additional discharge point or cross-section, will affect the stability. Also, because of the very small space steps, the time taken for the simulation increases and the output file for a year grows to about 12 Mb for the flow and about 50 Mb for the quality constituents.

CHAPTER SEVEN
FLOW MODEL SENSITIVITY, CALIBRATION AND VERIFICATION

7.1 INTRODUCTION

Important steps in any conventional modelling process are: *calibration, sensitivity analysis* and *verification*. As the water quality part of the model is dependent on the calibrated hydraulic component, and every error introduced in the flow module will influence the water quality calculations, it was decided to separate the calibration and verification of the hydraulic and water quality modules into two distinct processes reported in two Chapters. This chapter deals therefore with the calibration and verification of the hydraulic component of the model, while Chapter 8 follows with the calibration and verification of the water quality module. The first section of this chapter describes the objective functions used to analyse the results of the simulation. In the second section of this chapter the calibration of the flow simulation is discussed. Lastly, the results of the model verification are presented. The model was first verified in *space* then in *time.*

Note : For detailed explanation, results, tables and graphs the reader is referred to the main report provided in the enclosed CD.

7.2 OBJECTIVE FUNCTIONS

"*The term objective function is now widely used to describe any specific fitting criterion employed in the parameter estimation process"* (Görgens, 1983, pg 141). Therefore, the term **objective function** is used to describe the correspondence of simulated and observed values by several specific statistical procedures (goodness-of-fit criteria). These statistical tests are used to quantify the agreement between predictions and observations. The objective functions used in this study are:

- % error in mean
- % error in volume or load
- % error in std deviation
- Coefficient of determination [(correlation coefficient)2]
- Coefficient of efficiency

7.3 MODEL CALIBRATION AND SENSITIVITY PROCEDURE

The process of adjusting parameters by running the model at different parameter values until a satisfactory result is obtained, is called *calibration* (Grijsen, 1986). A close correspondence between observed data and simulated values is required. The *sensitivity* of parameters means the relative significance of each parameter in the performance of the whole model (Görgens, 1983; pg. 194). The calibration procedure consisted of the following steps:

- Determination of reliable calibration period
- Determining accuracy of boundary conditions
- Introducing flows of ungauged tributaries
- Calibrating the flow model by adjusting the resistance in the model, which is portrayed by the Manning=s roughness coefficient.

7.4 CALIBRATION PERIOD

The calibration period October 1993 to October 1994 was chosen, as this was the optimal period in terms of availability of water quality data and completeness of flow data.

7.5 BOUNDARY CONDITIONS AND INITIAL CONDITIONS

The accuracy of the inflow hydrograph and the downstream rating curve is important when considering calibration, especially for the numerical accuracy of the model. Accuracy ratings of the gauging stations were obtained from a re-rating survey (DWAF(a), 1994).

7.6 ADDITION OF UNGAUGED SUB-CATCHMENT FLOWS

The lack of flow data for certain tributaries causes difficulties in the comparison between measured flows and simulated values. The winter flow is underestimated due to ungauged inflow, which then has an impact on the simulated water quality loads. The ungauged tributary runoff therefore had to be estimated. In the absence of rainfall-runoff catchment model, a pragmatic adjustment, based on hydrological response pattern was undertaken.

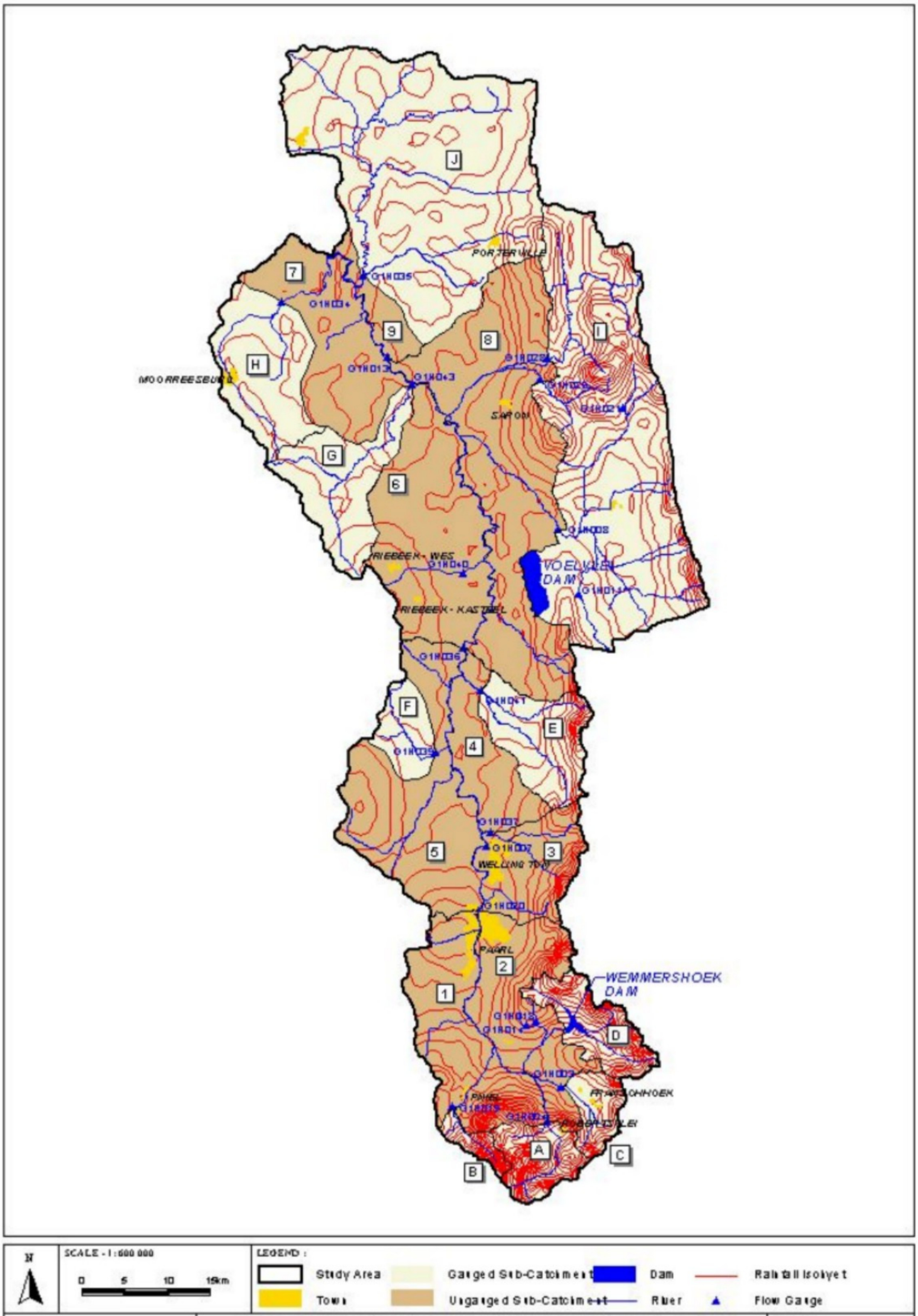
The Berg River catchment was subdivided into sub-catchments according to the MAP and also west and east, as the tributaries are perennial on the eastern side and semi-perennial on the western side. A further consideration was that runoff from the Malmesbury shales areas is much higher in TDS than runoff from Table Mountain sandstone areas. The ungauged areas in the Berg River catchment were marked out on topographical maps and the area sizes were determined. The ungauged hydrographs for the river were then estimated by multiplying the nearest or most suitable gauged daily hydrograph by the ratio of the ungauged runoff area to the gauged area. Additionally, a MAP-MAR (mean annual precipitation-mean annual runoff) weighting from the WR90 study (Midgley *et. al*, 1994) was applied. Tables 7.1 and 7.2 summarize all relevant information used in these estimates. The locations of the corresponding areas are illustrated in Figure 7.1.

Table 7.1 Description of Gauged Tributaries

Catchment Number (Figure 7.1)	Flow Gauge	River	Description	Catchment Area	MAP
				km^2	mm
A	G1H004	Berg	Driefontein	72	2600
B	G1H019	Banhoek	Bosmanshoek	22	1804
C	G1H003	Franschhoek	La Provence	46	1005
D	G1R002	Wemmers	Wemmershoek	88	1302
E	G1H041	Kompagnjies	De Eikeboomen	122	707
F	G1H039	Doring	Grensplaas	42	433
G	G1H043	Sandspruit	Vrisgewaagd	150	437
H	G1H034	Holle	Moorreesburgspruit	160	410
I	G1H008	Klein Berg	Mountain View	615	624
J	G1H035	Matjies	Matjiesfontein	671	410

Table 7.2 Areas and Correction Factors of Ungauged Tributaries

Catchment Number (Figure 7.1)	Ungauged Area	Area	MAP	MAP/MAR Factor (WR90)	Ungauged Area/ Gauged Area	Flow	Comments
		km^2	mm			m^3/s	
1	west area upstream of G1H020	222	978	0.56	222 / 22	5.65*G1H019	
2	east area upstream of G1H020	188.5	900	0.58	188.5 / 88	1.2*G1R002	
3	G1H037	130	939	1.8	130 / 122	1.9*G1H041	No data available from 1993 onwards
4	area at G1H041	164	574	0.64	164 / 122	0.86*G1H041	
5	area surrounding G1H039	225	574	0.5	225 / 42	2.7*G1H039	
6	G1H040 and surrounding area	260	547	2.5	260 / 150	4.3*G1H043	No data available for G1H040
7 and 9	G1H034 and surrounding area	170	400	0.63	170 / 160	0.64*G1H034	
8	G1H008 surrounding area	400	450	0.18	400 / 615	0.12*G1H008	



ASSESSMENT OF A HYDRODYNAMIC WATER QUALITY MODEL, DUFLOW, FOR A WINTER RAINFALL RIVER

DATE : JULY 2000

Isohyetal Map Showing Gauged and Ungauged Sub-Catchments in the Berg River Region

FIGURE No : 7.1

Discussion:
The sub-catchment of G1H039 is used as gauged sub-catchment although it has an accuracy rating of 0; the usage of this flow record is still necessary as there is no other gauged sub-catchment on the western side of the Berg River downstream of G1H020 and thus had to be used as an estimate of the runoff from the western tributaries into the main stem of the river. Prior to the addition of the ungauged sub-catchments, a mass balance of all the incoming flow, gauged and ungauged, was completed. Flow volume which is still lacking between the measured and the flow added in the mass balance, could possibly be due to higher ungauged runoff than estimated or inaccuracy in the high flow measurements at the various gauging stations. Most of the ungauged flow occurs in the reach between G1H036 and G1H013. G1H020 and G1H036 are slightly overestimated after addition of the ungauged inflow.

7.7 SENSITIVITY OF FLOW RESISTANCE

The hydrodynamic model was calibrated against the observed daily flow data for G1H020, G1H036, G1H013 and G1R003. Calibration was achieved by adapting the Manning's roughness coefficient until a satisfactory fit was achieved between the observed daily flow values and the model results. The percentage changes are however very low (mostly below 1%), which indicates that the flow simulation is influenced minimally by the resistance. For the final calibration a Manning's value of 0.06 was obtained by a trial and error approach.

7.8 RESULTS OF FLOW MODEL CALIBRATION

Summer Flow:
(Refer to Table 7.3)
It is evident from the large positive error in the low flow period (summer), that more abstractions take place than those registered/permitted (i.e. recognized by our configuration). The hydrograph of G1R003 shows well-defined short-lived increases in the simulated low flow. These are due to the irrigation releases made from Voëlvlei Dam into the Berg River. For G1H020 and G1H036 the low flow pattern does not follow the measured data as consistently as for G1H013 and the correlation coefficient is very low. For all gauging stations, March, April, October and November are clearly over-simulated.

Table 7.3 : Results of model calibration

	G1H020	**G1H036**	**G1H013**	**G1R003**
		% diff in mean		
Total	**5.6**	**17.6**	**-8**	**10**
Summer	**13.4**	**54**	**26**	**88**
Winter	**4.5**	**14.8**	**-10**	**6**
		R^2		
Total	**0.98**	**0.98**	**0.92**	**0.94**
Summer	**0.83**	**0.71**	**0.73**	**0.64**
Winter	**0.97**	**0.98**	**0.92**	**0.93**
		MCE		
Total	**0.95**	**0.95**	**0.81**	**0.87**
Summer	**0.41**	**0.54**	**0.47**	**0.22**
Winter	**0.94**	**0.96**	**0.82**	**0.88**
		% diff in std deviation		
Total	**-2.4**	**9.6**	**-29**	**-13.7**
Summer	**18.8**	**-5.7**	**-12**	**1.47**
Winter	**-3.5**	**9.5**	**-30**	**-15**

Winter Flow:
(Refer to Table 7.3)

The simulated winter (high) flow follows the pattern of the measured winter flow hydrograph for all stations, although the peaks are underestimated at G1H013 and G1R003. G1H013 and G1R003 have an additional simulated peak in July, which is the result of the inflowing hydrograph of G1H008, and the additional runoff from the ungauged sub-catchment 8 that has been corrected with the flows of G1H008. The correctness of this adjustment may be suspect. The under-simulated flood peaks could be the result of errors in the correction of ungauged sub-catchments or errors in the measurement of the water level at tributary gauging stations, when flooded. The correlation coefficient at all stations for the high flow is acceptable. The volume and the mean are over-simulated although the actual peaks are under-simulated. This is due to the short period when the actual peak occurs.

7.9 MODEL VERIFICATION

The term *verification* will be used to describe the process of ensuring that the configuration of the model applied to the specific river for a particular set of calibration data can be applied to another period of data; this is to ensure that the errors in the simulated values are acceptable. The configured and calibrated model was verified in space and time. Verification in time shows whether the calibration errors are consistent for a totally independent set of data in time; and whether the correction factors of the addition of ungauged runoff are reasonable. Verification in space indicates the degree of accumulation of errors along the four river reaches and whether the correction of the ungauged runoff is reasonable.

7.9.1 Verification in Space

To verify the model in space, two model runs were completed. Firstly, the recorded flow at G1H020 was used as inflow hydrograph at G1H020 in the model to verify the results obtained in the reach of G1H020 to G1H036, and secondly, the flow recorded at G1H036 was used as inflow hydrograph at G1H036 to verify the model results from G1H036 to G1R003.

It was clear after a verification run, using the G1H020 hydrograph as input at G1H020, that most of the errors downstream of this gauging stations occurred due to addition of ungauged inflow in this reach. Table 7.4 summarizes the results of the verification run, the measured data and the original model run. The correlation coefficient of the verification run is higher than the configured model and this could be due to less error introduced in the run. The systematic error (R^2 - MCE) is much less than in the calibration run. Most of the errors that take place at G1R003 could be the result of incorrect estimates of flow from the ungauged catchments between G1H020 and G1H036. This is portrayed by the improvements in the errors when using G1H036 as inflow hydrograph. Ungauged abstractions may also occur in this reach.

7.9.2 Verification in time

Verification in time was completed by using a totally independent set of flow data and comparing the errors with the errors resulting from the configuration model. The year 1994/1995 was chosen for verification in time, as it had relatively complete flow data sets. Unfortunately, for the station G1H036 the flow measurements are also incomplete from the 3rd of July onwards. It therefore should be noted that the statistical comparison for the high flows have only been included up to that date and are thus not a complete reflection of the correspondence with the measured data. This year experienced much higher flows and also more high peaks (three larger peaks before July) than the calibration year's data (one defined peak).

It can be seen that the simulation errors for the verification data are less than for the calibration data. This indicates that the correction factors applied to the ungauged runoff are reasonable. G1R003 is again over-simulated by a high percentage for the summer period. This would be the result of ungauged abstractions, given that the contribution of flow from the corrected ungauged areas 7 and 9 is minimal in this period, as the tributary G1H034 is semi-perennial. The simulated low flow displays a better degree of correspondence than the calibration run, and all coefficients of determinations are above 0.8. Again, it can be concluded that the correction factors applied to the ungauged runoff and the information obtained about the abstractions prove to be satisfactory for the low flow, except for the reach G1H013 to G1R003.

7.10 DISCUSSION OF FINAL MODEL RESULTS

The objective in this chapter was to develop a flow model capable of predicting the hydrograph at any point in the main river channel. It can be concluded from the statistics mentioned for the various calibration and verification runs, that the model has the ability to simulate, with reasonable accuracy, the hydrograph at any downstream section in the river. The accuracy is mainly dependent on the accuracy of the inflowing measured hydrographs and also the estimated runoff of ungauged sub-catchments. Other factors such as the accuracy of the boundary conditions also contribute to errors. The model reliably simulates the mass balance in the system, but the errors resulting for underestimation of the high flow peaks and overestimation of the low flow, are mainly the result of inaccurate estimation of the ungauged flow. This can be seen from the verification simulation in space. To be able to simulate a flow hydrograph reliably, the upstream input flows and all the information about abstractions and return flows need to be known. Unfortunately, for most situations, this information is either inaccurate, incomplete or non-existent.

The verification in time proved that the correction factors applied to the low flow are satisfactory. The results of the verification in time proved to be better than the calibration data results. The correction factors for the high flow are however not always acceptable, as the peak flows which are higher than the configured peaks are about 125 m^3/s less. Either the actual peak flows measured at the gauging stations are unacceptable or additional correction may need to be applied to the ungauged runoff.

Table 7.4 Results of Verification Run using G1H020 as Inflow Hydrograph

		G1H036	G1H013	G1R003
		% diff in mean		
original model run	Summer	54	26	88
	Winter	14.8	-10	6
verification run	Summer	37	16	68
	Winter	7	-15	0.5
		R^2		
original model run	Summer	0.71	0.73	0.64
	Winter	0.98	0.92	0.93
verification run	Summer	0.96	0.85	0.77
	Winter	0.97	0.91	0.93
		MCE		
original model run	Summer	0.54	0.7	0.22
	Winter	0.96	0.82	0.88
verification run	Summer	0.64	0.65	0.08
	Winter	0.93	0.79	0.86

Table 7.5 Results of Verification Run using G1H036 as Inflow Hydrograph

		G1H013	**G1R003**
% diff in mean			
original model run	Summer	26	88
	Winter	-10	6
verification run	Summer	-7	27
	Winter	-20.5	-5
R^2			
original model run	Summer	0.73	0.64
	Winter	0.92	0.93
verification run	Summer	0.94	0.85
	Winter	0.94	0.95
MCE			
original model run	Summer	0.77	0.22
	Winter	0.82	0.88
verification run	Summer	0.87	0.71
	Winter	0.77	0.87

Table 7.6: Verification in time (1994/1995)

	G1H020	**G1H036**	**G1H013**	**G1R003**
% diff in mean				
Total	-27	12	-30	-8
Summer	5.8	31.3	15.1	72
Winter	-34.6	-0.4	-36	-16.7
R^2				
Total	0.91	0.86	0.82	0.88
Summer	0.8	0.82	0.86	0.81
Winter	0.9	0.86	0.8	0.87
MCE				
Total	0.63	0.72	0.5	0.76
Summer	0.91	0.78	0.82	0.6
Winter	0.69	0.79	0.57	0.8
% diff in std deviation				
Total	-51	0.3	-55	-28.2
Summer	-7.5	-11	14	9.8
Winter	-52	3.8	-58	-29

CHAPTER EIGHT
WATER QUALITY MODEL SENSITIVITY, CALIBRATION AND VERIFICATION

8.1 INTRODUCTION

The focus of this chapter is on the sensitivity of the water quality parameters used in the various water quality processes in DUFLOW and the calibration and verification of the water quality simulation. The reliability of the water quality parameters is largely dependent on the reliability of the flow simulation. The sensitivity analysis of the water quality parameters determines the adjustments of these parameters in order to obtain a satisfactory fit that compares reasonably well with the observed data.

Note : For detailed explanation, results, tables and graphs the reader is referred to the master report.

8.2 MODEL CALIBRATION AND SENSITIVITY PROCEDURE

A similar calibration procedure to that of the flow calibration (refer to section 7.3) was followed; with the following special considerations :

- The period Oct 1993 to Oct 1994 was also a reliable calibration period with respect to water quality data
- Setting up representative water quality boundary conditions
- Introducing water quality of ungauged tributaries
- Calibrating water quality by adjusting the parameters
- Introducing point sources .

8.3 ESTIMATION OF UNGAUGED WATER QUALITY SUB-CATCHMENT LOADS

The water quality load contributions from areas that were ungauged had to be estimated. The same ungauged areas are applied for estimating the ungauged water quality loads as was used for ungauged flows (Figure 7.1).

Table 8.1: Correction of Ungauged Concentration

Ungauged Catchment Runoff of Area Number:	Infilled with water quality grab samples of station:	Comment
1 and 2	G1H020	The water quality samples of the upstream gauged Table Mountain Sandstone areas (A,B,C,D) are of better quality, than from the areas 1 and 2. It has therefore been assumed that the water quality concentration of areas 1+ 2 would follow a similar pattern to the data that has been sampled at G1H020.
3	G1H041 (E)	It has been assumed that the water quality from area 3 would be similar to the water quality at G1H041, as both sub-catchments drain Table Mountain Sandstone soil, which is of better quality than the water quality of the runoff from the Malmesbury Shales.
4 and 5	G1H039 (F)	As sub-catchments 4 and 5 experience similar rainfall-runoff patterns to sub-catchment F and also drain Malmesbury Shales, it has been assumed that the corrected runoff from 4 and 5 could be linked to the water quality samples of G1H039.
6	G1H043 (G)	Sub-catchment 6 has been linked with gauged sub-catchment G, because of similar rainfall-runoff and soils.
8	G1H008 (I)	It has been assumed that the water quality from area 8 will be similar to the water quality at G1H008, as both sub-catchments drain primarily Table Mountain sandstone soil. The rainfall experienced in sub-catchment 8 is however less than sub-catchment H, and portions of the flow is diverted to Voëlvlei Dam.
7 and 9	G1H034 (J)	The water quality sampled at G1H034 has been assumed to have similar characteristics to the water quality that can be expected at sub-catchments 7 and 9, given similarity in soils and geology.

It was assumed that the ungauged runoff has similar water quality characteristics as the neighbouring gauged tributaries. As a moving regression is suitable to describe the water quality-flow relationship, the same *'infilling'* method, as has been described in Section 6.3.1, has been used to approximate the daily water quality of ungauged runoff. The ungauged runoff that has been calculated has been matched with the water quality grab samples of a gauged tributary that is surmised to have similar water quality response characteristics. A time series was generated via the moving regression infilling method. Table 8.1 shows the gauged and ungauged areas that have been linked, and has to be read in conjunction with Table 7.1 and Figure 7.1.

Most of the ungauged areas experience higher runoff than the gauged areas, primarily due to area size, and this is reflected in the negative "error" in the TDS infilling. Areas 1 and 2 receive less runoff than G1H020 and therefore a positive error in mean concentration is calculated. Interestingly, the infilled phosphate values show negative errors in mean compared with the original grab samples.

Table 8.2: Statistics of Ungauged TDS Values

Sub-catchment No	No of Samples	Mean Conc (infilled) (mg/l)	Mean Conc (mg/l)	% error in mean	Std. Dev (infilled)	Std. Dev (grab samples)	R^2
1 and 2	319	60.4	60.2	3	9.7	12.1	0.97
3	234	159.7	174	-8	51	88	0.78
4 and 5	130	2636	2712	-3	710	897	0.81
6	110	4693	4718	-0.5	1293	1356	0.77
8	300	113	117	-4	29.4	40.4	0.72
7 and 9	315	6304	6253	8	2214	2297	0.91

Table 8.3: Statistics of Ungauged PO_4 Values

Sub-catchment No	No of Samples	Mean Conc (infilled) (mg/l)	Mean Conc (mg/l)	% error in mean	Std. Dev (infilled)	Std. Dev (grab samples)	R2
1 and 2	326	0.024	0.028	-14	0.013	0.05	0.75
3	231	0.02	0.024	-15	0.01	0.02	0.57
4 and 5	128	0.29	0.33	-10	0.15	0.21	0.71
6	110	0.03	0.036	-17	0.01	0.02	0.6
8	294	0.016	0.017	-7	0.01	0.01	0.75
7 and 9	317	0.15	0.176	-17	0.15	0.18	0.74

8.4 SENSITIVITY OF WATER QUALITY PARAMETERS

8.4.1 Dispersion

The calibration of the transport dispersion was attempted by adjusting the dispersion for the conservative constituent, TDS. TDS is only dependant on the dispersion and therefore is a good indicator of the influence of the dispersion parameter. As can be seen from the Figure 8.1, dispersion has a minimal effect on the simulated results.

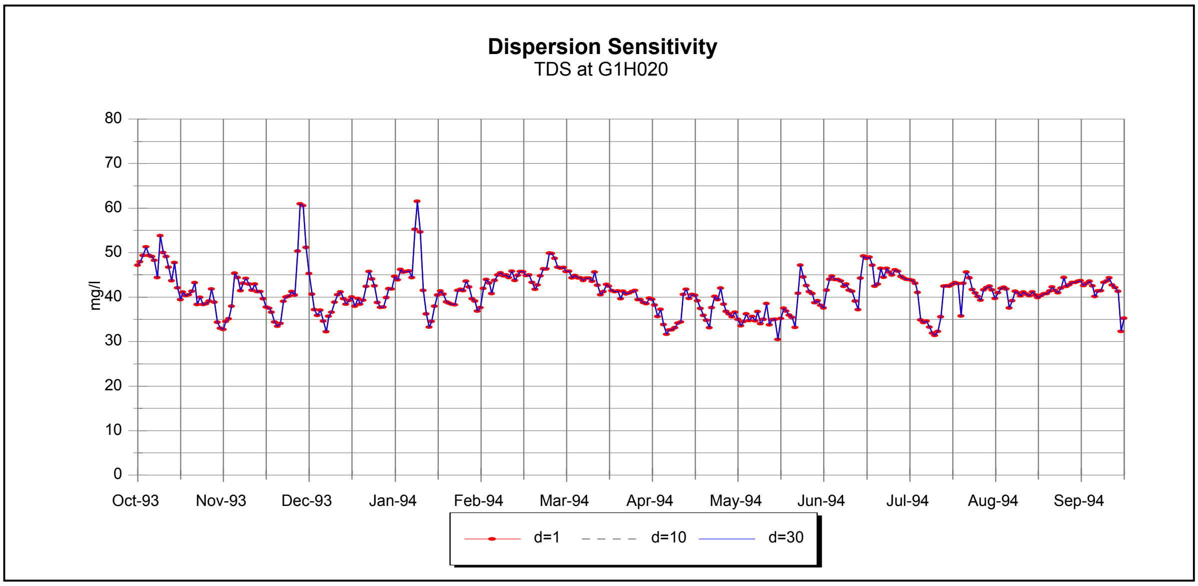


Figure 8.1: Dispersion Sensitivity

8.4.2 Phosphorous

Sensitivity analyses have been performed for the parameters that affect the phosphorous concentration, which are Θ_{min} and k_{min}. The sensitivity runs show that these parameters have insignificant influence on the concentration, and therefore the phosphorous concentration is only dependant on the transport calculations.

8.4.3 Temperature

The parameters that can be changed for calibration purposes occur in atmospheric longwave radiation and water longwave back radiation.

Parameters:
The parameters that have an influence on the atmospheric longwave radiation are A, a constant, and R_L, the cloud cover. The Stefan Boltzmann constant cannot be varied. The term describing the back radiation of the water surface contains the parameter **,** (emissivity of a body), as it is represented by Stefan Boltzmann's law.

Figures 8.6 to 8.9 summarize the results for the summer temperatures of the different sensitivity runs completed for the parameters A and R_L. The summer temperatures are more sensitive to changes in the parameters (due to the low flow water depth, refer to equation 5.39). It was decided after the sensitivity runs that a R_L value of 0.03 and an A value of 0.55 seemed to depict an acceptable maximum summer temperature when compared with the maximum summer temperatures of the observed data. The average values calculated are, however, all lower than the measured data when using these parameters. The reasonable overall averages and visual comparisons of the trends however, allowed acceptance of these parameters.

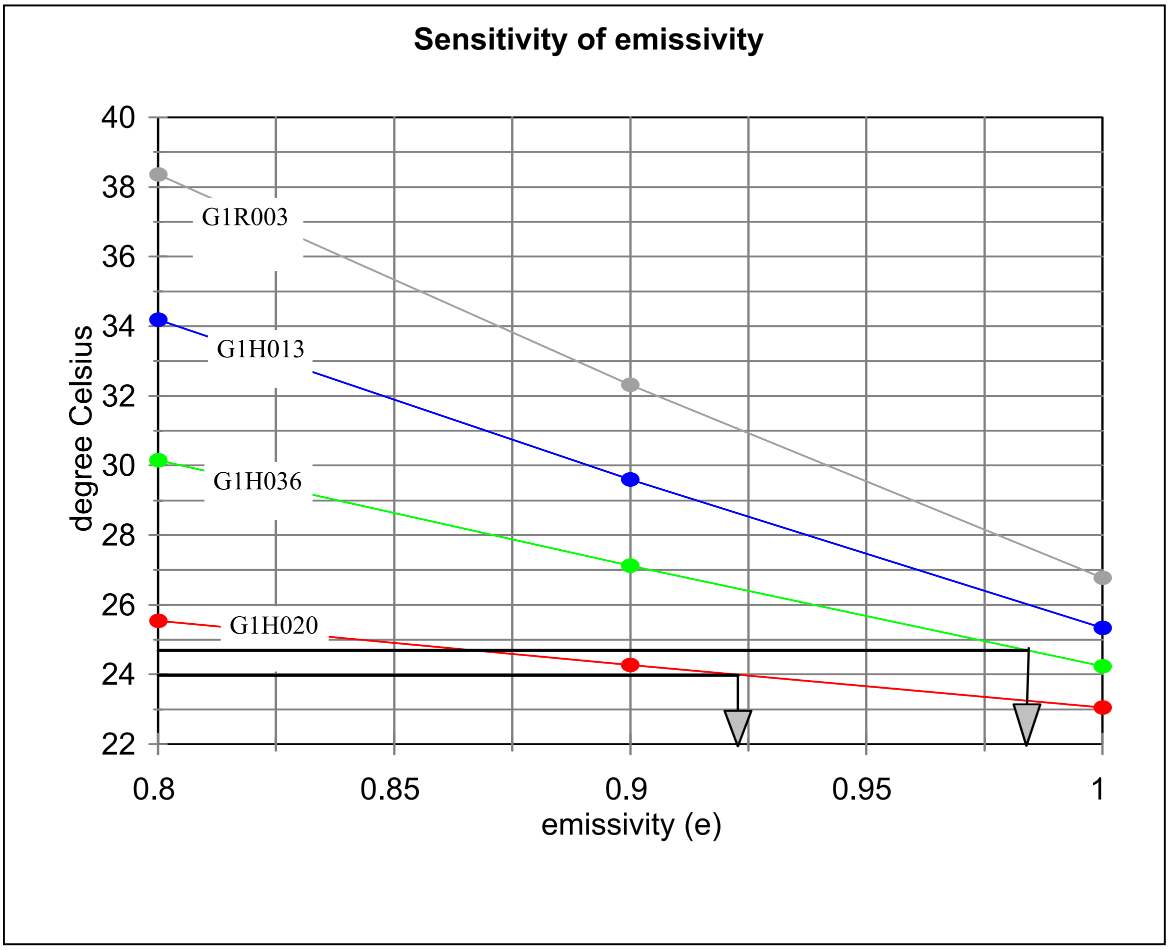


Figure 8.2: Sensitivity of temperature parameter ,

Figure 8.2 shows the sensitivity of the emissivity parameter , on temperature. The figure shows the summer temperature averages that were calculated from three runs of emissivity factors of 0.8, 0.9 and 1 for all the stations in the main stem river. For G1H020 an emissivity of 0.92 would simulate an average of 24EC as was measured (refer also to Table 1.4.3 in Appendix 1.4 in the main report on the enclosed CD). An emissivity factor of 0.98 would simulate an average of 24.6EC for G1H036, while for G1H013 and G1R003 an emissivity factor of 1 would simulate their average temperature measured. The average emissivity of all four , factors simulated is 0.975; this value was used for the Berg River model simulation runs. This value is close to the default value of 0.97.

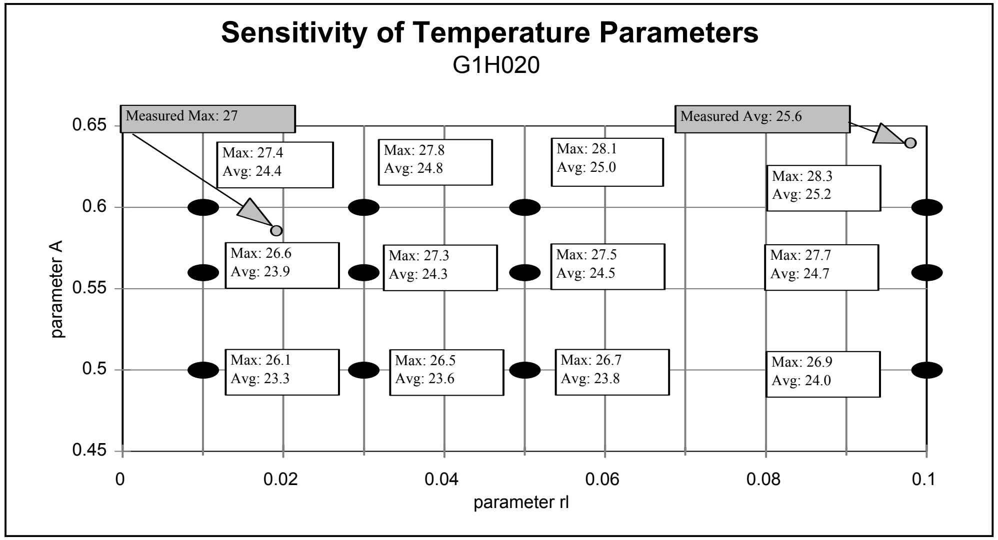


Figure 8.3: Sensitivity of temperature parameters at G1H020

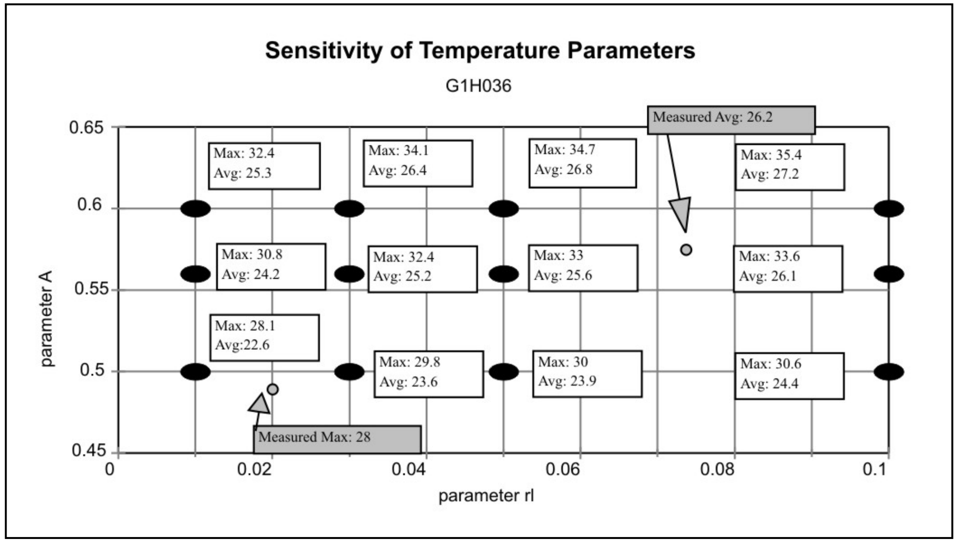


Figure 8.4: Sensitivity of temperature parameters at G1H036

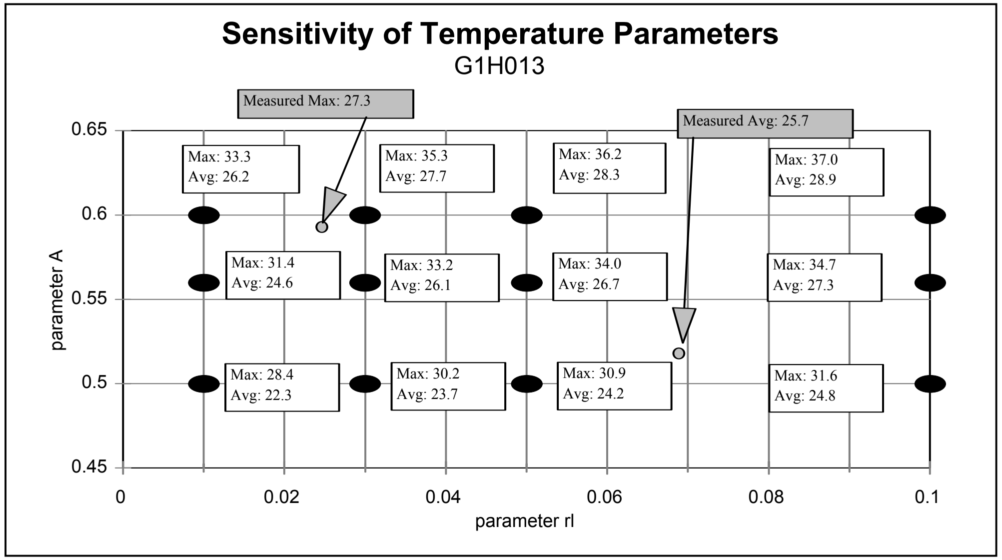


Figure 8.5: Sensitivity of temperature parameters at G1H013

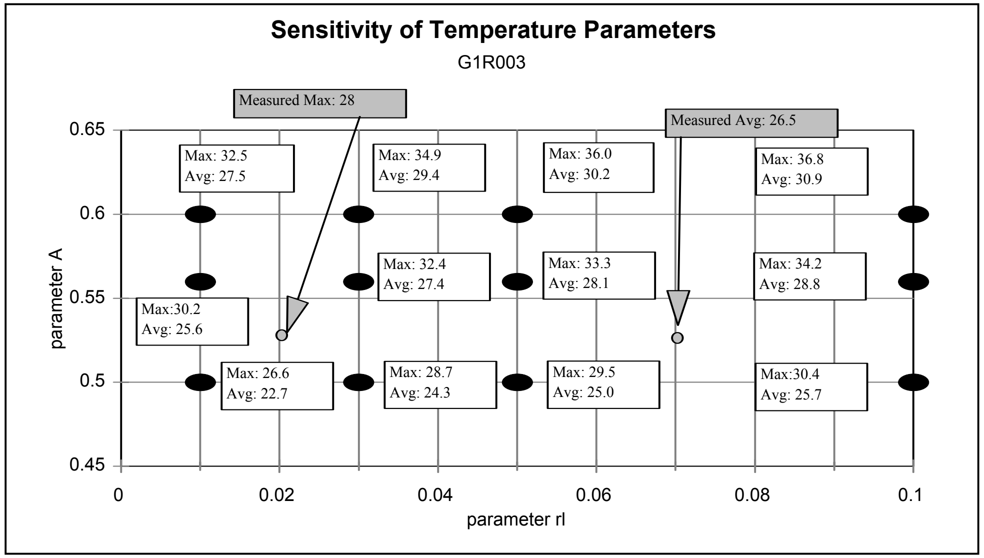


Figure 8.6: Sensitivity of temperature parameters at G1R003

Depth:
All the terms are dependent on the depth of the water. It is evident from the equations that the influence of the water depth on the temperature is much stronger than the influence of the various calibration parameters. Figure 8.7 illustrates an example of how the temperature term is influenced by the depth of the water. Below a depth of 0.5m the temperature term increases exponentially. This will occur in the summer months when there is low water depth and the solar radiation and air temperature are at their maximum and contribute therefore additional heat.

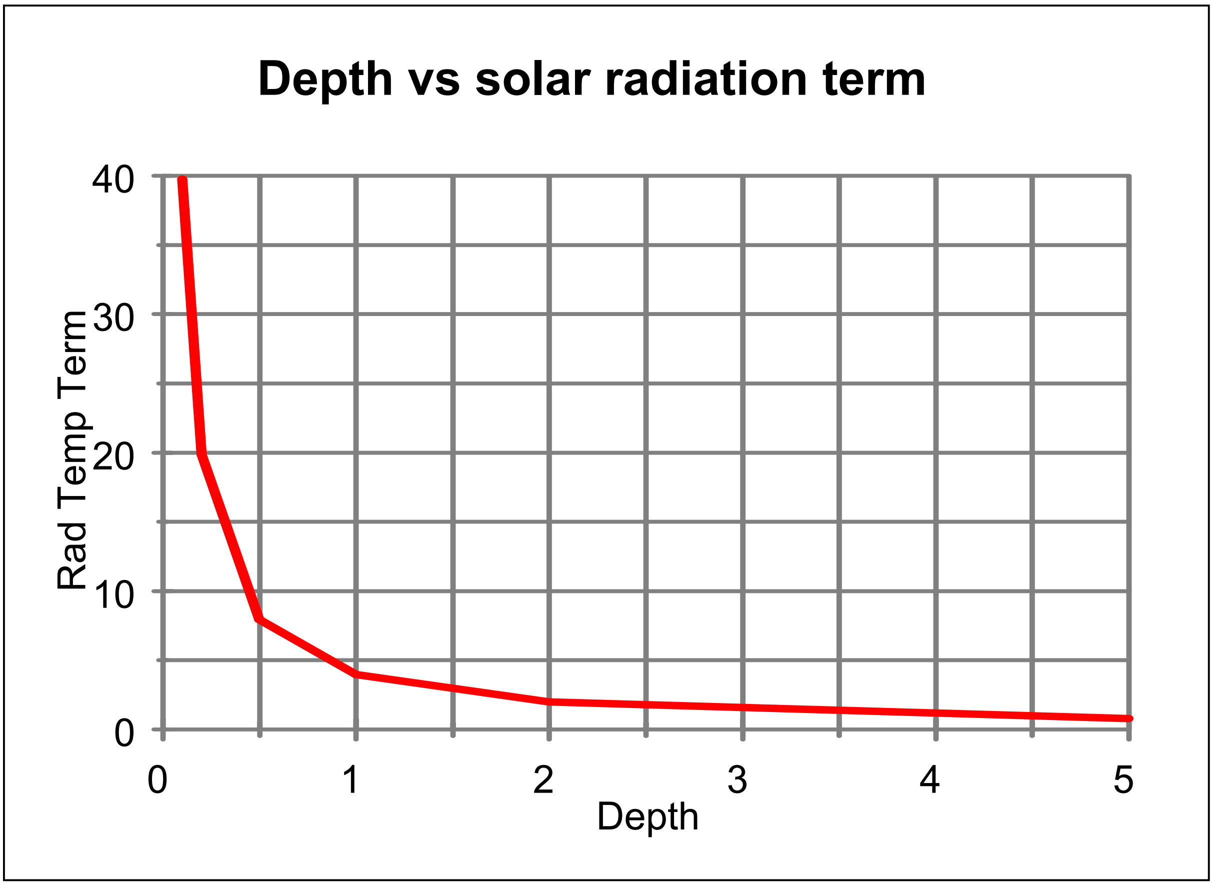


Figure 8.7: Depth influence on solar radiation

8.4.4 Oxygen

As only the water quality variables TDS, PO_4 and Temperature are modelled additional to the oxygen, the effect of the essential influences on the oxygen concentration is not modelled. These are the influences of plant growth and therefore photosynthetic oxygen production; and the oxidation of carbonaceous and nitrogenous waste material, respiration of plants and oxygen demand of the sediments. In this model only two variables influence the modelling of oxygen: k_{re}' and $\mathbf{2}_{re}$ and the effect of temperature on the re-aeration. The effect of temperature is seen as an external variable and although the sensitivity of the oxygen to the temperature can be assessed, it cannot be altered in the calibration process. As no data is available for the oxygen concentration, estimating the correct value for the parameters is therefore difficult, the default values have been accepted for the Berg River.

8.5 SENSITIVITY OF GRAB SAMPLES COMPARED TO INFILLED SAMPLES

Referring back to Section 6.3.1, the water quality data was ‘infilled’ by means of a moving regression. In order to investigate the sensitivity of incorporating the actual grab samples back into the infilled time series, a sensitivity run was completed with grab samples included in the infilled time series and the results were compared to the results of the simulation runs, using only ‘infilled’ concentration values. It can be seen from Figures 8.8 that incorporating grab samples in the infilled series does not show significant difference when compared to the runs that were completed with only ‘infilled’ values.

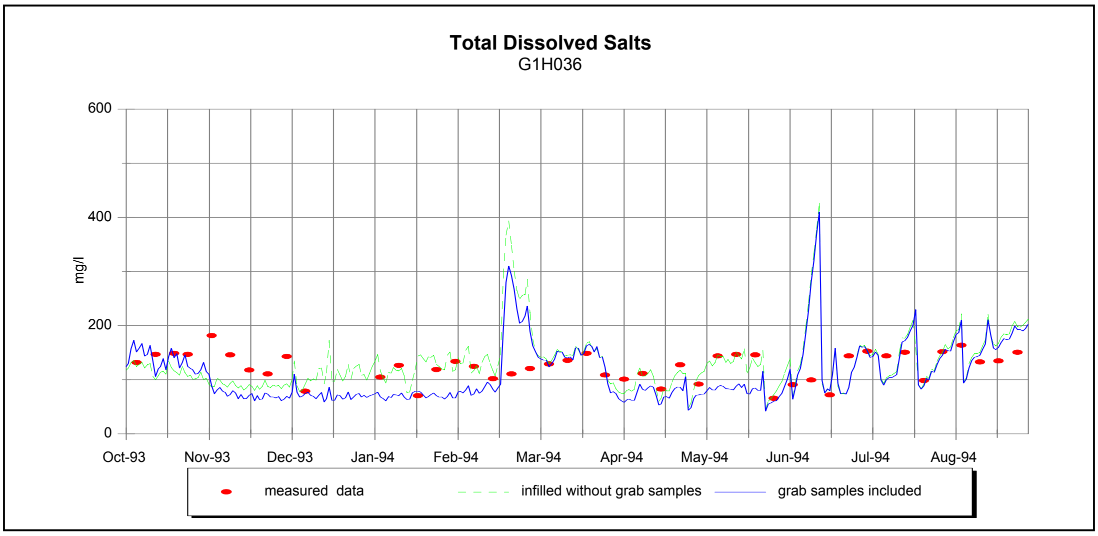


Figure 8.8: Comparison of TDS simulation at G1H036

8.6 POINT SOURCES

The Water Quality Situation Analysis (DWAF (g), 1993) identifies the major point sources in the Berg River catchment. Much of the industrial activity in the Berg River catchment is associated with the agricultural sector, and therefore many of the effluent producers are also associated with this sector. For the DUFLOW model only point sources that have been issued with a permit have been considered. This data was available from the Polmon database from DWAF as monthly measurements. Unfortunately, effluent data was only available for the major sewage treatment plants and only a few point sources that irrigate their effluent. There are, however, a number of piggeries and wineries in the Berg River catchment that also produce effluents, which are high in oxygen demand and organic loading. Only 12 sources are authorised to discharge into the Berg River or nearby tributaries. Many of the point sources do not have quality requirements in their permits as they all irrigate their effluent. The majority of the point sources identified have not been issued with permits. Lack of data makes it difficult to evaluate the volume of effluent that gets irrigated. The point sources that do have permits, and measured water quality and flow volume, have been included in the model. It has been assumed for the point sources (where flow and quality data is available) which do not discharge directly into the Berg River and irrigate their effluent or discharge far up in a tributary that about 25 % of the effluent flow reaches the Berg River. Only one authorized point source, Paarl sewage treatment works, discharges effluent directly into the Berg River.

It is clear that for a water quality simulation model, if ever used for management and control purposes, a more extensive database is needed to evaluate the impact of point sources and non-point sources more exactly.

8.7 RESULTS OF WATER QUALITY MODEL CALIBRATION

8.7.1 TDS

The simulated values were compared with the measured data and *'infilled values'* for low flows (October to March) and high flows (April to September) and overall. The contribution to the salt load in the Berg River from the point sources with a permit seems to be insignificant when compared to the total salt load contributed by the tributaries. Paarl sewage treatment works adds a yearly load of 145.2 tons, while the total load measured at G1H020 already consists of 15798 tons of TDS in the year. Of concern, however, is all the non-point sources and point sources that are not controlled, which have an additional impact on the overall TDS load.

Irrigation return flows, which are high in salts and nutrients, have not been included in the model, due to insufficient knowledge of the volumes and concentrations. The irrigation return flows have a significant impact on the TDS and phosphate concentrations, particular in the summer months, and the absence of these concentrations should be borne in mind when analysing the results.

- ***TDS Concentration results:***

(Table 1.2, Figures 1.9-1.12 in Appendix 1)
The coefficient of determination is low for the concentration analysis (Table 1.2), between 0.3 and 0.67 for the high flow period and only between 0.03 and 0.47 for the low flows.

High TDS Concentration is discharged into the river in the reach between G1H020 and G1H036. This can be seen from Figures 1.9 and 1.10, and also from Table 8.11, where the % error increases from -31% to 14%. This is the result of additional TDS concentration from sub-catchments 4 and 5, that have been infilled by using grab samples of G1H039. Figure 8.14 shows the TDS concentration of G1H039 and also of G1H041, which also discharges into the river in this reach (refer to Figure 7.1). Sub-catchments 4 and 5 follow the same pattern as the TDS concentration of G1H039. The high concentration peaks shown in February and also in the winter months at G1H036 and the stations downstream are also a result of the high TDS discharging into the river from sub-catchments 4 and 5. Unfortunately, the accuracy of the gauging station G1H039 was rated 0 (Table 7.1), but it was the only estimate of gauged TDS loads (refer to section 7.6 and 8.5). The actual effect of incoming TDS concentration from G1H039 is little, due to low flows. As sub-catchments 4 and 5 have however a higher runoff, the loads discharging into the river do have an impact on the concentration. It can therefore be concluded that the TDS concentration of sub-catchments 4 and 5 is considerably less than was assumed. Low TDS concentration is discharged into the river during the summer months. The concentration shows high under-simulation at all stations (Figures 1.9 to 1.12 in Appendix 1.4), especially at G1R003, while the phosphate simulation shows hardly any under-simulation during the summer months (Figures 1.21-1.24 in Appendix 1). The under-simulated TDS concentration could therefore be due to a missing TDS point source.

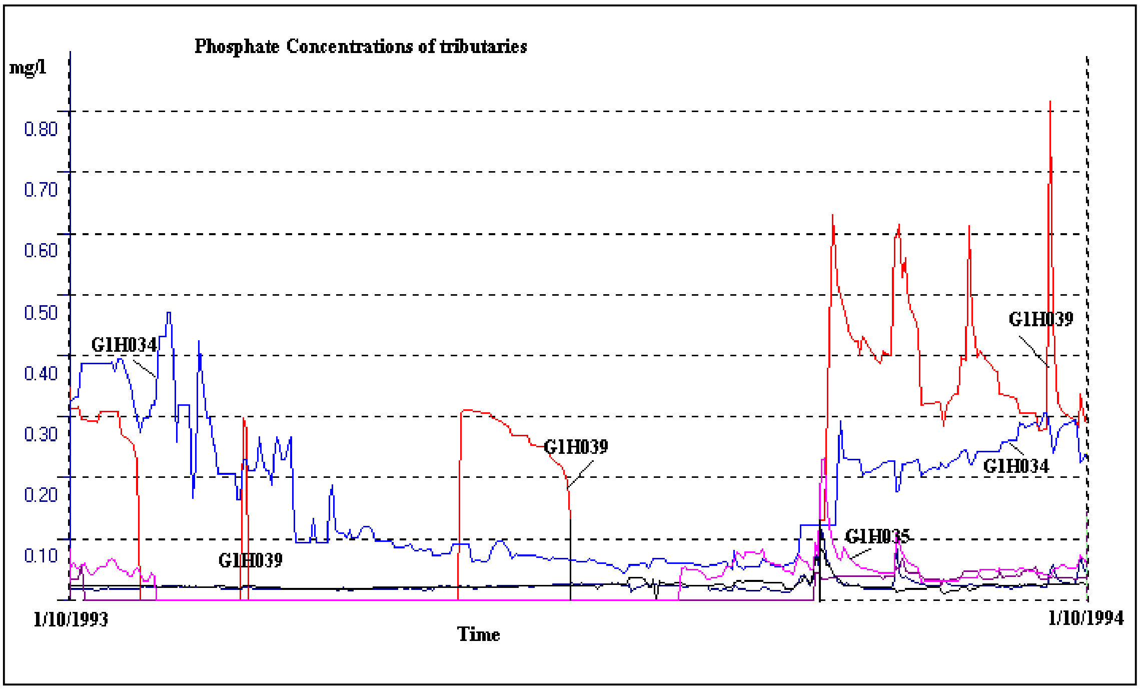


Figure 8.9: TDS Concentration of G1H039 and G1H041

- ***TDS Loads Results:***

Low Flow :
(Table 1.1, Figures 1.1-1.4 in Appendix 1)
The coefficient of determination for the loads is higher than for the concentration (Table 8.8), this is because the load is dependent on the flow simulated. For the low flow period the load follows the trend of the measured data less accurately than the high flow (refer to Figures 1.1 to 1.8 in Appendix 1). Referring to Table 7.6, it can be seen that the discharge in the low flow period is over-simulated by 54% at G1H036, and this explains the 68% error in the TDS loads at G1H036, as this could be the result of the flow over-simulated for the periods March and April. The other

stations also show similar errors in the load simulation when compared to the flow simulation (Tables 1.1 in Appendix 1.4 and Table 7.6). Interestingly, the TDS load shows however a smaller error in the loads for the low flow period than the flow simulated (88% error in the flow and only 35% error in the TDS load simulation), which could be the result of addition of ungauged TDS loads of the ungauged areas 7 and 9 (Figure 7.1). These areas contribute minimal runoff to the main stem, but significant TDS loads (as these areas drain the Malmesbury shales, which produce high salinity concentration). Referring to Figures 1.1 to 1.4 in Appendix 1, one can see that the short lived peaks introduced by releases from Voëlvlei Dam are clearly defined in the load simulation at G1H013 and G1R003.

High Flow:
(Table 1.1, Figures 1.5-1.8 in Appendix 1)
The overall TDS loads for the high flow months are over-simulated at all stations, except at G1H020. The TDS peak shows a difference of - 50000 g/s at station G1R003 (Figure 1.8),-30000 g/s at G1H013 (Figure 1.7) and a over-simulation of 25000 g/s at G1H036 (Figure 1.6). The error introduced therefore occurs mainly in the reach from G1H036 to G1H013, and could be the result of additional non-point salinity runoff.

8.7.2 Phosphate as PO_4

The phosphate modelling is influenced by advection only (the biological and chemical processes have been omitted due to lack of data on other dependent variables). This has to be borne in mind when analysing the results, as phosphate concentration is in reality not only influenced by advection, although it is often the most influential.

Irrigation return flows, which are high in salts and nutrients, have not been included in the model, due to insufficient knowledge of the volumes and concentrations. The irrigation return flows have a significant impact on the TDS and phosphate concentrations, particular in the summer months.

- ***PO_4 Concentration results:***

  (Table 1.4, Figures 1.21-1.24 in Appendix 1)
  The coefficient of determination is low for the concentration analysis (Table 1.4), between 0 and 0.68 for the high flow period and only between 0.15 and 0.57 for the low flows. Station G1H036 shows a 0% coefficient of determination and referring to Figure 1.20, it can clearly be seen that the concentration is greatly under-simulated between March and June, the error in the simulation decreases from -1% to -32% (Table 1.4) from G1H020 to G1H036. This under-simulation is not evident at the downstream stations (Figures 1.21 and1.22). The measured phosphate concentration has decreased from 0.04 mg/l to 0.024 mg/l (low flow) and from 0.08 mg/l to 0.05 mg/l (high flow) from station G1H020 to G1H036. The errors in concentration mean are also the highest for station G1H036 (-32% at low flow and -55% for high flow). From the verification runs it can also be seen that although the values are under-simulated at G1H036, the measured phosphate values decrease at the downstream stations and the % error between the measured and the simulated phosphate is less. This error could be due to a missing point source in the reach of G1H020 and G1H036, as the flow is not under-simulated during these months (refer to Figure 7.4); the TDS concentration is under-simulated in these months, but not to such a high degree as for the phosphate simulation.

  The simulated mean phosphate concentration does not differ between G1H013 and G1R003 for low and high flows. The measured phosphate mean concentration does however decrease from G1H013 to G1R003 for the high flows; this could be due to missing ungauged flows in this reach.

  One can see from Figures1.22 to1.24 that small phosphate concentration peaks are simulated in June and end September at all three stations: G1H036, G1H013 and G1R003. Figure 8.15 shows the phosphate concentrations of the gauged tributaries discharging into the Berg River main stem. As one can see from Figure 8.15, the small peaks simulated in the winter months are mainly a result of phosphate inflow from the sub-catchments 4 and 5 that have been estimated with grab samples of G1H039.

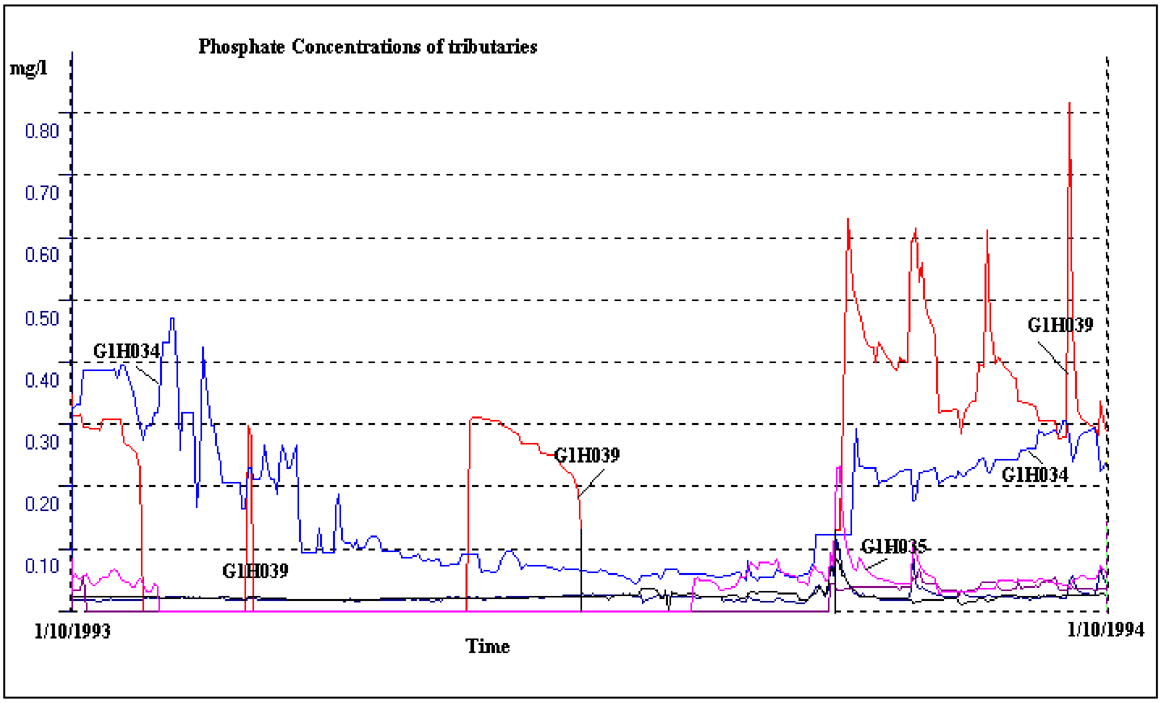


Figure 8.10: Phosphate Concentrations of Tributaries

- ***PO_4 Loads Results:***

Low Flow :
(Table 1.3, Figures 1.13-1.16 in Appendix 1)
The coefficient of determination for the loads is higher than for the concentration (Table 1.1 and 1.3), this is because the load is dependent on the flow simulated. For the low flow period the load follows the trend of the measured data less accurately than the high flow. As for the TDS loads, the phosphate loads are over-simulated in the months March/April, due to the flow over-simulated in these months. At all stations the phosphate loads are over-simulated, especially at G1R003 where the simulated values show a 103% over-simulation. This over-simulation is mainly due to 88% over-simulation of flow at G1R003 (Table 7.6). The other stations also show similar errors in the load simulation when compared to the flow simulation (Tables 1.4.3 and 7.6). Referring to the figures, one can see that the short lived peaks introduced by releases from Voëlvlei Dam are clearly defined in the load simulation at G1H013 and G1R003, this explains also the improvement of the coefficient of determination downstream of G1H036.

High Flow:
(Table 1.3, Figures1.17-1.20 in Appendix 1)
The phosphate peak in the summer was measured to be approximately 60 g/s at G1H013 and 40 g/s at G1R003. For all stations the phosphate peak is under-simulated. This could be the result of additional non-point runoff occurring during a flood. The high flow phosphate loads show high coefficient of determinations (0.95 to 0.98). At G1H020 the total load in the summer period is already under-simulated by 42%. The model adds phosphate loads from the tributaries and ungauged sub-catchments in the reach from G1H013 to G1R003, where in reality the phosphate mass has reduced from 48.2 tons to 25.6 tons.

8.7.3 Temperature

(Figures 1.25 to 1.28 and Table1.5 in Appendix 1)
It can be perceived from the results, that the temperature model predicts the winter months better than the summer months. This could be the result of the algorithm, as the temperature increases exponentially when the water depth decreases (equation 5.39 and Figure 8.10). The water depth is simulated very low (0.2-0.6m) in the summer months. The model follows the seasonal trend quite accurately (R^2 between 0.8 and 0.98). At station G1R003 the temperature is over-simulated for the

summer months and under-simulated for the winter months. The occasional outliers in the simulation are due to outliers in the radiation and evaporation rates (refer to Figures 6.6 and 6.7).

8.7.4 Oxygen

(Table 1.6, Figures 1.29-1.31)
The calibration of the oxygen model concentrated on the temperature simulation, as oxygen is dependent on the values of temperature in the river. Many factors affect the concentration of oxygen, such as plant photosynthesis and point sources. The error of the simulated data is also very dependent on the accuracy of the meteorological influences on the oxygen. There are outliers simulated for the May and June months, and this is due to occasional peaks from the radiation data and minor instabilities in the simulation calculation, due to higher velocities in the winter months.

8.8 WATER QUALITY MODEL VERIFICATION

Unfortunately, for the station G1H036 the flow measurements are incomplete from the 3rd of July onwards. It therefore should be noted that the statistical comparison for the high flows are not included for this station. The simulated values were compared with the measured data and *'infilled values'* for low flows (October to March) and high flows (April to May) and overall, as well as to the errors that were experienced in the calibration simulation.

8.8.1 TDS

In the year October 1994 to October 1995, several peaks are experienced during the high flow months instead of one defined peak, as was the case for the calibration year. The maximum peak occurs mid-July and reaches only a value of approximately 40000 g/s at G1H013 and G1R003, compared to the maximum peak of 120000 g/s (at G1R003) for the calibration year (refer to Figure 8.25 and 8.57). The measured data for the low flow period nevertheless has more or less the same pattern as for the calibration period.

- ***TDS Concentration results:***

  (Table 1.8, Figures 1.43 -1.46 on Appendix 1)
  The coefficient of determination is low for the concentration analysis, between 0.04 and 0.58 for the high flow period and between 0.23 and 0.30 for the low flows. Although the concentration shows high over-simulation in March and April for the calibrated TDS simulation (Figures 1.9 to1.12), this is not evident in the verification simulation. The concentration is over-simulated downstream from G1H036 for the high flow period in the calibration year, while the verified run shows under-simulated concentration at all stations. G1H020 shows similar errors to the calibration simulation, while for G1H013 and G1R003 the yearly errors are higher than the errors of the calibration run. This could be the result of different point sources and non-point sources that have occurred in this year. The simulation of the concentration during the winter months shows an erratic pattern, which is the result of high inflowing TDS from G1H043 (Figure 8.16). For the calibration year, sub-catchments 4 and 5 (due to pattern of G1H039) contributed most of the salts in the winter months. As one can see from Figure 8.16 high TDS concentration is discharged from G1H034; the flow however is an average of 0.006 m^3/s for G1H034 during these months and therefore the load contribution to the river is minimal. Similar to the calibration results, there exists under-simulation in the summer months at all stations. At G1R003 the simulated and measured TDS values are about 125 mg/l different (Figure 1.44). This could be the result of the same missing point sources or also due to unknown abstractions.

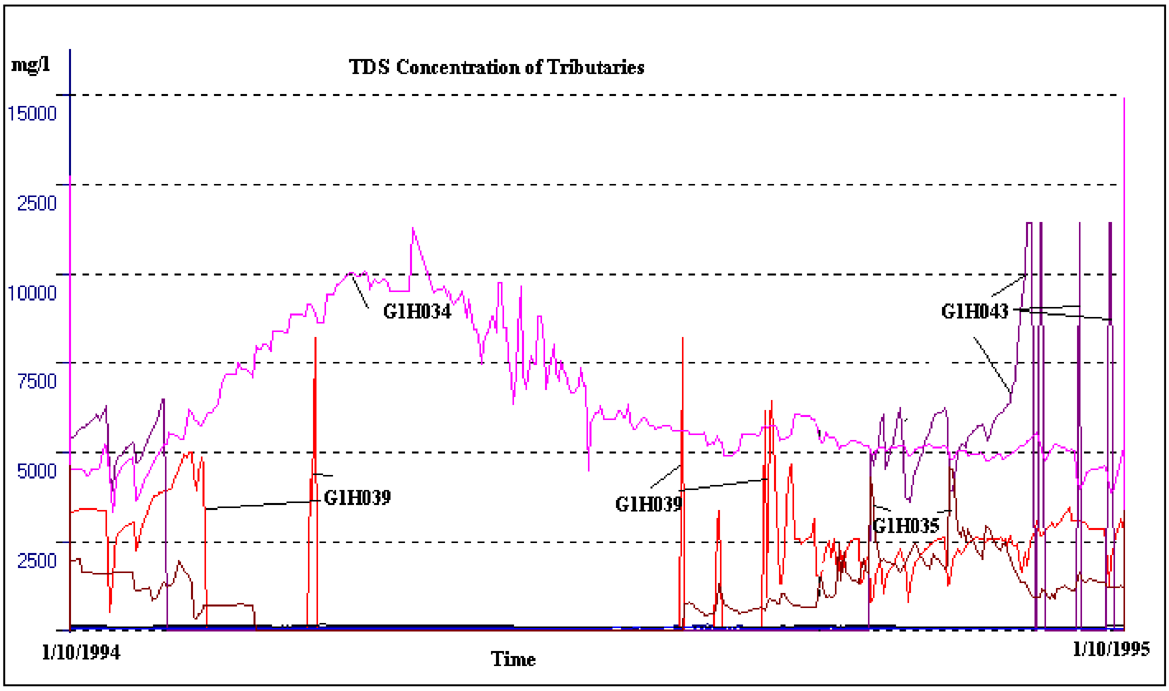


Figure 8.11: TDS Concentration of tributaries for the verification year

- ***TDS Loads Results:***

  Low Flow :
  (Table 1.7, Figures 1.33 - 1.36 in Appendix 1)
  As for the calibrated run, the coefficient of determination for the loads is higher than for the concentration. This is because the load is dependent on the flow simulated. One can see from the figures that the short lived peaks introduced by releases from Voëlvlei Dam are clearly defined in the load simulation at G1H013 and G1R003, but that the model is unable to simulate these loads to near zero load, as was measured. This is because the model gets unstable for zero water depths, and for modelling purposes a minimum water depth has been provided for in the coding. Interestingly, just as for the concentration, the loads are under-simulated for all stations for the verification run and over-simulated downstream from G1H020 for the calibration run. This could be the result of the definite over-simulation of loads in March/April for the calibration values, which does not occur in the verification run. The verification values show a higher coefficient of determination than for the calibration values (compare Tables 1.1 and 1.7).

  High Flow:
  (Table1.7, Figures 1.37 - 1.40 in Appendix 1)
  It can be seen from Figures 8.56 and 8.57 that the infilled salt loads stay consistent for the main peak in mid-July downstream from G1H013. In the model, however, salt loads are added from the ungauged sub-catchments and the tributaries, which can be seen by the increased simulated values for this peak. In the calibrated year the infilled TDS values do however increase in the peak (Figures 1.6 and 1.7), and this could mean that in reality most of the salts have already been discharged into the river by the previous flow peaks in the verification period, whereas in the calibration period only one major peak occurs. The overall TDS mass for the high flow months is under-simulated at all stations, except at G1R003.

8.8.2 Phosphate as PO_4

In the year October 1994 to October 1995, several peaks are experienced during the high flow months instead of one defined peak, as was the case for the calibration year. The maximum peak occurs mid-July and reaches only a value of approximately 15 g/s at G1H013 and G1R003, compared to the maximum peak of 40 g/s (at G1R003) for the calibration year (refer to Figure 8.37 and 8.69). The measured data for the low flow period nevertheless has more or less the same pattern and the same mass as for the calibration period.

- ***PO_4 Concentration results:***

  (Table 1.10, Figures 1.53-1.56 in Appendix 1)
  The coefficient of determination is low for the concentration analysis; the verified model shows however a better correlation to the measured data than the values for the verification simulation (Tables 1.10 and 1.4). Both the verification values and the calibrated values show a high over-simulation at G1H036 (Figures 1.54 and 1.22), this error therefore could be the result of an unknown point or non-point source between the reach G1H020 and G1H036, and is not only the result of a sudden high concentration measurement. The concentration is under-simulated most of the time at all stations (except at G1R003). This is also the case for the calibration year, except that G1R003 shows a 6% under-simulation for the low flow for the calibrated values and a 3% over-simulation for the verified values (Table 1.10 and 1.4). The simulation of the concentration during the winter months shows an erratic pattern, which is a result of the phosphate concentration discharging from G1H039 (refer to Figure 8.17).

- ***PO_4 Loads Results:***

  Low Flow :
  (Table 1.9, Figures 1.45-1.48 in Appendix 1)
  At all stations the phosphate loads are over-simulated, especially at G1R003 where the simulated values show a 159% over-simulation. The calibrated values show an over-simulation of 103% (Table 1.3), and it can therefore be concluded that the flows (88% over-simulation, Table 7.6) and the loads are over-corrected in the reach from G1H013 and G1R003. The other stations also show similar errors in the load simulation when compared to the flow simulation (Tables 1.9 and 7.6), and it is evident that the mass errors are dependent on the errors of the flow simulation. Referring to the figures, one can see that the short lived peaks introduced by releases from Voëlvlei Dam are clearly defined in the load simulation at G1H013 and G1R003, just as for the calibrated values and the coefficients of determinations, as well as the errors, are similar.

  High Flow:
  (Table 1.9, Figures 1.49-1.52)
  The phosphate peak in the summer was measured to be approximately 19 g/s at G1H013 and 15 g/s at G1R003. At all stations the phosphate peak is under-simulated, except for G1R003 where the phosphate peak is over-simulated as additional loads are introduced between reach G1H013 and G1R003 (compare also to Figures 1.17 and 1.18). This could be the result of additional non-point runoff occurring during a flood. The high flow phosphate loads show high coefficients of determination (0.92). The errors are less at G1H013, with only -18% under-simulated compared to -55% under-simulation for calibrated values.

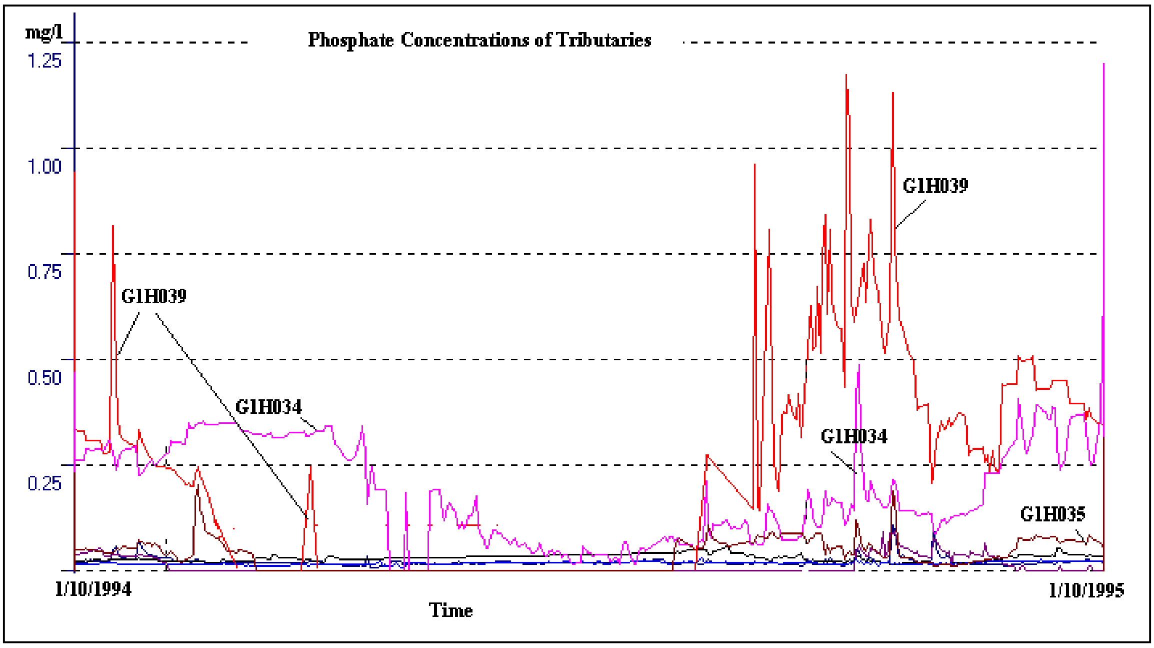


Figure 8.12: Phosphate Concentration of tributaries for verification year

8.8.3 Temperature

(Table 1.11, Figures 1.57-1.60 in Appendix 1)
The temperatures are simulated higher for the summer period for the verification run than for the calibrated model. The verification results show higher temperature values than the actual measured temperature, while the calibrated simulation results produced lower temperature values . The overall errors are less for the verified model than for the calibrated model, except for the reach from G1H013 to G1R003, where the error in the low flow period has increased to about 18%. The standard deviations have all increased (refer to Table 1.11).

From Figure 1.60 it can be seen that the summer temperatures are over-simulated at G1R003, and this could indicate that the parameters, that were acceptable for the calibration year, might not be acceptable for the verification year.

8.8.4 Oxygen

(Table 1.12, Figures 1.61-1.64 in Appendix 1)
The verification run showed small variation to the calibrated run. Table 1.12 summarizes the results and the percentage difference from the measured data. The percentage errors should be compared with the errors obtained from the calibration simulation (Table 1.6). Both runs are influenced by the saturation oxygen concentration, as little information is available on the oxygen in the Berg River. Only the flow and the meteorological data influence the oxygen concentration in this study. The low flow period shows a 1% over-simulation, while the high flow shows a 1% under-simulation. The standard deviations do not differ significantly. From the slight differences between the calibrated and the verified oxygen simulations it can be perceived that the parameters applied in the oxygen simulation are acceptable for another time period. The outliers seen in Figures 1.61 to 1.64 are due to under-simulation of temperature in the winter months.

8.9 WATER QUALITY SIMULATION WITHOUT UNGAUGED RUNOFF

The addition of ungauged runoff and loads was based on the conclusion that a considerable volume of flow and therefore also loads are missing in the mass balance (refer to Table 7.4). To assess whether the method (of adding ungauged loads and runoff) applied was successful, a simulation run without ungauged sub-catchments was completed. The results, compared to the actual measured data, were compared to the simulation results of Section 8.9.

8.9.1 TDS

- ***TDS Concentration Results:***

  (Table 1.14, Figures 1.73 -1.76 in Appendix 1)
  Comparing Figures 1.73 to 1.4.76 to Figures 1.9 to1.12, it can be seen (as already mentioned in section 8.9.1) sub-catchments 4 and 5 overcorrect the concentration in March and April. The peaks simulated in the winter months, which have also been added by sub-catchments 4 and 5, are also missing. The addition of the ungauged flow improved the concentration for September, October and November; but it had little improvement in the summer months. This can be seen especially at G1R003 (Figures 1.76 and 1.12), where considerable concentration is still missing. The concentration at G1H036 has been overcorrected the most, as the % error in concentration shifted from -32% to 14% for the low flow and -36% to 44% in the high flow. The overall concentration at high flow is always under-simulated without the addition of ungauged concentration, and over-simulated with ungauged runoff (except at G1H020).

- ***TDS Loads Results:***

  Low Flow :
  (Table 1.13, Figures 1.65 - 1.68 in Appendix 1)
  With the low flow load results it can be seen again that the estimation of the ungauged TDS has been overcorrected in March and April with the addition of sub-catchments 4 and 5. The TDS loads have improved considerably, when including the ungauged loads, for the months October and November (Figures 1.65 to 1.68 and 1.1 to 1.6). The short-lived peaks occurring from

releases of Voëlvlei Dam, are already slightly over-simulated without any additional loads. The loads simulated in the three months December, January and February show little change.

High Flow :
(Table 1.13, Figures 1.69 - 1.72 in Appendix 1)
Referring to Figure 1.4.69 and 1.4.70 the peak simulated in high flow has improved with the addition of ungauged TDS loads for G1H020 and G1H036. A TDS load peak of 2090 g/s has been simulated with addition of ungauged loads at G1H036, while 888 g/s has been simulated without the addition of ungauged loads. The measured peak was 2529 g/s, thus the % error improved from -65% to -17%. Interestingly, the peak measured at G1H013 and G1R003 is already higher simulated with only gauged loads (G1R003 is 79% and G1H013 26% higher), than the measured peak. This could be due to unknown abstractions of winter floods.

It can be concluded that the addition of ungauged sub-catchments does improve the TDS concentrations and loads for the months of October and November, and in the winter months. Little change has been found during the months December, January and February. Sub-catchments 4 and 5 however overcorrect the TDS concentrations and loads, especially in the months March and April. This can also be seen in Table 8.8 which shows that a 57% improvement in errors occurred for the TDS concentration in the second reach (G1H020 to G1H036). The estimated TDS loads for sub-catchments 4 and 5 seem incorrect (also refer to Figures 8.16). The TDS loads have been estimated with grab samples of station G1H039. Unfortunately, the station has a accuracy rating of 0 (refer to Table 7.1), but due to no additional choice of tributary, these grab samples were the only estimate.

Table 8.4: Absolute % error difference between the simulation without ungauged loads and the simulation with ungauged loads for TDS

Yearly % error difference	G1H020	G1H036	G1H013	G1R003
TDS Loads	28	96	64	68
TDS Concentration	7	57	38	26

8.9.2 Phosphate as PO_4

- ***PO_4 Concentration results:***

(Table 1.16, Figures 1.85-1.88 in Appendix 1)
Comparing the errors in concentrations between the simulation with ungauged phosphate loads and the simulation run without ungauged phosphate loads (Table 1.4 and Table 1.16), one can see that the % error has improved for all the stations for low and high flow, when including the ungauged phosphates. The % error has improved about 10% for the low flow and about 20% for the concentrations at high flow. One can see in Figures 1.85 to 1.88 and Figures 1.21 to 1.24, that the addition of ungauged phosphates does correct the concentration peaks especially in the winter months.

- ***PO_4 Loads Results:***

Low Flow :
(Table 1.15, Figures 1.77-1.80 in Appendix 1)
One can see from Figures 1.4.77 to 1.4.80 that the PO_4 loads have improved in the months October and November (as also the TDS loads). There is little change in the low flow loads, except for the small peaks occurring in November and December at station G1H036 (compare Figure 1.78 to 1.14), that are improved. The overall % error is less for stations G1H020 and G1H036, but have been over-corrected for stations G1H013 and G1R003. This is because, without any ungauged phosphate loads, the loads are already over-simulated at these stations.

High Flow :
(Table 1.15, Figures 1.81-1.84 in Appendix 1)
One can see from the figures that the PO_4 load peaks are very under-simulated for all stations, if additional loads from the ungauged sub-catchments are missing. The % error in the simulation run without the ungauged phosphates shows about 80% under-simulation. This error has been improved to about 40% under-simulation when the ungauged loads are added to the model.

It can be concluded that the addition of ungauged phosphate loads has proved to be successful for the high flows, as the error has been halved in the high flows. This proves that a considerable percentage of phosphate load is discharged into the river in a flood. Table 8.9 shows the % error improvements from the run without ungauged loads and the simulation run with ungauged loads for the overall yearly values.

Table 8.5: Absolute **% error difference between the simulation without ungauged loads and the simulation with ungauged loads for phosphates**

Yearly % error difference	G1H020	G1H036	G1H013	G1R003
PO_4 Loads	38	41	28	52
$_{PO4}$ Concentration	14	17	21	28

CHAPTER NINE
SCENARIO ANALYSIS

9.1 INTRODUCTION

A simulation model such as DUFLOW allows a user to understand the behaviour of a river system as a whole, or any of its parts, in space and time. Application of DUFLOW allows analysis of different scenarios that can illustrate the potential outcome of certain 'what if' situations. Figure 9.1 shows how a model can be used after verification, by implementing various water quality control actions and examining how the water system reacts to different scenarios and what the model's capability is to predict the outcome of these various scenarios.

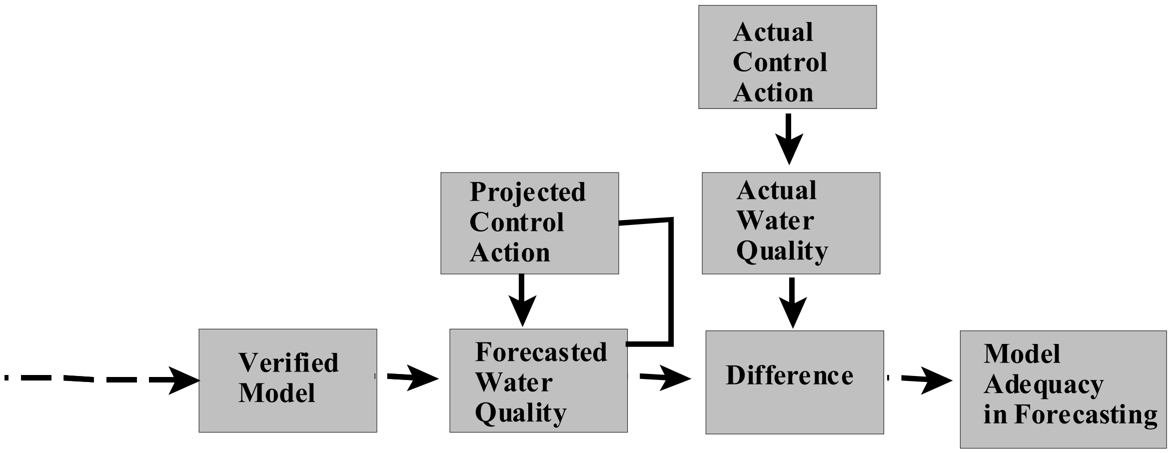


Figure 9.1: Post-audit of models (after Thomann and Mueller, 1987; pg. 8)

In this chapter the use of DUFLOW in different scenarios are examined, in order to determine the model's ability to predict the outcome of different situations that would be important in a water quality control programme. The scenarios that are studied have been divided into three categories:

- Short-term scenarios, such as a pollution spill discharging into the river.
- Long-term alteration of flow and water quality by linking the river simulation model to releases from a reservoir model.
- Long-term control management of concentrations and loads.

These scenarios and the ability of the model to predict the outcome, will be discussed in this chapter.

9.2 OPERATIONAL SHORT-TERM SCENARIO

The magnitude of a sudden spill of an effluent can be examined in a short-term scenario. The questions that are normally of interest to the river system manager if a sudden spill occurs, are:

- What is the time of travel of the effluent ?
- At what rate does the effluent attenuate ?

It was decided to divide the short-term scenario into two different scenarios that could occur:

- *spill without option of release of fresh water:*
  If no option of fresh water release is available, the question will be what degree of impact the spill will have on the river and how far, as well as how long, the increased water quality constituent concentration will travel downstream.

- *spill with option of releasing fresh water downstream*
  If fresh water can be released, the question will be what volume and duration of water releases from an upstream source would then be required.

The DUFLOW model was linked to the Water Quality Information System (WQIS), discussed in Volume 2, in which the user is prompted to enter the following:

- Location of an effluent spill
- Peak value of concentration of a spill, either for COD, TDS or PO_4
- Start and end times and dates of an effluent spill
- The spill hydrograph shape (Figure 9.2)
- If the user decides to increase the release water, the user is prompted to enter the discharge value and whether the discharge is from Skuifraam (the proposed future dam upstream in the Berg River, refer to Section 3.4.5), or from the Voëlvlei Dam (if an effluent spill occurred downstream of the release point of Voëlvlei, refer to Section 3.4.1 on details of Voëlvlei Dam).

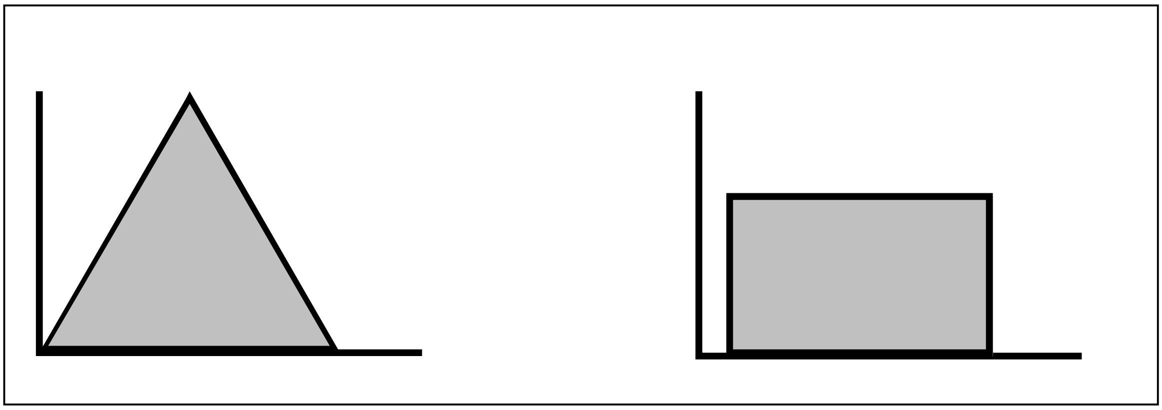


Figure 9.2: Effluent Spill Hydrograph Shapes

A DUFLOW simulation run is then performed and the impacts of the spill can be assessed graphically; either as a longitudinal section in a time step (refer to Figures 9.7 to 9.12), or at a specific cross-section over a time period (refer to Figures 9.5 and 9.6). To demonstrate the short-term scenario analysis, two runs were completed: one without releases from Skuifraam Dam and one run with releases.

Simulation without any releases:
The month February was chosen as a good indication of a ‘worst case’ scenario, as the flow in the river was very low. The spill occurred over a 4 day period, from the 15th February to the 19th February. The average discharge in the river was between 3 and 4 m^3/s. A phosphate spill of triangular effluent shape (refer to Figure 9.2) and a peak concentration of 10 mg/l were inserted at Wemmers River; the discharge in Wemmers River at the time of the peak (17th February) was 0.2 m^3/s.

Simulation with upstream releases:
For the second simulation run, the same effluent spill incident as for the above mentioned simulation was used, but a release discharge of 20 m^3/s was included additionally in the model. The discharge was released on the 16th February, a day after the occurrence of the effluent spill, and was of trapezoidal shape. By using the simulation model and inserting different volumes of releases, the user can assess on a trial and error approach the volume of water needed to decrease the concentration to an acceptable water quality limit at given downstream points.

Figure 9.3 shows the phosphate concentration over time at selected points downstream from Wemmers River without the release, while Figure 9.4 shows the phosphate concentrations experienced in the river if the release is included in the simulation run. As one can see from Figure 9.3 the concentration between Wemmers River and G1H020 is about 1 mg/l and attenuates to 0.4 mg/l at G1H013, while for the simulation run with the releases included the river experiences a phosphate concentration of 0.6 mg/l between Wemmers River and G1H020 and 0.2 mg/l at G1H013 (refer to Figure 9.4).

The results can also be viewed in space, therefore the user can assess the impact of the spill for a certain time period over the whole river. Figures 9.7, 9.8 and 9.9 illustrate the phosphate concentration for 16 February (one day after the beginning of the spill), the 18th and the 26th February respectively, for the simulation run without any releases. Figures 9.10, 9.11 and 9.12 show the impact the phosphate has on the river with releases discharging from Skuifraam Dam. One can see that with releases from upstream, the concentration in the river is diluted at a faster rate.

The severity of the impact of an effluent spill can therefore be visualized and understood for different scenarios.

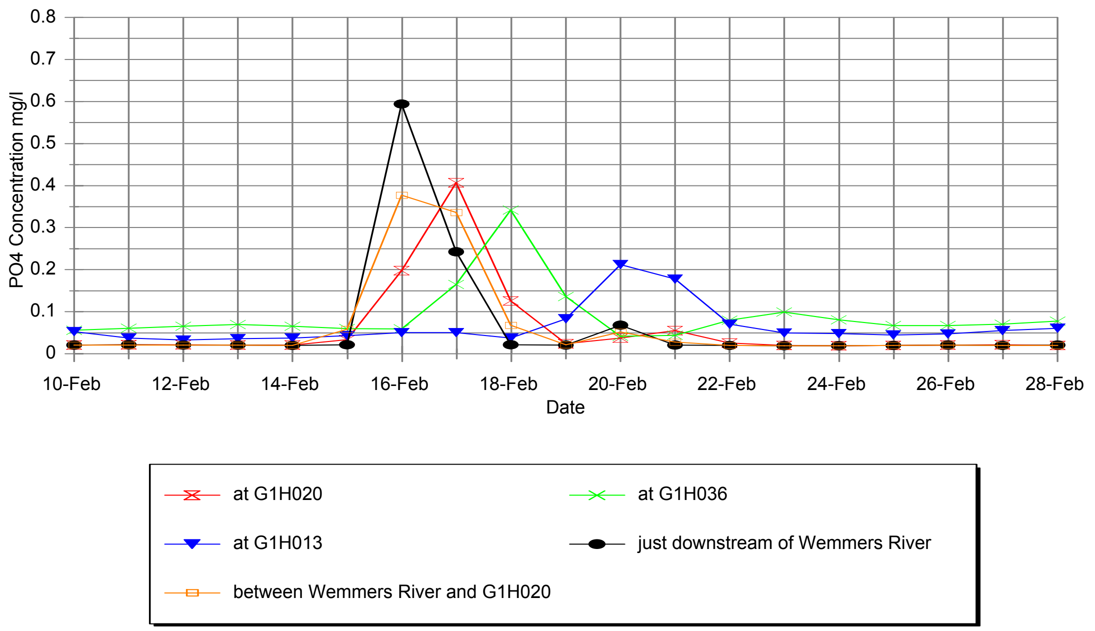


Figure 9.3: Results of Phosphate Spill without release shown in time

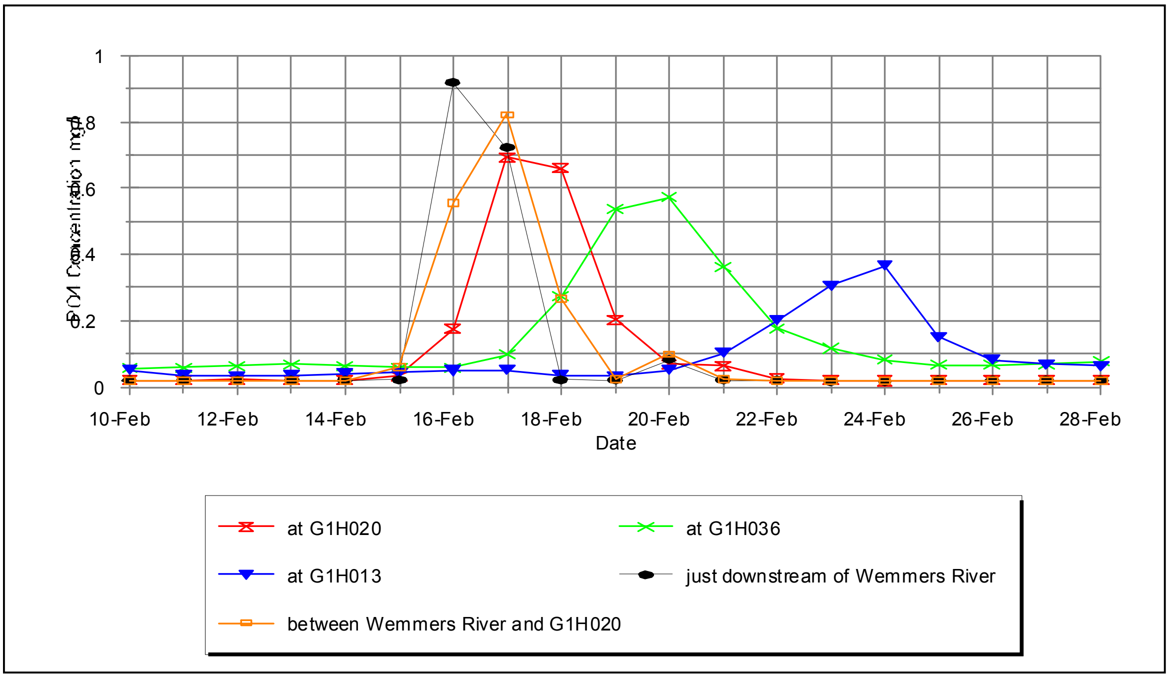


Figure 9.4: Results of Phosphate Spill with release shown in time

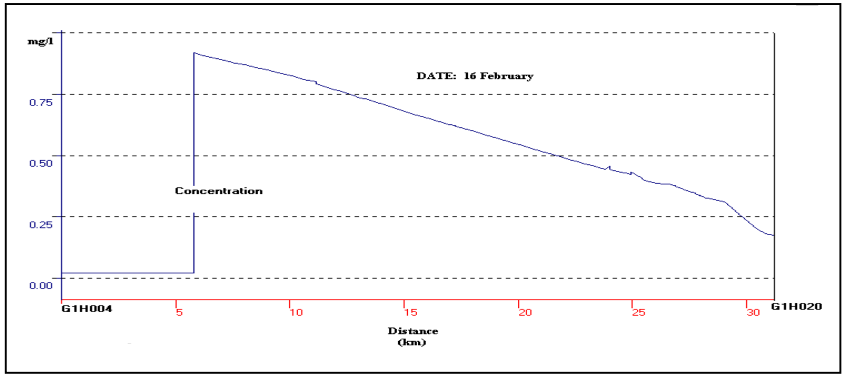


Figure 9.5: Results of Phosphate Spill without release for 16 February

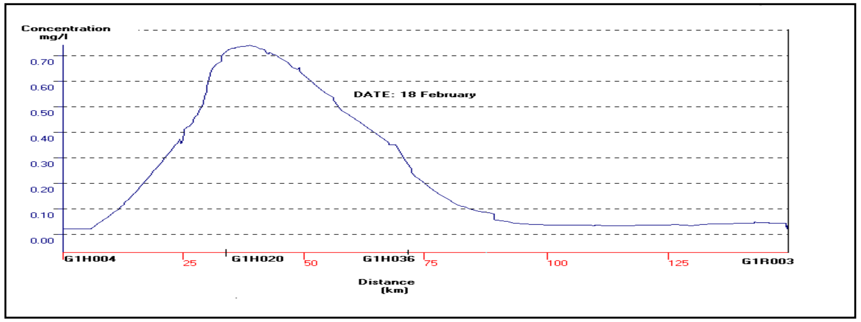


Figure 9.6: Results of Phosphate Spill without release for 18 February

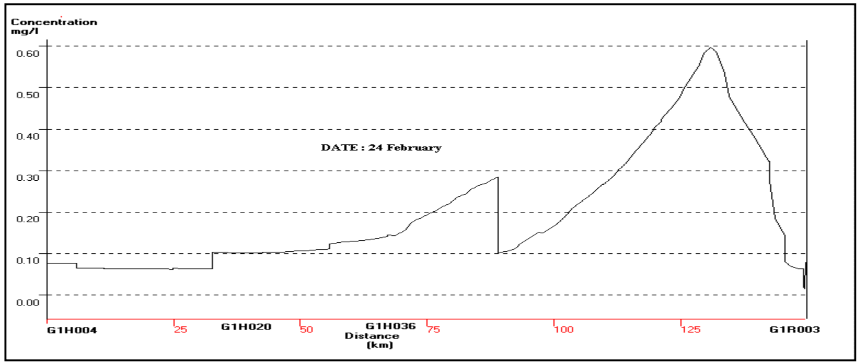


Figure 9.7: Results of Phosphate Spill without release for 24 February

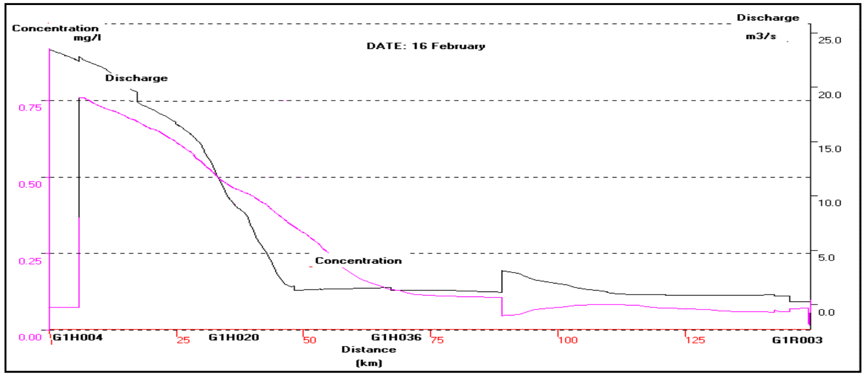


Figure 9.8: Results of Phosphate Spill with release for 16 February

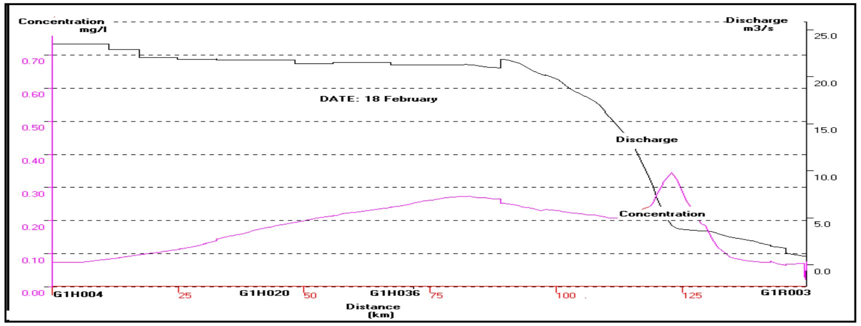


Figure 9.9: Results of Phosphate Spill with release for 18 February

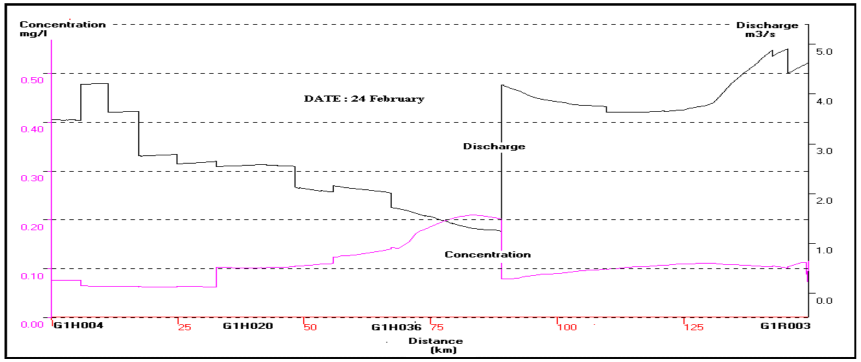


Figure 9.10: Results of Phosphate Spill with release for 24 February

9.3 LINKAGE TO RESERVOIR MODEL

The simulation model can be applied to a scenario where the upstream boundary conditions are varied according to the water quality and the flow releases that would occur if a reservoir were to be constructed in the upstream reaches of the river. The impact of the construction of a dam on the river can therefore be investigated. The reservoir model, CE-QUAL, was configured for Skuifraam Dam, as described in Section 3 of this volume, representing the water quality situation that would occur if Skuifraam Dam were built. The inflows used in the CE-QUAL reservoir model are the corresponding flows (G1H004) that were used originally as inflows into the river model. The water quality readings at G1H004 and the meteorological conditions at the site were used to drive the reservoir model, these are identical to the data that was used for the historical river model. Therefore, all conditions for the reservoir model were the same as in the river model, except that the flow and water quality were first routed through a reservoir before routed down the river. The simulated water quality release and spill time-series of the dam were used as the inflowing boundary water quality in the river model. The variables modelled were: TDS, Phosphate as PO_4, temperature and oxygen.

9.3.1 Flow

The environmental and agricultural releases calculated for the Berg River for a large-scale water resources planning study (Ninham Shand, 1999) were used as the upper boundary flow pattern. Figure 9.11 shows the comparison between the historical flow hydrograph and the release pattern developed for the reservoir.

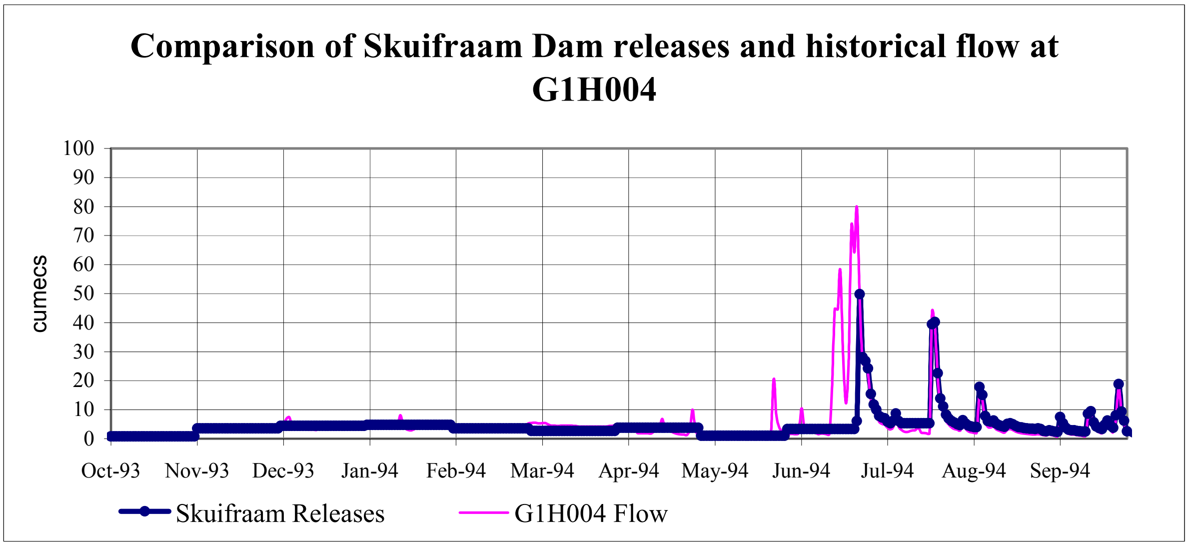


Figure 9.11: Comparison of historical inflow hydrograph and releases of Skuifraam Dam

Table 9.1: Comparison of flows at G1H004 and dam release/spill pattern

	Skuifraam Dam	Historical Data
Total (Mm^3)		
Summer Winter Yearly	51.5 180.9 232.4	55.9 222.9 278.9
Mean (m^3/s)		
Summer Winter Yearly	3.3 3.8 3.7	3.6 4.7 4.4
Maximum	49.7	79.7
Minimum	0.8	0.4

It can be seen that the flood peaks experienced in the winter months would be intercepted in the dam, until spill occurs. The maximum flow that would be experienced downstream in the river is 49 m^3/s compared with the 79.9 m^3/s of the historical data (refer to Table 9.1). The total water volume does however not change significantly, as the releases are more consistent and additional water is made available in the summer months. The flow in March and April do not deviate in mean, while the summer months experience higher flow than historically, and the winter slightly lower flow.

9.3.2 TDS

It can be noticed from Figure 9.12 that the historical data measured at G1H004 displays more erratic TDS concentrations than the TDS releases of the dam. The consistency is a result of the controlled releases of volumes of water from the dam, smoothed by mixing, while without the dam, the TDS concentration changes with the nature of the historical flow. A slight increase in TDS concentration from 40 mg/l to 48 mg/l is experienced in mid-June. The overall incoming TDS load into the Berg River from upstream does not vary significantly; although the river will experience a slight increase in TDS for all months. The TDS concentration measured in the upper reaches of the Berg River are minimal when compared with the concentrations that are found in the lower reaches.

Table 9.2: Comparison of released TDS from Skuifraam Dam and historical TDS at G1H004

	Skuifraam Dam	**Historical Data**
Total (tons)		
Summer	752.3	666.4
Winter	777.6	619.2
Yearly	1529.9	1285.9
Mean (mg/l)		
Summer	43.5	38.5
Winter	44.7	35.6
Yearly	44.1	37
Maximum	**48.9**	**79.8**
Minimum	**26.6**	**23.5**

Results:

The results of the simulation are shown in Table 9.3 for the concentrations and Table 9.4 for the TDS loads. The mean of the TDS concentration does not show much difference for all the stations. The total load has increased in the summer months and decreased in the winter months (refer to Table 9.4). It can therefore be concluded that the construction of the dam for this particular year would have had ineffectual impact on the TDS in the river, as the higher salinities experienced in the river are due to the high salinity discharged from the lower tributaries. A WCSA study (DWAF (a), 1993) on the salinity experienced in the river after construction of Skuifraam Dam, also calculated that the effect of the dam on TDS concentration would be relatively small if 1990 conditions persisted.

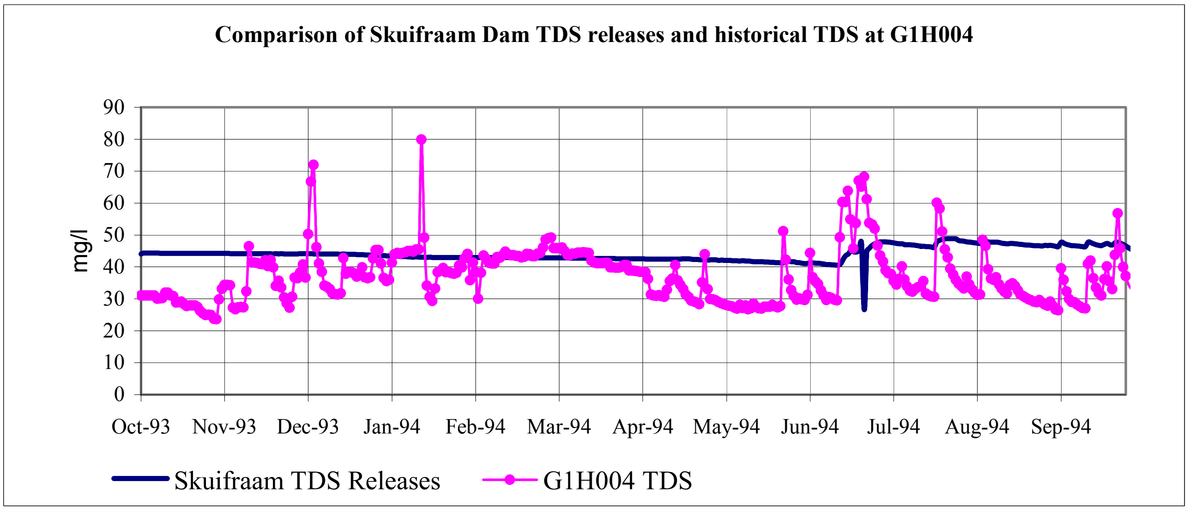


Figure 9.12: Comparison of historical TDS at G1H004 and TDS releases of Skuifraam Dam at G1H004

Table 9.3: TDS Concentration after simulation of dam releases

	mean (simulation with historical data) mg/l	mean (simulation with dam concentration) mg/l	% diff in mean
	Low flow period		
G1H020	43	45	5
G1H036	136	141	3.4
G1H013	123	118	-4
G1R003	162	148	-8
	High flow period		
G1H020	41	45	9.7
G1H036	177	178	0.6
G1H013	196	177	-9.7
G1R003	224	217	-7
	Yearly		
G1H020	42	44	4.7
G1H036	156	159	2
G1H013	159	147	-7.5
G1R003	193	184	-4.7

Table 9.4: TDS Loads after simulation using dam spills and releases as the upstream boundary

	Total Load Historical Data (tons)	Total Load Dam Releases (tons)	% Difference
Low flow period			
G1H020	2077	3077	48
G1H036	5401	6333	17
G1H013	6751	7624	13
G1R003	7595	8196	7.9
High flow period			
G1H020	12729	9896	-22
G1H036	54475	47694	-12
G1H013	99558	79615	-20
G1R003	133148	119376	-10
Yearly			
G1H020	14806	12973	-12
G1H036	58760	54027	-9.7
G1H013	106309	87240	-18
G1R003	140744	127572	-9

9.3.3 Phosphate as PO_4

Comparing the phosphates of the historical data measured at G1H004 and the phosphates that would be released from Skuifraam Dam at G1H004, one can conclude that the phosphate values will increase after construction of the dam. The phosphate values show a 200% increase in the summer months. This could be due to eutrophication. Algae growth is significant at this time, as the temperature and radiation are at a maximum (refer to Section 4.5.2 for description of phosphate sinks and sources). In the months July to September the phosphate values are also slightly higher for the dam releases than for the actual grab samples taken in the river without dam (refer to Table 9.5 and Figure 9.13). This could also be due to algae growth in the dam, which will be more significant in a reservoir as in a river.

Table 9.5: Comparison of Phosphate as PO_4 released from Skuifraam Dam and historical data at G1H004

	Skuifraam Dam	Historical Data at G1H004
Total (tons)		
Summer	1.2	0.4
Winter	0.7	0.3
Yearly	1.9	0.8
Mean (mg/l)		
Summer	0.07	0.03
Winter	0.04	0.02
Yearly	0.05	0.02
Maximum	0.09	0.05
Minimum	0.01	0.005

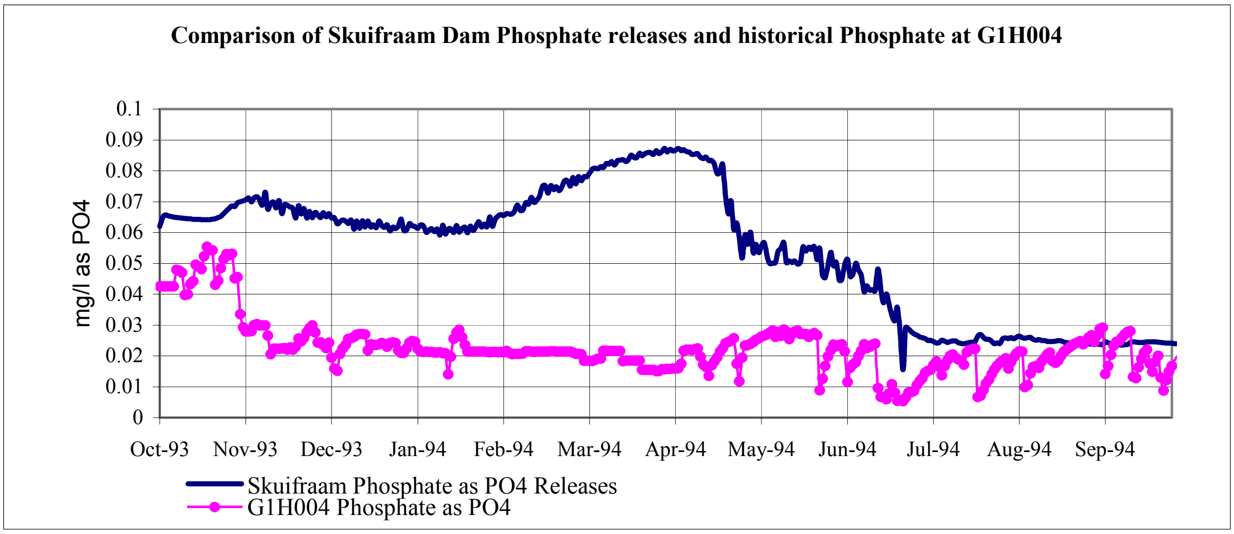


Figure 9.13: Comparison of historical Phosphate as PO_4 and releases from Skuifraam Dam

Results:
Table 9.6 summarizes the simulated concentration, while Table 9.7 shows the loads that will be experienced when the dam is constructed.

Higher phosphate loads are experienced in the dam for the summer months. This increase has an impact on the river, as can be seen from the simulation results. The results are higher for all months and at all stations, with the summer concentration showing an increase of about 76% at G1H020. The loads are also more significant and a 230% increase in the loads is experienced in the river reach from Skuifraam Dam and G1H020 during the summer months. The loads simulated in the winter months show only 12% difference. The increase in phosphate values perceived could have a vital impact on the already high phosphate values measured in the river.

Table 9.6: Phosphate Concentration after simulation using dam spills and releases as the upstream boundary

	Mean (Simulation with Historical Data) mg/l	Mean (Simulation with Dam Concentration) mg/l	% Diff in mean
Low flow period			
G1H020	0.025	0.044	76
G1H036	0.026	0.049	88
G1H013	0.023	0.041	78
G1R003	0.023	0.042	83
High flow period			
G1H020	0.023	0.027	17
G1H036	0.040	0.042	5
G1H013	0.034	0.040	17
G1R003	0.034	0.040	17
Yearly			
G1H020	0.023	0.036	56
G1H036	0.031	0.046	48
G1H013	0.028	0.040	43
G1R003	0.028	0.041	46

Table 9.7: Phosphate Loads after simulation using dam spills and releases as the upstream boundary

	Total Load historical data (tons)	Total Load dam releases (tons)	% difference
Low flow period			
G1H020	1.0	3.3	230
G1H036	1.2	3.0	150
G1H013	1.4	3.0	114
G1R003	1.2	2.8	133
High flow period			
G1H020	7.9	8.1	2.5
G1H036	15.9	17.8	12
G1H013	21.2	23.0	8.5
G1R003	24.0	26.1	8.8
Yearly			
G1H020	9.0	11.4	26
G1H036	17.2	20.8	21
G1H013	22.6	26	15
G1R003	25.2	28.9	14.7

9.3.4 Temperature

The temperatures of the dam simulation outflows and G1H004 vary significantly. The maximum temperature is of equal value, but it is experienced in April, while for the historical data the maximum temperature is experienced in December and January (refer to Figure 9.14 and Table 9.8). The temperature of the dam releases do not drop as low as the historical data, as the temperature in the dam will not change as significantly with the meteorological conditions as the river, due to the smoothing effect of the storage in the dam. In December, a difference of -10º Celsius is simulated. The upper layer of the dam will experience these summer increases at nearly the same time as the river, while the lower layers of the dam (where the release takes place) stay cold due to stratification. These differences could have a significant ecological impact in the river. Additional research should be undertaken to investigate the impact these changes would have on the river ecology.

Table 9.8: Comparison of temperature released from Skuifraam Dam and historical temperature at G1H004

	Skuifraam Dam Outflows	Historical Data at G1H004
Mean (□C)		
Summer	15.2	22
Winter	19.7	13.1
Yearly	17.5	17.5
Maximum (□C)	24.6	25
Minimum (□C)	13	10

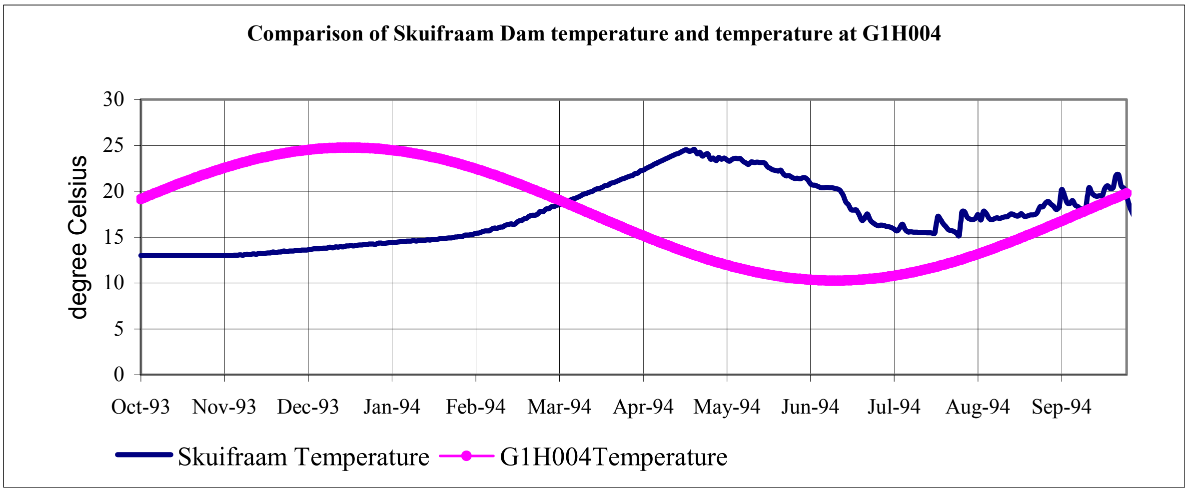


Figure 9.14: Comparison of historical temperature and temperature releases of Skuifraam Dam

Results:

The results of the simulation (refer to Table 9.8) show that the temperature experienced in the river will be lower for the summer months and higher in the winter months. The effect the released temperature of the dam will have on the river will be felt particularly in the reach from the dam (G1H004) to G1H020. The effect the delay of the maximum temperature has on the overall statistics is averaged out when calculating the temperature values over six months. The mean temperature is lower in the summer months, while in the winter months the temperatures all show higher values. This can also be seen when comparing the released temperature of Skuifraam Dam to the temperatures in the river prior to a dam (Figure 9.14). The maximum temperature in the river does not vary in value, but in time, as was seen in Figure 9.14, this delay in maximum temperature could have a significant effect on the ecology of the river and further studies should take place on the degree of impact this delay will have.

Table 9.9: Temperature after simulation using dam spills and releases as the upstream boundary

	Mean Historical Data (ºC)	Mean Dam (ºC)	% Diff. in Mean	Standard Deviation Historical Data	Standard Deviation Dam	% Diff. in Standard Deviation
Low flow period						
G1H020	23	20.1	-13	3.0	3.1	3
G1H036	24	20.7	-14	2.7	2.8	4
G1H013	24.5	22	-10	3.6	3.1	-14
G1R003	24.7	22.8	-7	3.5	3.1	-11
High flow period						
G1H020	13	15.1	16	2.5	3.4	36
G1H036	12.8	14.1	10	2.7	3.3	22
G1H013	12.5	12.7	2	2.9	3.3	14
G1R003	12.5	12.3	-2	2.9	3.4	14
Yearly						
G1H020	18	17.6	-2	5.7	4.1	-28
G1H036	18.3	17.4	-5	6.5	4.5	-30
G1H013	18.5	17.3	-6	6.9	5.7	-17
G1R003	18.5	17.5	-5	6.9	6.2	-10

9.3.5 Oxygen

The oxygen discharged from the dam is much lower than the oxygen values estimated at G1H004. This difference is because the oxygen calculated for the river simulation is the actual saturation oxygen, as no real data was available to include into the model. The oxygen of the dam is less than the saturation oxygen, because of the dynamics that influence and depletes the oxygen concentration in the dam (refer to Section 5.4.5 for more description on oxygen processes in a water body) and because the releases are made from the lower layers of the dam. A minimum of 1.3 mg/l is calculated for the dam oxygen, while the saturation oxygen only decreases to a minimum of 8.4 mg/l. Higher oxygen is released in the winter months, when the spill occurs and oxygen from the upper layers of the dam is released into the river (refer to Figure 9.15).

Table 9.10: Comparison of oxygen released from Skuifraam Dam and oxygen at G1H004

	Skuifraam Dam	Historical Calculated Saturation Values
Mean (mg/l)		
Summer	0.3	8.8
Winter	5.3	10.5
Yearly	2.8	9.7
Maximum (mg/l)	8.6	11.2
Minimum (mg/l)	0	8.4

Results:

Referring to Table 9.11, there is an insignificant difference in oxygen mean for low and high flow period. The yearly values show that there is 0% difference, while the low flow period indicates slightly higher values, with 3% difference the maximum at G1H020, and the high flow period shows slightly lower values, with -5% the maximum difference experienced at G1H020. The minimal differences perceived from the simulations might be due to high saturation oxygen discharging into the river from the tributaries and also that re-aeration of the depleted oxygen takes place shortly after the upstream releases. Therefore, the oxygen level in the river increases to saturation oxygen before reaching the gauging stations. The results indicate that although the oxygen concentration is low in the top reaches of the river, the river has the ability to re-aerate and depending on the quality of the water from the tributaries, the oxygen in the river could recover at a fast rate. There is, however, need for additional research on the severity of the impact of low oxygen discharging into the river.

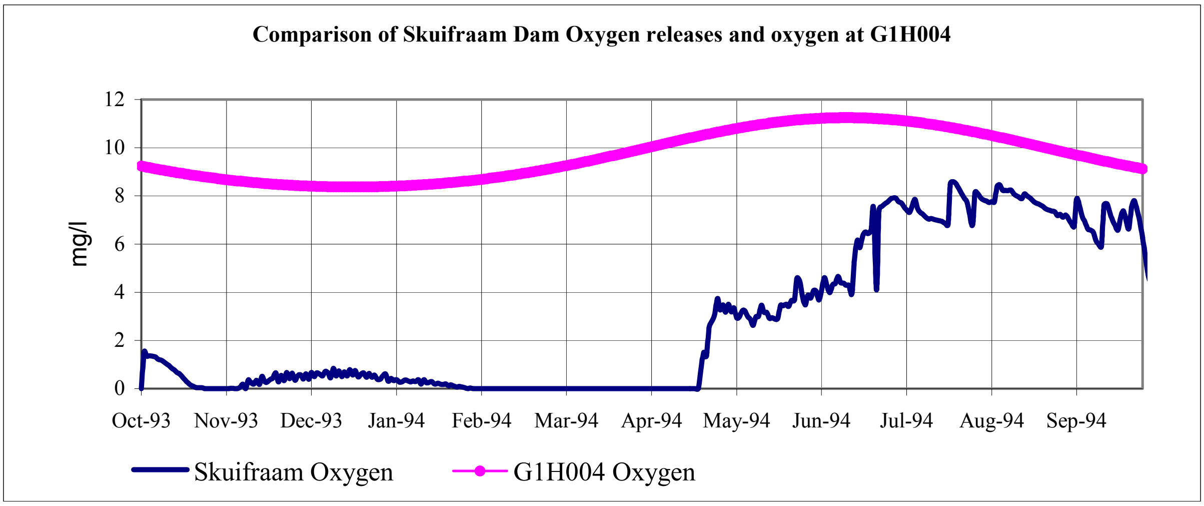


Figure 9.15: Comparison of historical oxygen and releases of Skuifraam Dam

Table 9.11: Oxygen after simulation using dam spills and releases as inflow

	Mean Historical Data (ºC)	Mean Dam Spills and Releases (ºC)	% Diff. in Mean	Standard Deviation Historical Data	Standard Deviation Dam Spill and Releases	% Diff. in Standard Deviation
Low flow period						
G1H020	8.7	9.0	3	0.44	0.45	2
G1H036	8.6	9.1	6	0.50	0.47	-6
G1H013	8.5	8.8	3.5	0.53	0.50	-6
G1R003	8.9	9.2	3	0.42	0.41	-3
High flow period						
G1H020	10.3	9.8	-5	0.60	0.69	15
G1H036	10.6	10.2	-4	0.86	0.76	-12
G1H013	10.7	10.5	-2	0.76	0.96	26
G1R003	10.8	10.6	-2	0.82	0.74	-10
Yearly						
G1H020	9.6	9.4	-2	0.9	0.66	-26
G1H036	9.6	9.6	0	1.2	0.85	-29
G1H013	9.7	9.7	0	1.3	1.12	-14
G1R003	9.8	9.9	-1	1.4	0.95	-32

9.4 LONG-TERM CONTROL

A central problem of water quality management is the assignment of allowable discharges to a waterbody so that a given water quality standard downstream of a particular effluent point is met. For instance, the deteriorating water quality in the Berg River is a result of the return flow from the agricultural land (i.e. non-point sources) and from the sewage treatment plants (i.e. point sources). Thus, the question can be asked: how should the load allocation between these two be divided?

DUFLOW cannot model non-point sources. Therefore, to investigate the aforementioned management question, the non-point sources were modelled as distributed "point sources". The user can insert water quality limits upstream at a selected discharge point and downstream at the point of interest to the user. The user is also prompted, as for the short-term scenario, for a concentration and a discharge that will be discharged at the selected location. The user can then by a trial and error approach identify the magnitude of loads that may be discharged at the specific location without violating the specific quality limitations. The point loads may also be altered and compared with the non-point discharges.

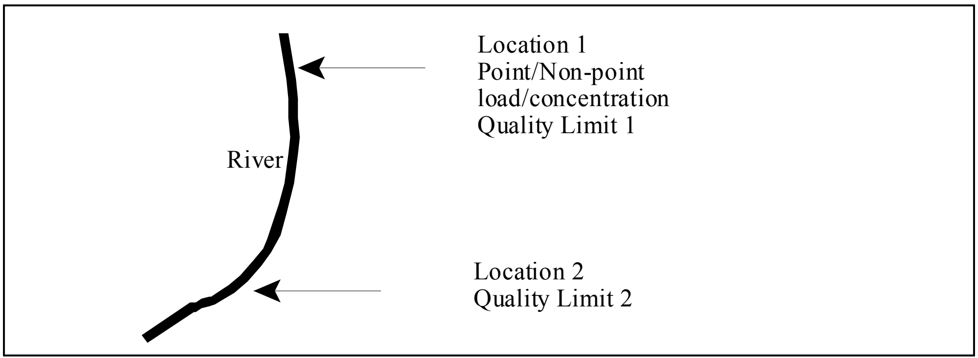


Figure 9.16: Schematisation of long-term control scenario

This scenario is similar to the short-term scenario, except that the user has additional control by assessing which mass a water quality load discharge into the river upstream may have without violating a particular water quality limit at a downstream source.

9.5 DISCUSSION

From the above discussions it is evident that DUFLOW does have the capability to assist in scenario analyses. It seemed reasonably easy to add releases and spills and the model remained computationally stable during the scenario simulation runs.

A limitation of DUFLOW is that no non-point sources can be modelled and this would have allowed for additional load allocation scenario analyses. The incorporation of a catchment model to the WQIS and DUFLOW would therefore be of advantage for the overall understanding and management of the river system. The DUFLOW modelling package does contain an additional precipitation runoff module (RAM) which has been developed by STOWA in order to improve the applicability of surface water models. RAM has however not been applied to many studies yet, and has not been tested for South African conditions. It is therefore recommended to use models that have been used and tested extensively for South African conditions. Examples of modelling systems used in South Africa are:

- *ACRU hydrological and water quality modelling system:*
  A sediment-nutrient version of the well-known ACRU modelling system has been configured and used for the Mgeni Catchment (Kienzle *et al*, 1997)
- *IMPAQ*
  IMPAQ has been developed by Ninham Shand and has been applied to the Amatole System in the Eastern Cape Catchment (DWAF(a), 1995)
- *HSPF*
  (Bricknell *et al*, 1993).

Matji (2000) compares the results of phosphorous runoff from various catchments with different runoff conditions for different catchment models, including some of the abovementioned models. The linkage of one of these runoff models would therefore improve the applicability of operational scenario analyses.

CHAPTER TEN
CONCLUSIONS AND RECOMMENDATIONS

10.1 INTRODUCTION

As water quality is becoming an increasingly important issue, the application of a water quality simulation model is useful for integrated management of the existing and future water resource systems. Since the early days of the development of computer models, as described in Chapter 2.2, models have become an essential "tool" to simulate solutions to different types of problems in water resources. The objective of this study was to assess the applicability of an existing European model for a winter-rainfall river in South Africa, under conditions very different to those applicable in its country of origin. Following selection criteria that have been declared important by management-orientated user groups (Chapter 2.6), it was decided to apply the hydrodynamic water-quality model, DUFLOW, and evaluate its adaptability for representing the Berg River with all its complexities.

The Berg River seemed to be a suitable river to model, as it contains a range of challenges for hydraulic modelling (fairly steep slopes, abstractions, diversions of flow, hydraulic structures) and also water quality (non-point and point sources, etc.). Aspects of the water quality in the Berg River are of great concern, especially in the lower reaches of the Berg River catchment, where the salinities are excessive and high nutrients are also becoming an intermittent. In Chapter 4 it was shown that the phosphorous concentrations have increased considerably over the last ten years. In the vicinity of Paarl/Wellington the sandstone formations give way to Malmesbury shale downstream that yield high salt loads into the main stream, via the tributary flows and through irrigation return flows. With the proposed construction of Skuifraam Dam (refer to Chapter 3.4.5), fresh water from the upper Berg River would be captured. Concerns have been raised that the downstream salinity might increase due to reduction of fresh water availability. It is therefore important that the model represents the water quality responses in the river realistically, as it can then be used to assist in developing management strategies.

The limitations and the capabilities of DUFLOW are discussed in the first section of this chapter. Recommendations are made on basis of the conclusions drawn and are presented in the second section of this chapter.

10.2 CONCLUSIONS

10.2.1 Flow Calculations

The finite difference approach that DUFLOW uses to calculate the St Venant equations of continuity and momentum is advanced and therefore allows the user to model complex systems. The finite difference approach allows varied space steps, which proved to be advantageous; especially in the upper Berg, where steep slopes required very small space steps for stable calculations. The lower Berg River could then be modelled in larger space steps in order to save running time and superfluous cross-sections. In total 108 surveyed cross-sections were included.

Structures that were included are weirs at the specific gauging stations and bridges that are found along the main stem of the Berg River. Information was available for most of the structures, and where difficulties were experienced with computational stability, the roughness coefficient was adjusted. The "trigger function" used in DUFLOW for structure control allows modelling of multiple notches at a weir, such as is often found in South African rivers.

10.2.2 Water Quality Calculations

An advantage of DUFLOW is the open code structure it uses for the water quality module. This allows the user to either change the water quality algorithms according to the degree of complexity required or add additional water quality processes that need to be simulated. In future use of the configured model, water quality processes can be added or deleted. Thus, the model is very flexible. In this study, TDS, COD and Temperature algorithms were added to the EUTROF1 module, as these are variables of concern specifically in the Berg River catchment. The Phosphate algorithm had to be simplified, as most of the processes could not be modelled due to lack of in-stream data. The results of the Temperature algorithms proved to be satisfactory.

Two-weekly water quality samples were available. As the model was configured on a daily time step, the samples had to be 'patched' (infilled) in order to include the variables as time series. DUFLOW has an option of entering the time series at irregular time steps, but DUFLOW linearly interpolates the values for the missing samples, which is not quite correct for the distribution of the water quality variables as they are also dependent on the flow value. A moving regression method was used to infill the TDS and soluble phosphate values, while a simple harmonic function was used for the temperature infilling.

Schematisation points were added at every location where a tributary discharges into the main stem or where a point source had been identified. A considerable number of point sources were not included, due to lack of information. It would be a pre-requisite, if the simulation model will be used as an operational tool, that all primary sources of water quality discharge into the river are identified and included in the model.

A limitation of DUFLOW is that it does not allow incoming loads to be input in a diffuse fashion along the length of the modelling reaches. It is therefore difficult to distinguish between non-point and point sources, if the model is to be used as a scenario tool, because the non-point sources have to be treated as distributed point sources.

10.2.3 Results

The accuracy of the results is mainly determined by the accuracy and availability of the input data. Errors in the water quality simulation are dependent on various factors, such as: accuracy of the 'infilling' method, availability of grab samples in the river, accuracy of the flow simulation, etc. The flow simulation is dependent on various factors such as cross-section data, channel roughness information, etc. The errors that are introduced at the beginning of the flow calculations (i.e. in the first reach) are carried all the way downstream to the end boundary.

The estimation of runoff from ungauged sub-catchments for the calibration of the flow module proved to be problematic. Considerable volumes of water were still missing during peak flows for most of the stations. This could be due to underestimation of the flood at the various gauging stations, which thus also leads to under-estimation for the ungauged runoff. The accuracy of the simulation of the water quality loads is dependent on minimising errors resulting from the flow simulation.

10.2.4 Learning curve

The learning curve time to use the model efficiently is greatly reduced by the user friendly interfaces that DUFLOW offers. This is a major advantage, as it can be operated easily for configuration and scenario analyses by the user. An understanding of the underlying hydraulics and water quality processes is however needed to fully understand the system.

10.2.5 Limitations

1. Although the finite difference approach to calculate the St. Venants equations proved to be advantageous due to the stability and the choice of unequal time and space steps, a limitation of this approach is, however, that it is very data intensive compared to other simpler flow calculation methods.
2. The different network objects (i.e. weirs, abstraction points, etc.) can only be altered in the network window itself. For adjustments to the objects it would have been easier to change the specific descriptions in an additional textfile or database, especially if numerous objects are configured.
3. The results are written in a textfile, which take up considerable space (about 50 Mb for the quality files). For use in other systems, such as the WQIS (Volume 2), a database format would have been more suitable for updating and presenting.
4. Like many European or American models, DUFLOW is not able to simulate evaporation losses from the water body. Such losses can be quite significant in South Africa, and are therefore of importance. These losses had to be treated as abstraction flows at schematisation points.
5. Non-point sources are not modelled as diffuse inflows by DUFLOW. These are however extremely important when considering the nutrient mass balance. From the water quality results it was evident that the agricultural runoff is significant in floods (all loads are under-simulated).

6. Water Quality calculations became unstable when "negative" water depths were experienced for the different runs. Negative water depths are a physical impossibility, but are sometimes simulated in the low flow period, due to inaccuracies between the calculated water level and the configured cross-section=s reference level. Although the process calculations were able to be coded to overcome this problem, the transport mathematical formulations were fixed, and the negative water depths affected the calculations. Much effort went into altering the time and space steps until a stable flow calculation was achieved.

10.2.6 Scenario Analysis

The text files produced by DUFLOW are easily altered for different scenario runs. DUFLOW is capable of simulating different scenarios that are of interest to the user. Three scenarios were looked at: a short term effluent spill scenario, a linkage to the hydrodynamic reservoir model, which is described in section 3 of this volume, and thirdly an operational long term management scenario. Although simulation time was long due to small calculation time steps (a calculation time step of 10 minutes proved to be stable) and the result file is large in terms of computer space, DUFLOW is capable of simulating various water quality related changes and predicting the outcomes of different water management scenarios.

10.3 RECOMMENDATIONS

Although the information for the Berg River Catchment is probably more extensive than for many other catchments in South Africa, there is still considerable need for additional research and data if a realistic representation of the river is desired. This is especially important when the model is not only used as an analysing “tool” for historical data, but also used to examine management scenarios. Research into the following areas may produce results that would strengthen the model’s capability to represent the Berg River Catchment:

10.3.1 Non-point and point sources

There is considerable need to improve the monitoring system for point and non-point sources along the Berg River catchment. This would make a database available of different sources that contribute to nutrient and salt loads in the river. Although DWAF already monitors point sources that have been issued with a water quality permit, there are numerous sources that contribute to the deteriorating water quality in the Berg River. As most of the phosphorous in the river is due to runoff from agricultural land (Bath, 1989), it would be of benefit to link the hydrodynamic river model to a catchment model to estimate water quality loads from ungauged areas, rather than the ungauged runoff estimation methods used in this study.

10.3.2 Expansion of data information on variables of interest in the Berg River

Oxygen is of interest in the river for ecological reasons, therefore it would be important to explore the oxygen mass balance in the Berg River, by taking grab samples over a longer period and incorporating COD discharges of the point sources into the river. Different algorithms relating to oxygen should be studied and adopted according to the specific river.

The scenario analysis showed that the summer temperature in the river would change considerably (-10 degree Celsius change) if Skuifraam Dam were to be built in the upper reaches. This is obviously of concern and there is need to investigate the ecological impact of these temperature changes in the river.

Although earlier studies have been conducted on the phosphorous transport in the Berg River (Bath, 1989), the DUFLOW model has been activated in only the advection equation to analyse the phosphate concentration, as insufficient data is available on other dependent variables. By including data on the suspended solids and therefore the mobilisation of particulates into the river, as well as production of algae, improved results on the simulation and a better understanding on the phosphorous concentration in the river can be expected.

10.3.3 Linkage to other models

As mentioned above, it would be beneficial for management support, if DUFLOW were to be linked to other models as this would also ensure that DUFLOW could be used in catchment-wide applications. In this research a user-friendly interface environment was developed and implemented as a Water-Quality Information System (WQIS) that provides analytical, spatial and graphical information based on the requirements of a wide spectrum of users and which integrates simulation models (river and reservoir) into the WQIS, as described in Volume 2. It would be important to broaden this study and integrate a catchment model into the WQIS so that it can provide tributary inputs to DUFLOW, as well as further develop the DUFLOW model to support scenario analysis to support decision making for integrated water management.

CHAPTER ELEVEN
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SECTION 2

APPLICATION OF A TWO DIMENSIONAL HYDRODYNAMIC RESERVOIR WATER QUALITY MODEL : CE-QUAL-W2:

APPLICATION TO THE PROPOSED SKUIFRAAM DAM ON THE BERG RIVER

CHAPTER ONE
INTRODUCTION

1.1 BACKGROUND

Impoundments and associated bulk water supply infrastructure are present in most South African river systems. Because of the disparate natural occurrence of rainfall and runoff, and its mismatch with water demand concentrations, many of these schemes have to incorporate inter-catchment transfers to meet demands in the face of inadequate local availability. Furthermore, water quality deterioration, because of human impacts through a wide range of land-uses and waste discharges, has for some time been recognised as a threat in South Africa, as it diminishes the utilisable part of the runoff in many catchments. These complexities increasingly offer challenges to water resource managers that require a response with integrative management philosophies and innovative management tools.

During 1997, in recognition of the aforementioned needs, the Department of Civil Engineering of the University of Stellenbosch, formulated a research proposal to the Water Research Commission (WRC) whose aim would be to serve the philosophy of Integrated Water Resource Management (IWRM), through the development of an integrated information system specifically for water quality – here abbreviated to “WQIS”. To be useful to IWRM, this WQIS was to provide diagnostic and predictive utilities to serve technical planning and operational decision-making in a river system, but, simultaneously, provide appropriate information to support water managers in communication with technical stakeholders. It was also recognised that the project would need identification of a “prototype” catchment for development of appropriate WQIS approaches and to provide a relevant database.

One of the aims of this project was to develop Water Quality Information Systems (WQIS) to support both integrated management of a water resources system, and to support communication about water quality management with stakeholders and communities in the catchments of that system - In this study the Riviersonderend-Berg River (RSE-BR) System was used as the prototype catchment. To develop this WQIS, however, it was necessary to combine a suite of water quality models with a user interface so that the results of the modelling could be visually interpreted. **DUFLOW** (refer to Section 2 of this report) was the model selected for simulating the river flow and quality within the system while **CE-QUAL-W2**, a two-dimensional hydrodynamic and water quality model, was used to simulate the flow pattern and constituent profiles in the proposed impoundment in the system. The application of the reservoir model, CE-QUAL-W2, is discussed in the ensuing chapters.

1.2 OVERVIEW OF CE-QUAL-W2 MODEL

As mentioned previously **CE-QUAL-W2** is a two-dimensional hydrodynamic and water quality model capable of simulating the flow patterns and constituent profiles within rivers, lakes, reservoirs and estuaries.

The model has been under development since 1975 and was originally known as LARM - **L**aterally **A**veraged **R**eservoir **M**odel (Edinger and Buchak, 1975). Subsequent additions of water quality algorithms by the United States Army Corps of Engineers have resulted in the version known as CE-QUAL-W2. Several South African reservoirs have been modelled using CE-QUAL-W2 and the results obtained provided insight into the biochemical processes, temperature changes, stratification and flow patterns which occur in these reservoirs (Bath *et al*, 1998 and Görgens *et al*, 1993).

Inputs to the model include the following:

- ***Bathymetric data*** - Data representing the lay-out and volumetric dimensions of the water body.
- ***Initial Conditions*** - Data representing the starting conditions within the reservoir in terms of temperature and constituent distribution.
- ***Meteorological Data*** - This data includes the site-specific values for air temperature, wind speed, wind direction, dew point temperature and cloud-cover.
- ***Upstream Boundary Conditions*** - This data includes the flow rates of the incoming streams as well as the time-varying concentrations of the constituents being modelled.
- ***Flow Rates of Releases*** - This includes the data describing the predicted (or measured) release pattern from the reservoir and is essential for volume balance calculations.

Output from the model can be specified in various forms depending on the type of information required and the post-processor available to the modeller. The standard output parameters are the time-varying water surface elevations, water velocities within a cell, constituent concentrations and temperature profiles.

Special features of the model are the abilities to simulate the chemical interactions of up to 21 constituents and to model dendritic-type reservoirs by using a branch algorithm.

An obvious limitation of any 2-dimensional model is the intensive data requirements. This is particularly true for the variables regarded as the driving forces (meteorological data, flow data and constituent concentration data).

1.3 LINKAGE TO RIVER MODEL

Growing demands from Theewaterskloof, Vöelvlei, Steenbras and Wemmershoek Dams threatened to exceed supply and it has been envisaged that the construction of a new dam would go some way towards solving this problem. The proposed Skuifraam Dam will be situated on the Berg River in the Western Cape Province, some 6.5 km south-west of Franschhoek. Water to be released from this dam is intended for irrigation as well as urban usage.

River modelling of the Berg River has been undertaken, using the hydrodynamic river flow model, DUFLOW (Section 2 of this Volume). In order to link the reservoir model to the river model, it was required that the water quality and quantity outputs from CE-QUAL-W2 have to be fed into DUFLOW as upstream boundary conditions. The water quality constituents of concern are phosphates, temperature, TDS and dissolved oxygen. Reservoir spills as well as the environmental flow releases are important flow inputs to DUFLOW.

CHAPTER TWO
PREPARATION OF INPUT PARAMETERS FOR SKUIFRAAM DAM

2.1 GEOMETRIC DATA

NB : For a more detailed discussion of the work covered by this chapter refer to Volume 1: Section3 - Chapter 2 of the Main Report on CD

The geometric description of the water body defines the finite difference matrix which allows the momentum and heat transfer equations to be solved numerically. The information required to perform this task was obtained from a 1:50 000 topographical map of the area and an area-capacity table obtained from the Department of Water Affairs (DWAF). The following procedure was followed:

- The full supply area of the proposed reservoir was digitised from a 1:50 000 topographical map.

- The reservoir was then divided into a number of longitudinal segments along the flow path. The user's manual suggests that the segment length should be between 500 m and 5000 m. As a first attempt, 17 segments were selected, with the segment length varying between 250 m and 500 m. These segment lengths proved to be too small and resulted in very long computer run-times. Eight active segments of lengths between 500 m and 1000 m were eventually selected (see **Figure 2.1**).

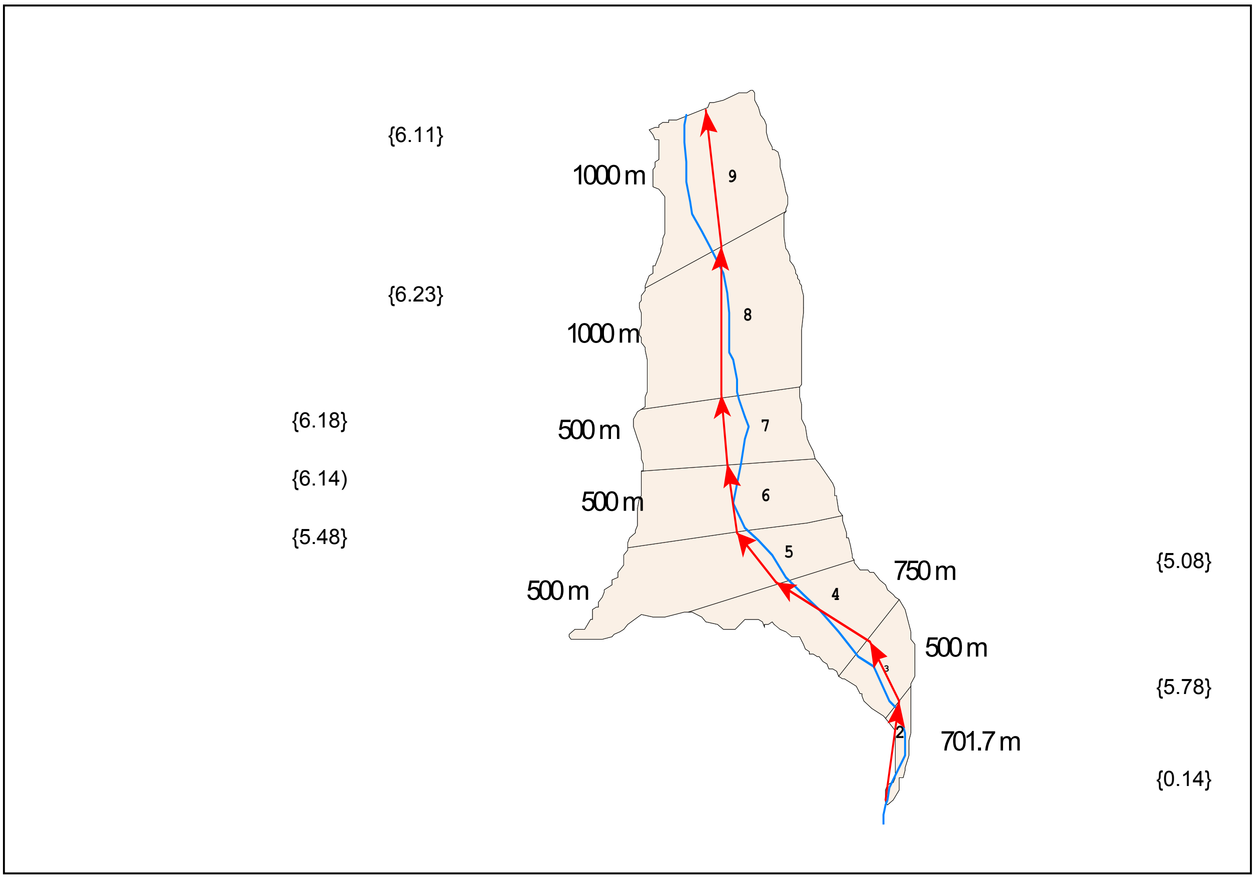

Figure 2.1 : Segments of proposed Skuifraam Dam
{ } = orientation in radians

- The reservoir was then divided into vertical layers extending from the top water level to the bottom of the reservoir. The user's manual suggests a layer height of between 2 m and 5 m. A uniform layer height of 2 m was selected for this application.

- The “width” of each cell within the matrix was obtained by dividing the area for each segment at a specific contour value by the length of the segment.
- The widths of the cells for which there was no direct information was obtained by interpolating between the known contours.
- The orientation of each segment was obtained by measuring the direction of a line drawn from the centre of a segment to the centre of the following segment.

It should be kept in mind that the bathymetric data is only a mathematical representation of reality and should be tested to confirm its description of the reservoir. F**igure 2.2** shows the agreement between the area-capacity table and the simulated values. The graph shows that the correspondence between the mathematical description and the measured reservoir volumes is favourable.

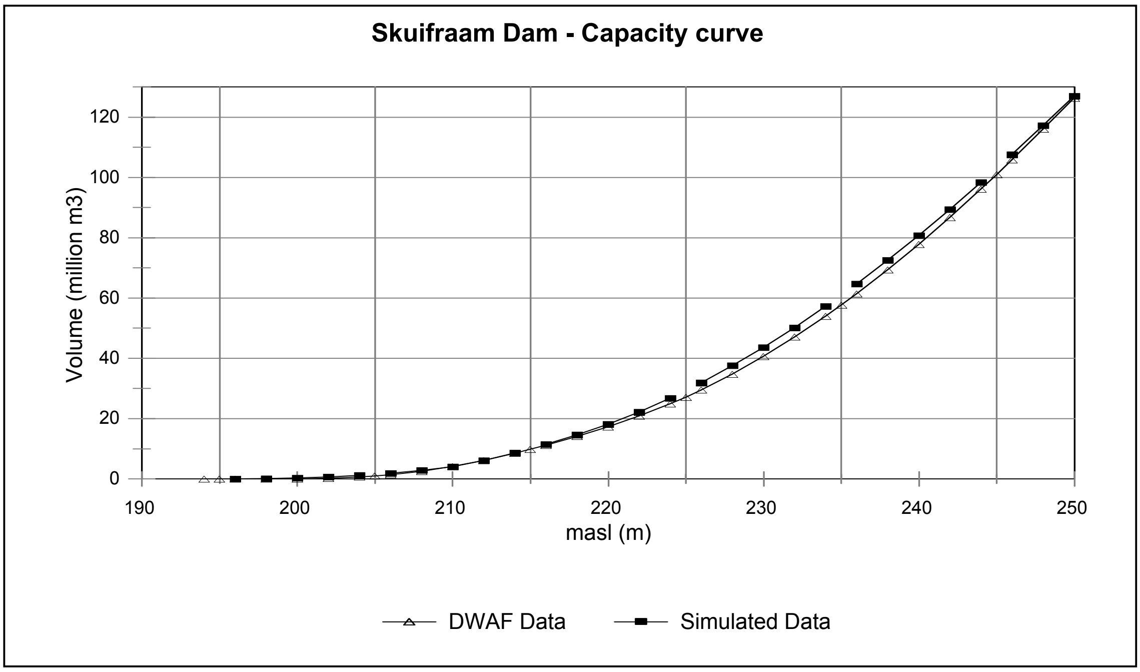

Figure 2.2 : Comparison between measured and simulated data for the proposed Skuifraam Dam

2.2 INITIAL CONDITIONS

These conditions describe the constituent and temperature profiles which exist within the reservoir at the start of the simulation period and can be specified either as a single value or a vertical profile or a longitudinal profile. Since Skuifraam Dam has not been built, these profiles cannot be measured. To obtain a reasonable estimate of the profile the model was run from 1 October 1993 to 1 November 1994 (with a single value as the starting condition) and the profile that existed on 1 October 1994 was then substituted to represent typical conditions at the start of the simulation period. The parameters modelled include temperature, total dissolved solids (TDS), phosphate and dissolved oxygen (DO) content.

The position of the inflows to the reservoir were also considered as starting conditions and for this application the flow from the Wolwekloof River (shown in **Figure 2.1**) had been combined with the flow from the Berg River to effectively create a single mainstem inflow. The feasibility study for the proposed Skuifraam Dam indicated the need to pump water into the reservoir from the Skuifraam supplement scheme (located downstream of the proposed Skuifraam Dam), while water from Theewaterskloof Dam entered Skuifraam Dam from the tunnel (DWAF, 2000). The Skuifraam supplement inflow was treated as a point source inflow and tentative positioning of this inflow was undertaken. Releases from Skuifraam Dam include the base flow irrigation and environmental releases, transfers to Theewaterskloof Dam and spill from the dam. In this application the transfer was modelled as a lateral withdrawal at the dam wall. All other releases were modelled as flow through outlets.

2.2.1 Meteorological Data

This data includes the daily varying values for air temperature, dew point temperature, cloud cover, wind speed and wind direction. For air temperature, the closest weather stations recording temperature were situated at Jonkershoek and Villiersdorp. The information for these stations was obtained from the South African Weather Bureau (SAWB) and extended from 1 August 1993 to 31 December 1999. The closest dewpoint temperature measuring station and cloud cover measurements was located at Cape Town International Airport. Wind speed data was obtained from Paarl and Villiersdorp. Wind speeds recorded at Villiersdorp were higher than those recorded at Paarl. Due to the sensitivity of the model to wind speed, two stability scenarios were modelled, a more stable stratification using Paarl data and a less stable stratification using wind data from Villiersdorp.

2.2.2 Upstream Boundary Conditions

This data includes the flow rates and temperatures of the incoming streams, as well as the time varying concentrations of the constituents. Data for the inflow was readily available on a daily basis, but constituent data was only available on a two-weekly basis and a substantial amount of infilling was required to produce a daily time series. The flow rates of the inflows from the Skuifraam Supplement (SS) and from Theewaterskloof Dam (TWD) have been obtained from the Skuifraam system analysis report (DWAF, 2000).

Constituent data for the inflowing streams required substantial infilling. The method used to infill the upstream constituent data was described in the Amatole Water Resources System Analysis study report (DWAF,1998) and will not be discussed in this report.

The temperature for the inflowing Berg River (at G1H004Q01) was measured every 7 to 14 days and the data was infilled by using the following relationship :

$\mathbf{y_t = A * (\cos \omega t + B)}$ where,
y_t = Temperature (°C) value of function at time (t)
ω = 360° / number of samples per year
A, B = Constants

At gauging station G1H004Q01 the relationship is: $\mathbf{y_t = 6.2 * (\cos (t) - 31450) + 16.5}$

2.2.3 Flow Rates and Patterns of Releases

Since Skuifraam Dam has not been built yet, no measured data is available for the withdrawal and release flow rates. These rates were, however, estimated in a study focusing on the sustainable yield obtainable from the Dam (DWAF, 2000). It should be noted that the simulation in this yield exercise only extended up to the year 1988 and did not overlap with the meteorological data set (1 October 1993 - 31 March 1997) used in this study. In this application the values for 1988 have been assumed to apply for the subsequent years.

To determine the spill flow rate from the dam, the daily reservoir volume balance model, **DAYRESIM** (Ninham Shand in-house software), was implemented. The same flow data implemented in **CE-QUAL-W2** was used in the volume balance reservoir model.

The inflow rates of the Theewaterskloof transfer as well as the Skuifraam Supplement Scheme were considered in the water balance, even though they were small in comparison to the Berg River inflow. With time, however, the volume contribution of these minor inflows could become more significant.

It is vitally important to assess the validity of the water balance before the inflow and outflow files are used as inputs to **CE-QUAL-W2**, because the model does not account for any spill, unless it is explicitly specified[1]. Failure to do this would result in an artificial build-up of water above the full supply height with the subsequent misrepresentation of water quality, temperature and flow patterns within the reservoir.

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[1] In version 3 of the model, this problem has been solved and spill is calculated if the water level increases beyond the full supply level.

CHAPTER THREE
SIMULATION RESULTS

3.1 SELECTION OF METEOROLOGICAL DATA SET

Both meteorological data sets were tested before applying the model to evaluate scenarios. The model simulations were first performed with the temperatures measured at Jonkershoek and the wind speed measured at Paarl and then with temperatures measured at Villiersdorp and wind at Villiersdorp. The site for the proposed dam is relatively sheltered and it is reasonable to assume that the full wind effect of Villiersdorp and Paarl will not be experienced at the Dam. With this in mind it should be noted that the wind effect at Jonkershoek and Villiersdorp have been multiplied by factors 0.8 and 0.5 respectively to reduce the mixing effect of wind on the dam to a realistic level.

A comparison of the time-depth plots and profile plots for winter and summer suggested that both temperature data sets give rise to almost similar profiles and that meteorological data obtained from Jonkershoek and Paarl is the more conservative data set. It was thus decided to use this data set in all subsequent model runs.

3.2 INTERPRETATION OF SIMULATION RESULTS

The following coefficients in **Table 3.1** were used in modelling the hydrodynamics and the temperature of the system.

Table 3.1 : Calibration coefficients for hydrodynamics and temperature

COEFFICIENT	UNIT	VALUE USED IN SIMULATION
Horizontal Eddy Viscosity	m^2/sec	1.0
Horizontal Eddy Diffusivity	m^2/sec	1.0
Chezy friction coefficient	$m^{0.5}$/sec	70.0
Wind Sheltering coefficient	dimensionless	0.8
Fraction of solar radiation absorbed in surface layer	dimensionless	0.7
Extinction coefficient for pure water	m^{-1}	0.45
Extinction coefficient for inorganic solids	$m^3m^{-1}g^{-1}$	0.05
Extinction coefficient for organic solids	$m^3m^{-1}g^{-1}$	0.2

The Horizontal Eddy viscosity, Chezy friction coefficient and wind sheltering coefficient affect the hydrodynamics and heat transport of the system, while the other coefficients have a direct influence on the water temperature. It should be noted that the heat transport and hydrodynamics are not mutually exclusive and that the flow characteristics within the dam can influence the heat transfer process.

If measured in-lake data were available for Skuifraam Dam then the simulated temperatures would have been calibrated by adjusting the coefficients above.

The water quality variables that were modelled include Phosphate, Oxygen and Total Dissolved Solids (TDS).

The **TDS** in the system was modelled as a **conservative substance**, which implies that the constituent is not affected by chemical reactions.

Phosphorus was treated as a non-conservative substance and can be accumulated or consumed/assimilated by several pathways. Phosphorus can be added to the system via the following pathways:

- Decay of dissolved organic matter (DOM) and detritus
- Algal dark respiration
- Desorption from settled sediments (only under anaerobic conditions)

and can be removed via the following:

- Algal photosynthesis
- Adsorption onto sediment particles

With this in mind it can be seen that phosphorus can only be added to the system by desorption from settled material, because no organic matter, detritus, algae or suspended sediment is included in the modelling. This effectively means that the respective concentrations of these constituents are zero and therefore their contribution to the overall rate is zero.

Dissolved oxygen was also not treated as a conservative substance and can be removed from the system via the following mechanisms:

- Transfer to atmosphere
- Algal respiration
- Nitrification
- Decay of material

It can be added to the system via the following mechanisms:

- Transfer from atmosphere
- Algal photosynthesis

From the description of the above processes it can be seen that a change in oxygen concentration can only be effected by mass transport between the atmosphere and the water interface and by the oxygen consumed during the decay of organic material on the sediment.

It should be noted that the omission of components such as algae, detritus and dissolved organic matter (DOM) may not be entirely correct, because these constituents may be present in the real situation.

CHAPTER FOUR
SCENARIO CASE STUDIES

4.1 SCENARIO CASE STUDIES

The simulation period extends from 1 October 1993 to 31 March 1997 and the configuration of the reservoir system is as follows:

1. Two major inflows, viz. main Berg River inflow and the Skuifraam Supplement Scheme inflow.
2. Meteorological Data : Temperature at Jonkershoek and wind at Paarl (wind * 0.8)
3. Two outlets viz. irrigation/environmental base releases and spills
4. Sediment oxygen demand (SOD) = 0.2 g/m^2/day (Bath *et al*, 1997)
5. Temperature and hydrodynamic coefficients as mentioned in Table 3.1

The scenarios which were evaluated relative to the control case are listed below:

Scenario 1 - SOD = 0.5 g/m^2/day - To introduce an upper limit for the SOD value.
Scenario 2 - SOD = 0.5 g/m^2/day and Skuifraam Supplement transfers entering at layer 25 (near the bottom of the dam)

4.2 PRESENTATION OF RESULTS

The variables which are changed in the scenarios above have a direct impact on the dissolved oxygen distribution in the Dam. Figures 4.1 to 4.3 (the colour version of these figures are more informative and appear on the enclosed CD) depict the time-depth plots for oxygen at the dam wall in the three scenarios at Segment 9, adjacent to the dam wall.

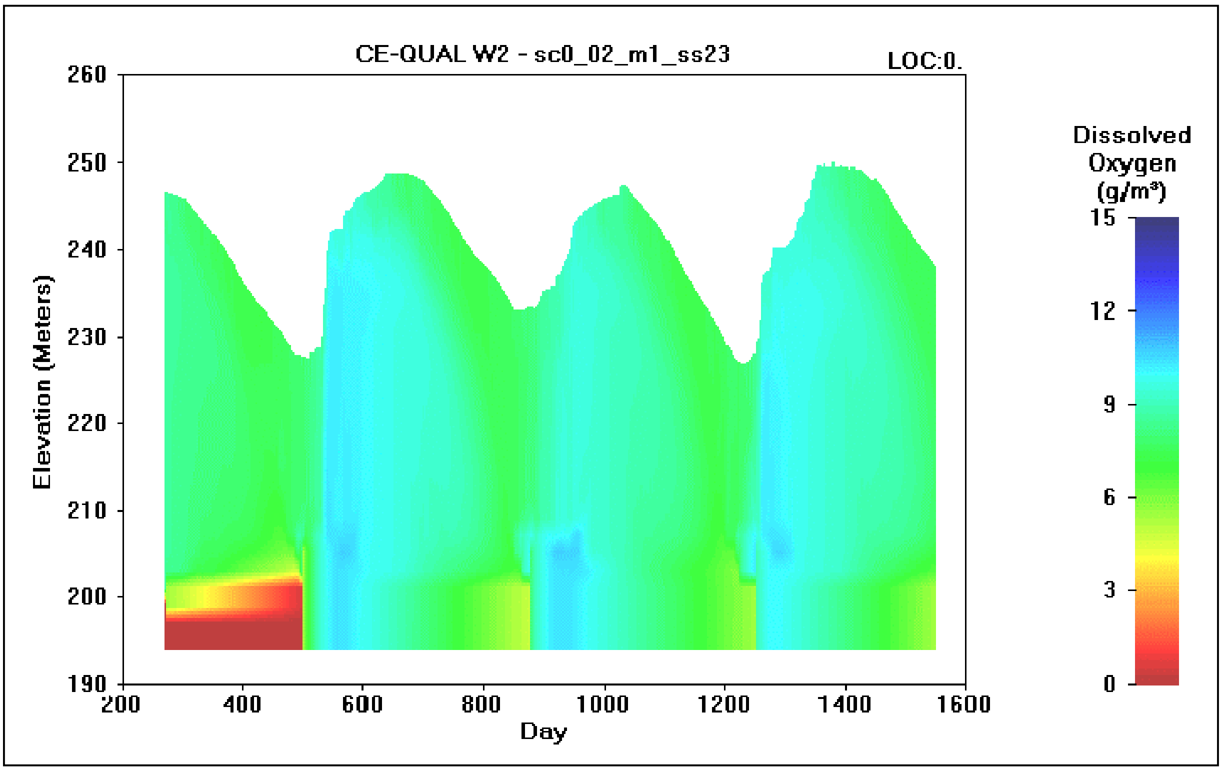

Figure 4.1 : Dissolved oxygen profile for Segment 9 in the control scenario (SOD = 0.2 G/m^2/day)

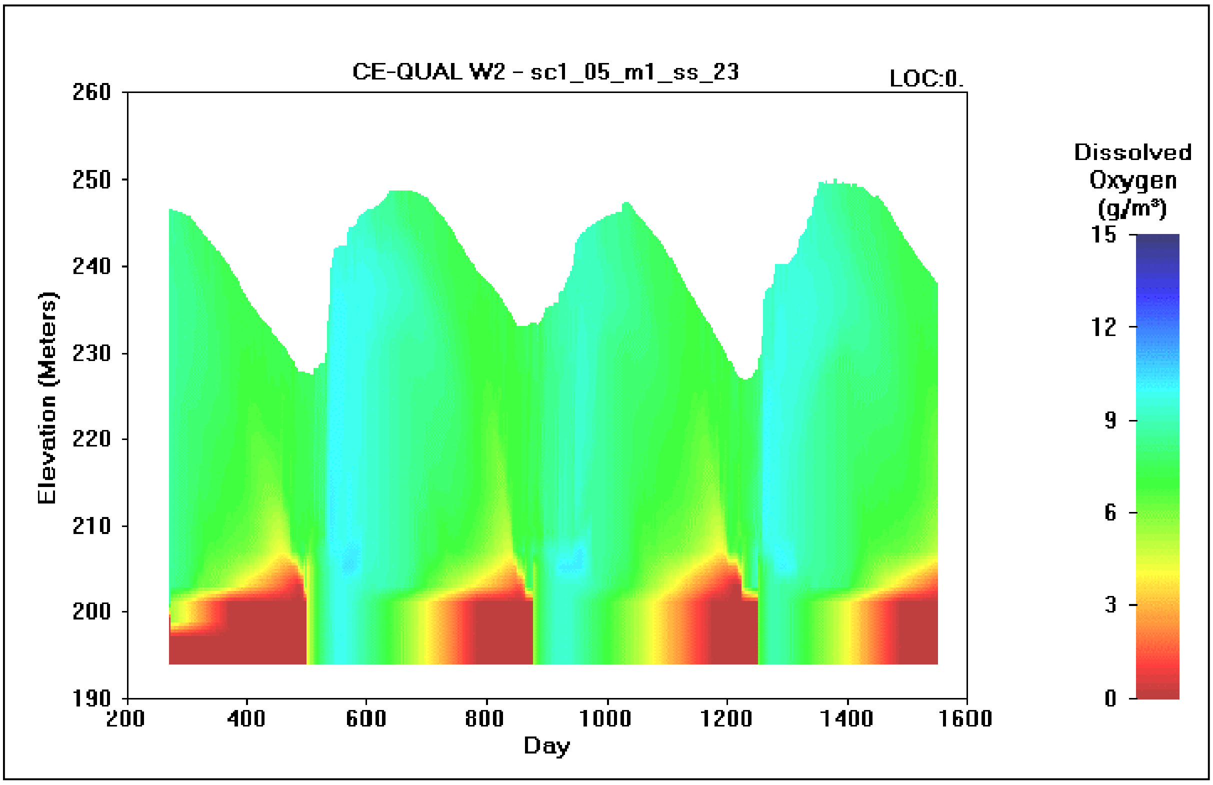

Figure 4.2 : Dissolved oxygen profile for Segment 9 in Scenario 1 (SOD = 0.5 g/m^2/day)

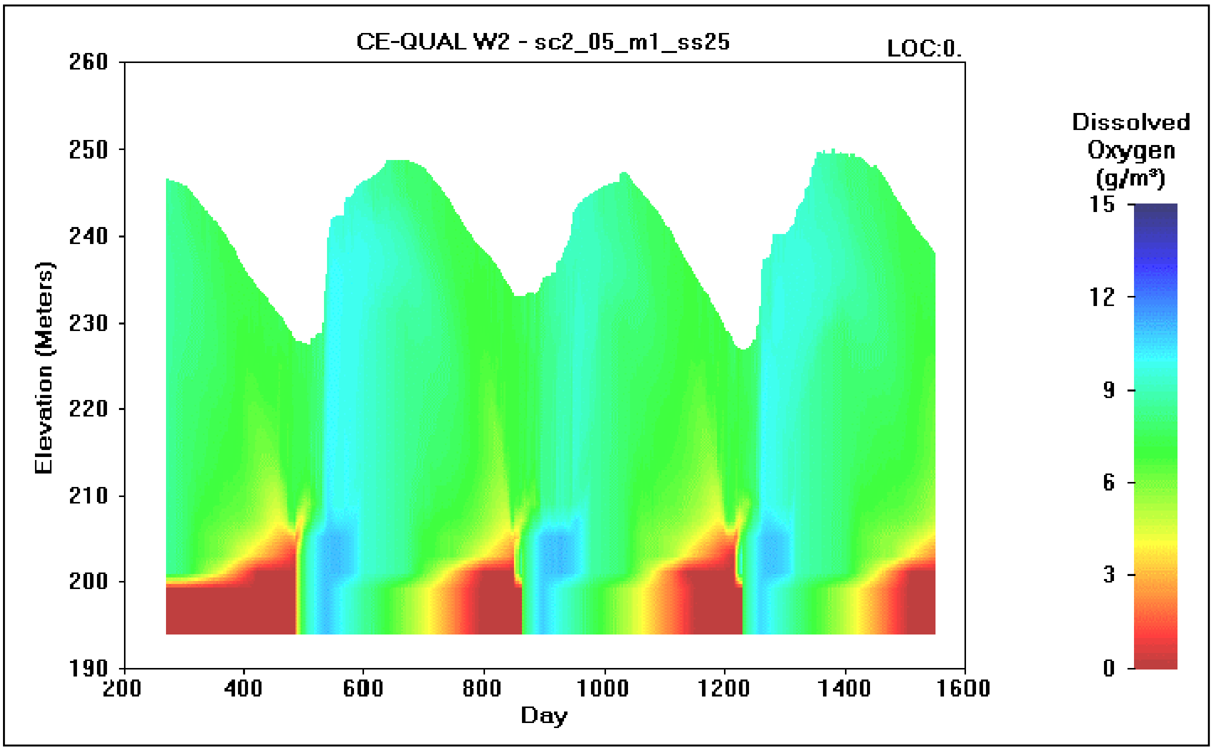

Figure 4.3 : Dissolved oxygen profile for Segment 9 in Scenario 2 (SOD = 0.5 g/m^2/day; Skuifraam Supplement entering at layer 25)

The results depicted above suggested that the model is relatively sensitive to the SOD value. With the change in SOD value from 0.2 to 0.5 g/m^2/day, the de-oxygenated layer appeared during each of the years being modelled. In addition, it can also be seen that the de-oxygenated layer protruded higher into the dam and thus closer to the outlet level (at 206 masl) of the base agricultural and environmental releases. In both the control Scenario and Scenario 1 the reservoir was completely mixed in winter, but in the control, the natural mixing which occurs after winter, was sufficient to prevent the lower portion of the reservoir from becoming completely de-oxygenated. In Scenario 1, however, the SOD rate was greater than the rate of oxygen transfer to the lower portion of the reservoir and this section subsequently became de-oxygenated. The introduction of the Skuifraam Supplement inflows at layer 25 (refer Figure 4.3) did not prevent the formation of the de-oxygenated layer. Introducing the Supplement inflows at an even lower level, however, may reduce the possibility of the formation of a de-oxygenated layer.

CHAPTER FIVE
CE-QUAL-W2 : APPLICATION

5.1 APPLICATION OF CE-QUAL-W2 : THE OPERATING LEVELS OF SKUIFRAAM DAM AND THE POTENTIAL USE OF A HIGH LEVEL SLUICE GATE FOR THE ENVIRONMENTAL FLOOD RELEASE

NB : For a more detailed discussion of the work covered by this chapter refer to Volume 1:Section 3 - Chapter 5 of the Main Report on CD

The ‘flood’ Instream Flow Requirements (IFR) releases from the proposed Skuifraam Dam can either be made through large sleeve valves situated near the base of the dam or through sluice gates located higher up the wall. **Table 5.1** summarizes the proposed ‘flood’ (or high) flow and ‘base’ (or low) flow’ IFR releases for Skuifraam Dam. This brief study investigates how often the water level in the dam will be high enough to make releases from gates situated 10, 20 and 30 metres below the dam’s Full Supply Level (FSL). The report also compares the water quality of the base release from RL206 (44m below the FSL) (**DWAF, 2000**) with the water quality of releases from the gates (higher up the wall).

Table 5.1 : In-Stream Flow Requirements Release Pattern (Skuifraam Dam) (DWAF, 2000)

MONTH	AVERAGE YEAR					DROUGHT YEAR				
	LOW FLOW		HIGH FLOW [1]			LOW FLOW		HIGH FLOW		
	m^3/s	$m^3 \times 10^6$	m^3/s	$m^3 \times 10^6$	Days	m^3/s	$m^3 \times 10^6$	m^3/s	$m^3 \times 10^6$	Days
October	0,8	2,14				0,5	1,34	0,8	0,07	1
November	0,5	1,30	4,5	0,5	1	0,3	0,78			
December	0,4	1,07	4,5	0,5	1	0,16	0,43			
January	0,3	0,80				0,16	0,43	0,3	0,03	1
February	0,3	0,73				0,16	0,39			
March	0,3	0,80				0,16	0,43			
April	0,5	1,30	5,0	0,8	5	0,30	0,78			
May	1,0	2,68				0,50	1,34			
June	1,6	4,15	30,0	4,5	7	0,80	2,07	15	3,0	7
July	0,6	4,29	65,0	9,8	7	0,80	2,14			
August	1,6	4,29				1,0	2,68			
September	1,2	3,11				1,0	2,59			
TOTAL		16,66		16,1		0,5	15,40		3,10	
	$42,8\ m^3 \times 10^6$					$42,8\ m^3 \times 10^6$				

Note 1 : The flow rate for high flow releases is given as the maximum daily average - the peak hourly flow could be over twice the maximum daily average flow. The actual release pattern should mimic a natural event occurring at the time.

5.2 OPERATING SCENARIOS FOR THE PROPOSED SKUIFRAAM DAM

The preparation and configuration of CE-QUAL-W2 has been discussed in Chapter 2 of this report and will not be discussed in this chapter. Using the observed inflow from 1993 to 1997, two scenarios were developed:

- **Stratified[1] Scenario** - Demands are kept low and mixing is not promoted (dam levels remain high)
- **Mixed Scenario** - Demands are kept high and mixing is promoted (dam levels are drawn down).

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[1] Stratified refers to the reservoir not being well-mixed. Definite layers (strata) with distinctive water quality and temperature characteristics are evident

Table 5.2 below summarizes the differences between the two scenarios.

Table 5.2 : Comparison of the Scenarios promoting stratification and mixing

Parameter	Stratified Scenario	Mixed Scenario
Volume transferred from the Supplement (million m^3/a)	9.4	40
Reduced Level at which Supplement water introduced to Skuifraam Dam (m)	240-50	206-8
Magnitude of agricultural releases (million m^3/a)	25.3	51.5
Reduced level of IFR Flood Release (m)	206/220/230/240	220
Magnitude of IFR Release (million m^3/a)	18.5	42
Volume transferred to Theewaterskloof (million m^3/a)	6.3	63
Wind	Paarl*0.8	Villiersdorp*0.8 (windier)
Air Temperature	Jonkershoek (warmer)	Villiersdorp

The flow in the abovementioned scenarios was based on the ‘present day’ (1999) scenario. The agricultural release in the ‘stratified scenario’ assumed that the agricultural release would be curtailed to half the present day consumption, as would occur during a drought. Similarly, the IFR release in the stratified scenario was reduced from the damage control (42 m^3*10^6/a) to the drought (18.5 m^3*10^6/a). The annual transfer from the Supplement to Skuifraam Dam in the stratified scenario was the third lowest annual transfer modelled for the ‘present day’ scenario in the yield analysis which was performed as part of this study. The smaller transfers during 1975 and 1976 occurred during wet years when transfers were reduced to avoid spillage over the Skuifraam and Theewaterskloof Dams. Conversely, the transfers in the ‘mixed scenario’ were similar to the high transfers modelled in 1947-49. The flows transferred from Skuifraam Dam to Theewaterskloof Dam in the stratified scenario (6.3 m^3*10^6/a) and the mixed scenario (63 m^3*10^6/a) is similar to the minimum and maximum transfers in the present day scenario

The following additional assumptions, necessary to configure the model, could affect the results significantly. The ground temperature at the bottom of the dam was assumed to be 13.5° C and the sediment oxygen demand was assumed to be 0.2g/m^2/day, a value used for a number of other dams analysed in South Africa (Bath, 1998).

An analysis of the simulation results for the two scenarios indicated the following:

5.2.1 Dissolved Oxygen

- *Flood Releases* : In both the stratified and mixed scenarios the dissolved oxygen in the IFR flood releases made from RL220 did not drop below 7mg/l.
- *Base Flow* : In the stratified scenario the dissolved oxygen level might drop below 7mg/l to less than 50% of the saturated level. An anoxic zone develops just below the base release outlet level. In reality this zone may be higher and measures should be implemented to break down this zone and to avoid releasing this anoxic water. However, it is unlikely that the low oxygen in the outflow would affect the downstream river. The outflow valve is designed to spray the water and this should result in good re-oxygenation and acceptable dissolved oxygen levels in the downstream river reach.

5.2.2 Temperature

The average temperatures for the summer (November-April) and winter (May – October) seasons in the two scenarios are summarized in Table 5.3.

Table 5.3 : Comparing the seasonal temperature of the inflow with the temperatures of the releases at different levels

Scenario	Season	Temperatures at Different Positions				
		Inflow	RL240: 10 m below FSL	RL230: 20 m below FSL	RL220 : 30 M below FSL	RL206 : Base Releases
Stratified	Summer	20.6	22.8	15.7	14.6	14.2
	Winter	13.1	17.8	16.8	14.8	14.0
Mixed	Summer	20.6			19.2	17.5
	Winter	13.1			15.9	14.1

- o *Flood Releases :* In the 'stratified scenario' the average temperatures 10 metres below the full supply level are up to 5 degrees warmer than the incoming streamflow. Releases from lower down – say 30 meters below the full supply level, are about 2 degrees warmer than the inflow. In the mixed scenario the releases from lower down are about 3 degrees warmer than the inflow. However, in late winter the temperature increase in the dam lags behind that of the inflow so that the release temperatures are colder than the inflow temperatures.
- o *Base Flow :* In summer the baseflow releases of the 'stratified scenario' are about 6 degrees colder than the incoming streamflow while in the 'mixed scenario' the baseflow releases are about 3 degrees colder than the incoming streamflow. However, releases from higher up can be at the same temperature or even warmer than the inflow during summer. In winter the average temperature of the baseflow releases is within a degree of the incoming streamflow, though at times the temperature of the baseflow can exceed the incoming stream temperature by 4 degrees.

5.2.3 Bottom Inlet from Supplement

In the mixed scenario the water from the Supplement diversion was pumped in near the bottom of the Skuifraam Dam (RL206), introducing oxygenated water and promoting mixing at that level. This strategy did not appear to work during October (Julien days 273 to 303), because the water was transferred immediately to Theewaterskloof Dam (short-circuit) by pumps acting at RL 213 before it had an opportunity to mix. In this case the inflow from the Supplement should be introduced as low and as far from the inlet of the pumps transferring water to Theewaterskloof Dam as possible, to encourage mixing.

5.3 CONCLUSIONS

Table 5.4 summarizes the frequency of making releases from various off-take levels and gives some indication of the dissolved oxygen and temperature of the released water. One can draw the following conclusions from **Tables 5.3 and 5.4:**

- ► If sluice **gates** are used for IFR 'flood' releases then the gates should be located below RL230 to be able to make the releases frequently enough. At RL240 and above the flood releases in July and June can only be made for about half of the time. During drier periods a few years may elapse before a flood release can be made. A gate at RL230 will be able to make releases at a more acceptable frequency.

- ► During summer and until some time in June, releases from the upper zones of the dam will be considerably warmer than the streamflow, which may impact on the riverine ecology. Later in winter, possibly in July, the temperatures of the releases from all levels of the dam are similar to the inflow. Thereafter, the streamflow warms up faster than the stored water so that the releases are colder than the streamflow.

- ► A multilevel intake tower with intakes at RL206, RL210 and higher should be used for base releases. There is a danger of anoxic base releases and an intake tower to take water from a higher level should be considered. Should the sediment oxygen demand be greater than the 0.2mg/l assumed, then the depth of the lower anoxic layer will increase. During summer the baseflow releases from Skuifraam Dam can average about 6 degrees C lower than the inflow, which may also impact on the riverine ecology. **Table 5.4** shows how summer temperature at the dam wall varies with time and depth. A multilevel intake tower will enable water from the appropriate level to be released to keep summer baseflow releases at the same temperature as the inflow.

- Introduce the transfer from the Supplement Scheme at as low a level as possible into Skuifraam Dam to help break up the anoxic zone. It would also be useful to be able to introduce water from the Supplement as low as possible into Skuifraam Dam (even below the bottom release level) when required to prevent an anoxic bottom zone from developing. The inlet for the pumps transferring water to Theewaterskloof should be positioned so that the Supplement inflows mix with the water in Skuifraam Dam and are not transferred directly to Theewaterskloof Dam.

Table 5.4 : The Probability, Dissolved Oxygen Range, and Temperature Range of IFR releases made from different levels

Reduced Level of Release	Apr				Jun				Jul			
	Frequency (%)	DO mg/l	Tem (C)	Temp relative to Inflow (C)	Frequency (%)	DO mg/l	Temp (C)	Temp relative to Inflow (C)	Frequency (%)	DO (mg/l)	Tem (C)	Temp relative to Inflow (C)
240	5	>7.5	8 to 25	+9 to 13	44	>8	12 to 20	+2 to 10	54	>8.5	12 to 15	0 to 3
230	62	>7.5	16 to 28	+0 to 12	79	>7.5	12 to 18	+2 to 8	84	>8.5	12 to 15	0 to 3
220	82	>7.5	15 to 24	-1 to +8	95	>7	12 to 16	+2 to 6	97	+7.5	12 to 15	0 to 3
206	90	>6.5	14 to 22	-2 to +6	98	>6[1]	12 to 15	+2 to 5	100	>6.5[1]	12 to 15	0 to 3

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

From the above discussion the following conclusions can be drawn:

- Two-dimensional hydrodynamic and water quality models can provide useful insight into the mixing of water and water quality variables as well as bio-chemical processes which occur within reservoirs.

- Outputs from two-dimensional models are useful in assisting decision-makers in the task of determining the water quality component of the ecological reserve.

- Regional meteorological data has proven extremely valuable as input (driving force) for CE-QUAL-W2 in the absence of site-specific meteorological data.

- Two-dimensional hydrodynamic and water quality models such as CE-QUAL-W2 require various rate constants to accurately model bio-chemical reactions. In this study it was found that the oxygen profile within dams are particularly sensitive to the Sediment Oxygen Demand (SOD) and that this data is not readily available for this type of modelling. Availability of this type of data will greatly improve the reliability of the model outputs.

- Water quality monitoring of inflowing streams is of utmost importance for water quality modelling. This study revealed the lack of stream temperature data which is an important driving force for heat transfer within the reservoir.

- The Berg River Water Quality Information System (WQIS) is a useful tool for managers and decision-makers, bringing together various modelling tools (DUFLOW and CE-QUAL-W2) and providing post-processing which allows visualization of model outputs.

6.2 RECOMMENDATION

From the above conclusions the following recommendations can be made:

- The systematic monitoring of meteorological data throughout the country should be continued and new initiatives should attempt to gather site-specific meteorological data specifically for important water storage facilities and along important river courses.

- The systematic monitoring of water quality constituents should be continued throughout the country and special attention should be given to **temperature and nutrient** data sampling.

- In September 2001 Nico Rossouw and Wageed Kamish of Ninham Shand Consulting Services attended a course on CE-QUAL-W2 (v3.1), in Portland (U.S.A) and personal contact was made with the developers of the model. It is therefore recommended that close relationship and contacts with these developers be maintained so that modelling of this type remains active in South Africa.

CHAPTER SEVEN
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VOLUME 1
APPENDIX 1

WATER QUALITY MODEL SENSITIVITY, CALIBRATION AND VERIFICATION TABLES AND GRAPHS

Table 1.1: Results of TDS Loads after calibration

	Total Load measured (tons)	Total Load simulated (tons)	% diff in total load	mean measured (g/s)	mean simulated (g/s)	Coeff of determination (R^2)	Coeff of efficiency
Low flow period							
G1H020	2577	2077	-19.4	164	132	0.84	0.13
G1H036	3204	5401	68	204	343	0.38	-2
G1H013	6078	6751	11	386	429	0.51	-0.16
G1R003	5598	7595	35	356	483	0.75	0.2
High flow period							
G1H020	13220	12729	-3.7	836	805	0.99	0.97
G1H036	39214	54475	39	2480	3445	0.89	0.74
G1H013	82042	99558	21.3	5189	6296	0.93	0.82
G1R003	81497	133148	63	5154	8421	0.94	-0.06
Yearly							
G1H020	15798	14806	-6.3	501	469	0.98	0.97
G1H036	42419	58760	41	1345	1898	0.9	0.78
G1H013	88120	106309	20.6	2794	3371	0.94	0.85
G1R003	87097	140744	61	2761	4462	0.95	0.15

Table 1.2: Results of TDS Concentration after calibration

	mean measured (mg/l)	mean simulated (mg/l)	% error in mean	Coeff of determination (R2)
Low flow period				
G1H020	62.6	43	-31	0.24
G1H036	120	136	13.8	0.47
G1H013	141	123	-12.3	0.03
G1R003	219	162	-26	0.1
High flow period				
G1H020	56.5	41	-27	0.3
G1H036	123	176.6	44	0.5
G1H013	158	196	23	0.67
G1R003	210	224	6.7	0.57
Yearly				
G1H020	59.5	42	-29	0.08
G1H036	121	156	29	0.48
G1H013	149	159	6.8	0.56
G1R003	215	193	-10	0.3

Table 1.3: Results of PO_4 Loads after calibration

	Total Load measured (tons)	Total Load simulated (tons)	% diff in total load	mean measured (g/s)	mean simulated (g/s)	Coeff of determination (R2)	Coeff of efficiency
Low flow period							
G1H020	1.02	1.07	4.7	0.065	0.068	0.39	0.15
G1H036	1.2	1.2	0.6	0.076	0.077	0.75	0.48
G1H013	1	1.4	38	0.06	0.09	0.76	0.3
G1R003	0.6	1.2	103	0.04	0.08	0.98	0.92
High flow period							
G1H020	13.9	7.9	-42	0.9	0.5	0.95	0.63
G1H036	28.6	15.9	-44	1.8	1	0.96	0.66
G1H013	48.2	21.2	-56	3	1.3	0.96	0.51
G1R003	25.6	24	-6.5	1.6	1.5	0.98	0.91
Yearly							
G1H020	14.9	9	-39	0.47	0.28	0.95	0.67
G1H036	29.8	17.2	-42	0.95	0.54	0.96	0.69
G1H013	49.3	22.6	-54	1.56	0.71	0.96	0.57
G1R003	26.2	25.2	-4	0.83	0.8	0.98	0.92

Table 1.4: Results of PO_4 Concentration after calibration

	mean measured	mean simulated	% error in mean	Coeff of determination (R2)
Low flow period				
G1H020	0.02	0.025	-0.8	0.3
G1H036	0.04	0.026	-32	0.15
G1H013	0.024	0.023	-3.4	0.2
G1R003	0.024	0.023	-5.9	0.57
High flow period				
G1H020	0.023	0.023	-32	0.68
G1H036	0.08	0.04	-55	0
G1H013	0.05	0.034	-33	0.32
G1R003	0.03	0.034	-9.8	0.25
Yearly				
G1H020	0.03	0.023	-20	0.49
G1H036	0.06	0.031	-48	0.25
G1H013	0.04	0.028	-24	0.42
G1R003	0.027	0.028	2.9	0.36

Table 1.5: Results of Temperature after calibration

	mean measured	mean simulated	% error in mean	Std Dev measured	Std Dev simulated	Coeff of determination (R2)
Low flow period						
G1H020	24	23	-4.4	2.5	3	0.92
G1H036	24.6	24	-2.9	2.75	2.73	0.81
G1H013	24.2	24.5	1.5	2.52	3.57	0.85
G1R003	25	24.7	-1.6	2.5	3.5	0.85
High flow period						
G1H020	14	13	-7	2.56	2.54	0.92
G1H036	13.6	12.8	-5.9	2.9	2.75	0.81
G1H013	14.1	12.5	-11	2.8	2.9	0.8
G1R003	15.3	12.5	-18	2.77	2.87	0.83
Yearly						
G1H020	19	17.98	-5.4	5.62	5.7	0.98
G1H036	19.1	18.3	-3.9	6.2	6.5	0.95
G1H013	19.1	18.5	-3.1	5.73	6.9	0.96
G1R003	20.15	18.5	-8	5.56	6.9	0.96

Table 1.6: Results of Oxygen after calibration

	mean sat. oxygen	mean simulated	% error in mean	Std Dev sat. Oxygen	Std Dev simulated	Coeff of determination (R2)
Low flow period						
G1H020	8.65	8.73	0.9	0.45	0.44	0.98
G1H036	8.55	8.61	0.7	0.52	0.5	0.97
G1H013	8.4	8.5	0.6	0.52	0.53	0.98
G1R003	8.3	8.9	7.6	0.51	0.42	0.9
High flow period						
G1H020	10.5	10.3	-1.8	0.62	0.59	0.93
G1H036	10.7	10.6	-0.6	0.72	0.86	0.7
G1H013	10.8	10.7	-0.2	0.79	0.76	0.88
G1R003	10.8	10.8	0	0.83	0.82	0.85
Yearly						
G1H020	9.6	9.55	-0.6	0.95	0.96	0.98
G1H036	9.62	9.61	-0.06	1.23	1.22	0.93
G1H013	9.6	9.62	0.15	1.35	1.31	0.98
G1R003	9.55	9.8	3.3	1.42	4.14	0.94

Table 1.7 : Results of TDS Loads after Verification

	Total Load measured (tons)	Total Load simulated (tons)	% diff in total load	mean measured (g/s)	mean simulated (g/s)	Coeff of determination (R2)	Coeff of efficiency
Low flow period							
G1H020	2683	2669	-0.5	171	170	0.81	0.41
G1H036	3738	4007	-7.2	238	255	0.9	0.8
G1H013	7008	6137	-12	446	390	0.93	0.84
G1R003	6811	6795	-0.2	433	432	0.92	0.75
High flow period							
G1H020	14132	6767	-52	894	428	0.93	0.41
G1H036	N/A						
G1H013	59589	51082	-14	3769	3231	0.92	0.76
G1R003	61961	70959	14.5	3919	4488	0.91	0.8
Yearly							
G1H020	16815	12030	-28	533	381	0.95	0.73
G1H036	**N/A**						
G1H013	66597	57218	-14	2112	1814	0.92	0.82
G1R003	68772	77756	13	2181	2465	0.92	0.85

Table 1.8 : Results of TDS Concentration after Verification

	mean measured (mg/l)	mean simulated (mg/l)	% error in mean	Coeff of determination (R2)
Low flow period				
G1H020	52.3	47	-21	0.23
G1H036	124	96	-27	0.22
G1H013	137	99	-27	0.3
G1R003	191	111	-41	0.11
High flow period				
G1H020	65	47	-27	0.04
G1H036	N/A			
G1H013	148	139	-7	0.58
G1R003	166	147	-12	0.47
Yearly				
G1H020	62	47	-24	0.04
G1H036	N/A			
G1H013	143	119	-17	0.42
G1R003	179	129	-27	0.22

NOTE *: For station G1H036 the flow measurements are incomplete from the 3rd of July to end September, and the statistical comparison have for this reason not been included.*

Table 1.9: Results of PO_4 Load after Verification

	Total Load measured (tons)	Total Load simulated (tons)	% diff in total load	mean measured (g/s)	mean simulated (g/s)	Coeff of determination (R^2)	Coeff of efficiency
Low flow period							
G1H020	1	1.1	5	0.06	0.06	0.25	-0.24
G1H036	2	1.1	-46	0.13	0.07	0.85	0.39
G1H013	1.4	1.5	11	0.09	0.098	0.86	0.58
G1R003	0.6	1.5	159	0.04	0.1	0.93	-4.2
High flow period							
G1H020	6	5.3	-11	0.38	0.34	0.43	0.15
G1H036	N/A						
G1H013	18.3	15.1	-18	1.2	0.95	0.93	0.8
G1R003	14.8	17.9	21	0.94	1.14	0.92	0.79
Yearly							
G1H020	7	6.3	-9	0.22	0.2	0.5	0.33
G1H036	N/A						
G1H013	19.7	16.6	-16	0.62	0.53	0.94	0.84
G1R003	15.4	19.5	26.5	0.49	0.62	0.93	0.86

Table 1.10: Results of PO_4 Concentration after Verification

	mean measured (mg/l)	mean simulated (mg/l)	% error in mean	Coeff of determination (R2)
Low flow period				
G1H020	0.02	0.017	-15	0.18
G1H036	0.062	0.019	-69	0.3
G1H013	0.02	0.019	-15	0.31
G1R003	0.02	0.021	3.4	0.26
High flow period				
G1H020	0.033	0.029	-8.8	0.14
G1H036	N/A			
G1H013	0.043	0.036	-15	0.15
G1R003	0.032	0.038	16	0.72
Yearly				
G1H020	0.026	0.024	-11	0.44
G1H036	N/A			
G1H013	0.031	0.028	-10	0.43
G1R003	0.026	0.029	12	0.72

NOTE : *For station G1H036 the flow measurements are incomplete from the 3rd of July to end September, and the statistical comparisons have for this reason not been included.*

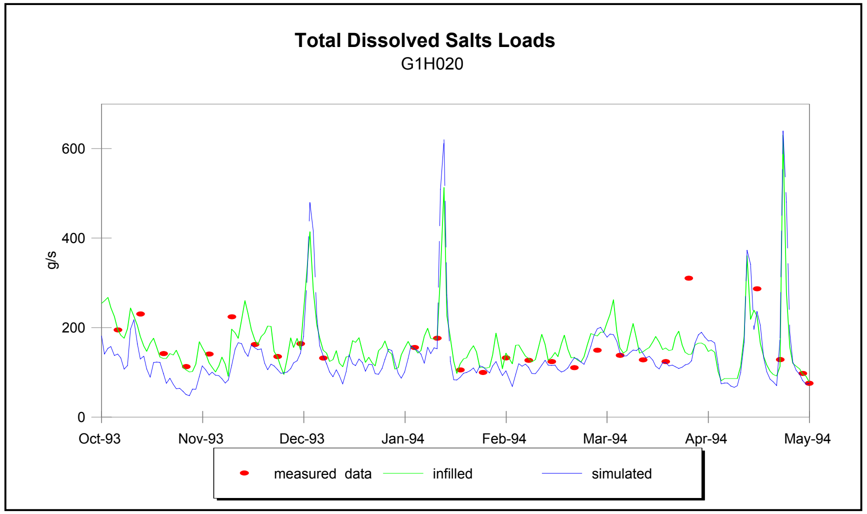
Table 1.11: Results of Temperature after Verification

	mean measured	mean simulated	% error in mean	Std Dev measured	Std Dev simulated	Coeff of determination (R^2)
Low flow period						
G1H020	24	23.1	-3.5	2.6	3	0.94
G1H036	24.7	24.3	-1.5	2.8	3.6	0.84
G1H013	24.2	25.7	5.9	2.6	4.2	0.75
G1R003	25.1	27.1	8.3	2.5	4.4	0.72
High flow period						
G1H020	14.1	13.3	-5.4	2.7	2.8	0.94
G1H036	13.6	13.4	-1.8	2.9	3.1	0.85
G1H013	14	13.2	-5.7	2.8	3.9	0.78
G1R003	15.2	13.1	-13	2.8	3.4	0.83
Yearly						
G1H020	19	18.2	-4.2	5.6	5.7	0.98
G1H036	19.1	18.8	-1.6	6.2	6.4	0.96
G1H013	19.1	19.4	1.6	5.8	7.5	0.93
G1R003	20.1	20.1	0	5.6	8.6	0.94

Table1.12: Results of Oxygen after Verification

	mean saturation oxygen	mean simulated	% error in mean	Std Dev sat. Oxygen	Std Dev simulated	Coeff of Determination (R2)
Low flow period						
G1H020	8.54	8.66	1.4	0.51	0.51	0.96
G1H036	8.3	8.36	1	0.55	0.57	0.93
G1H013	8.2	8.23	1.4	0.52	0.53	0.94
G1R003	8.3	8.2	1	0.51	0.52	0.93
High flow period						
G1H020	10.5	10.34	-1.5	0.68	0.7	0.89
G1H036	10.45	10.4	-0.4	0.79	0.82	0.79
G1H013	10.54	10.47	-0.75	0.94	0.96	0.76
G1R003	10.8	10.6	-1.8	0.95	1.1	0.75
Yearly						
G1H020	9.53	9.51	-0.2	1.15	1.04	0.97
G1H036	9.37	9.39	0.2	1.3	1.25	0.95
G1H013	9.35	9.36	0.14	1.43	1.37	0.94
G1R003	9.55	9.4	-1.5	1.4	1.8	0.92

Figure 1.1



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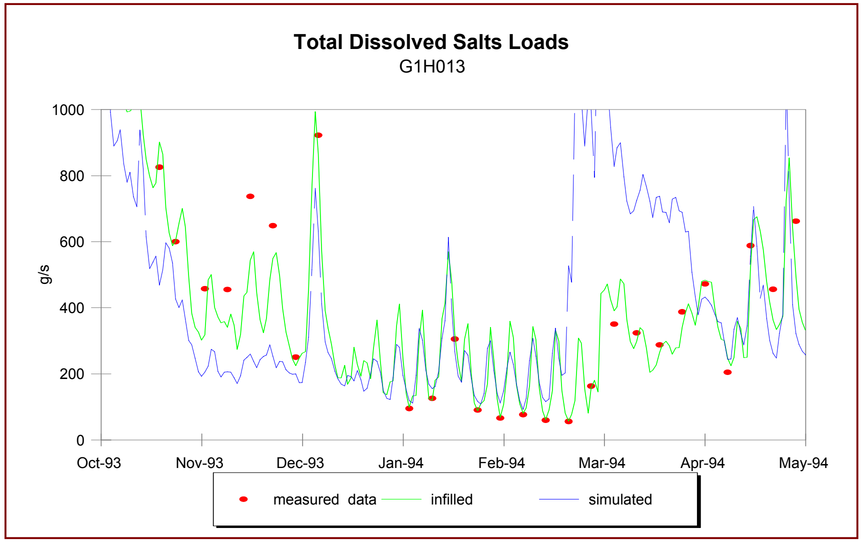

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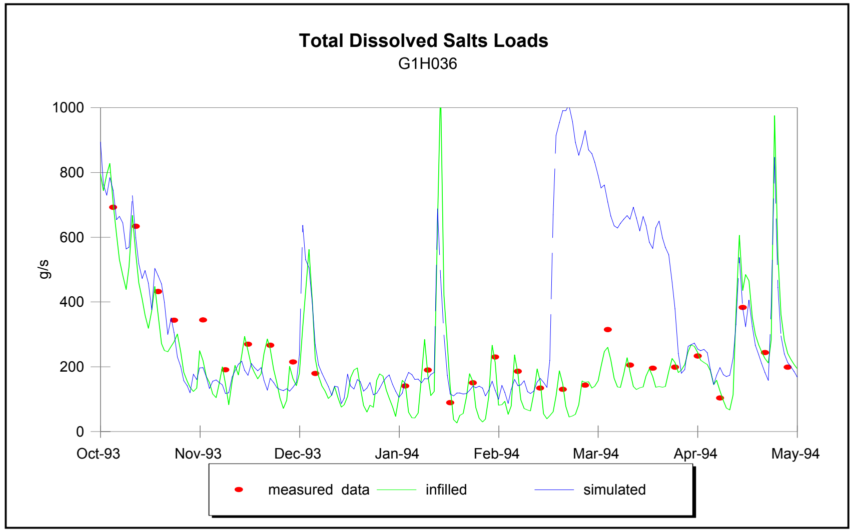

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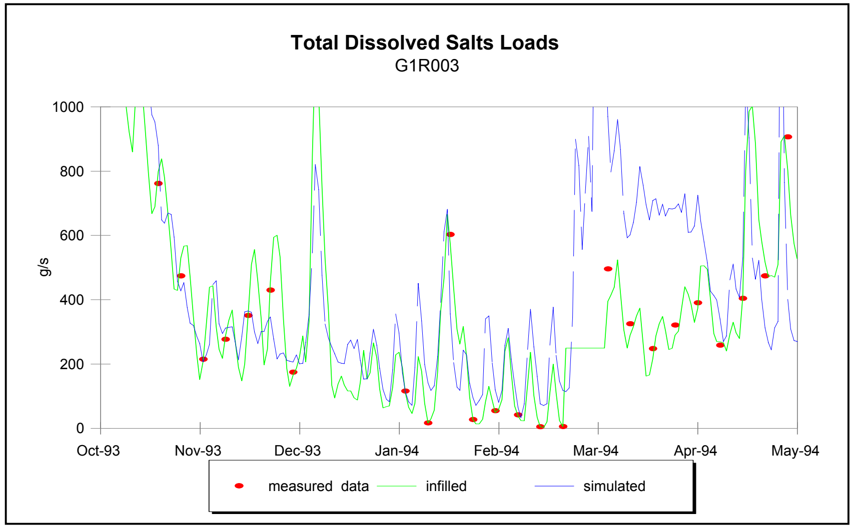

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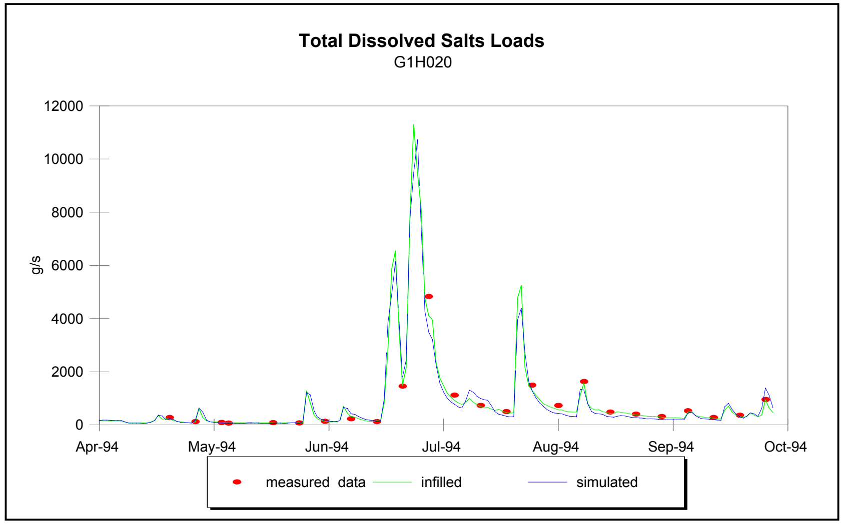

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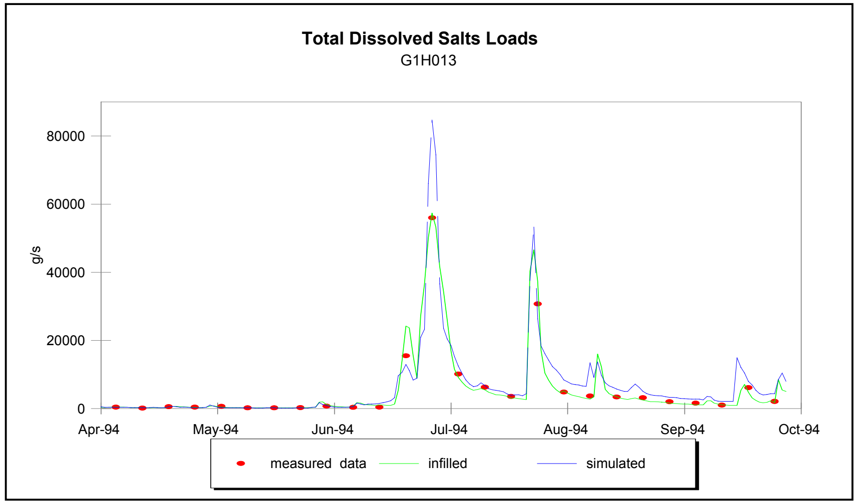

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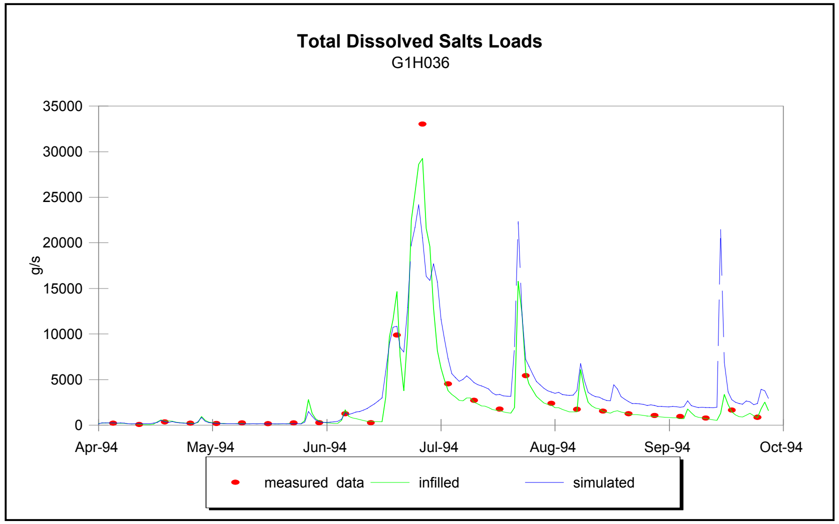

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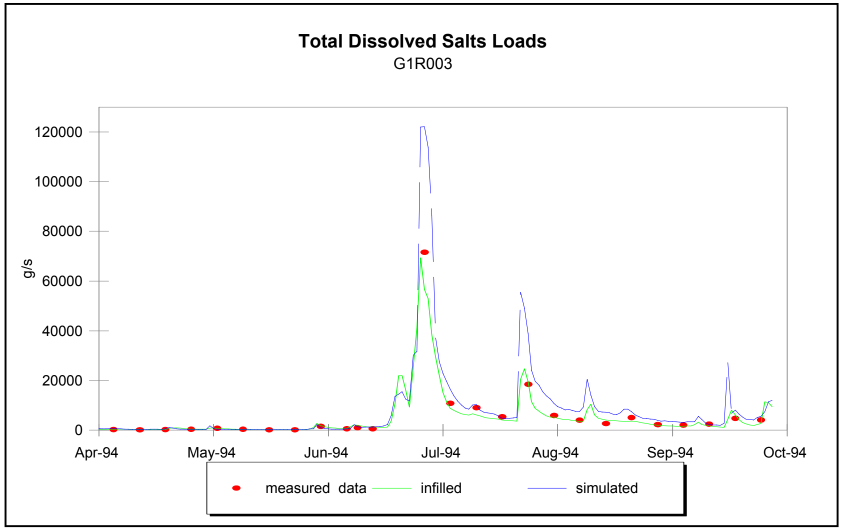

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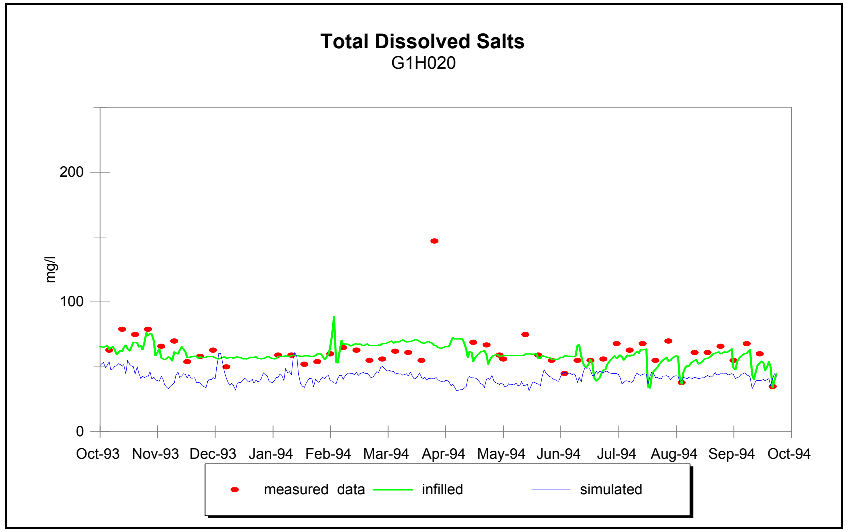

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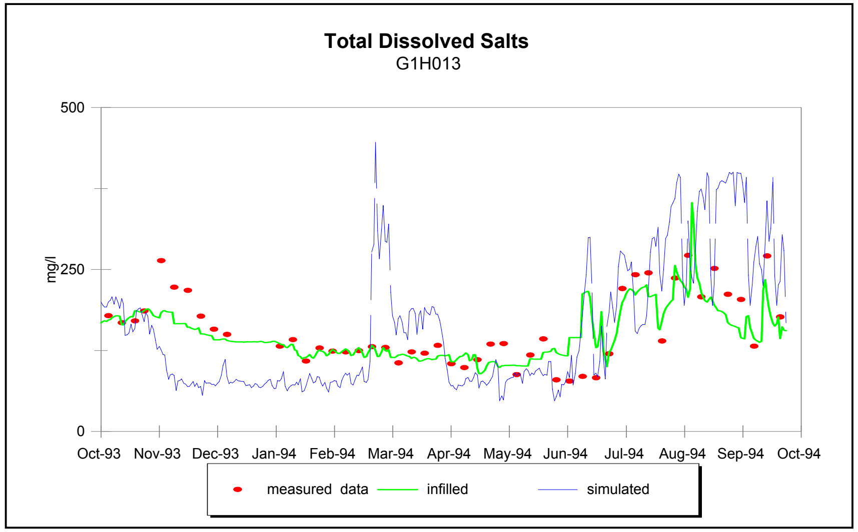

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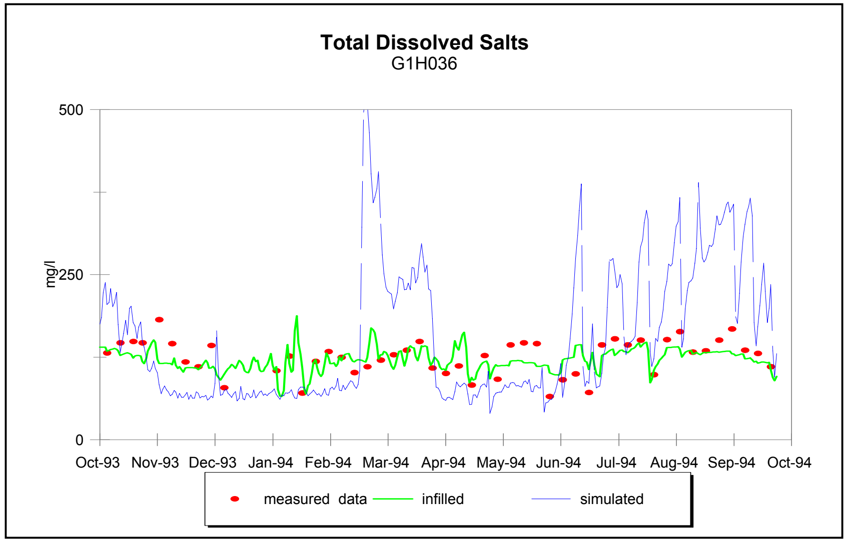

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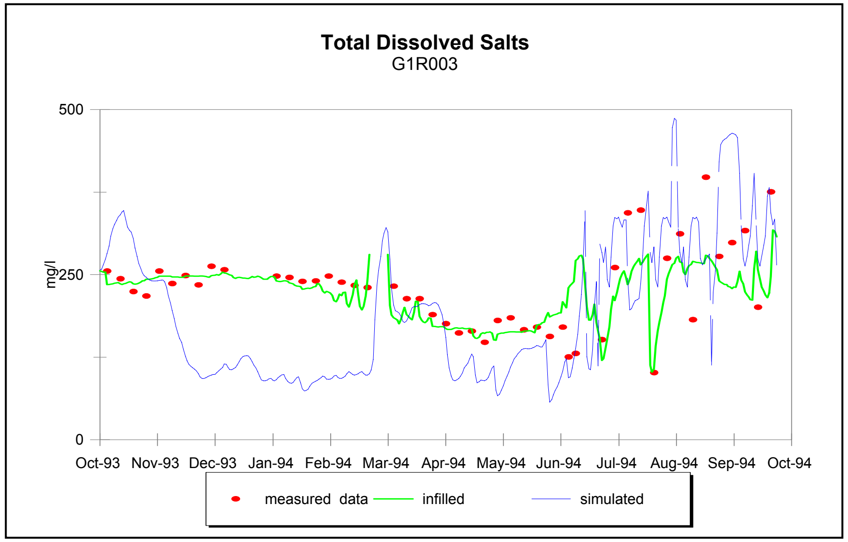

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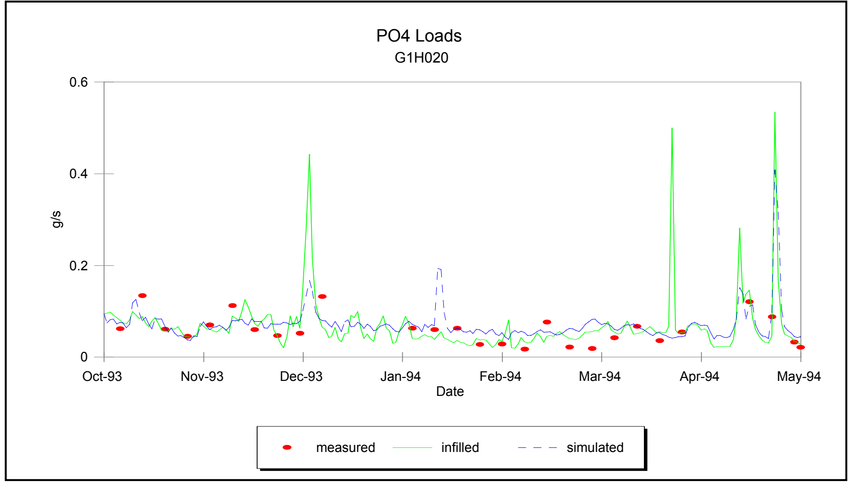

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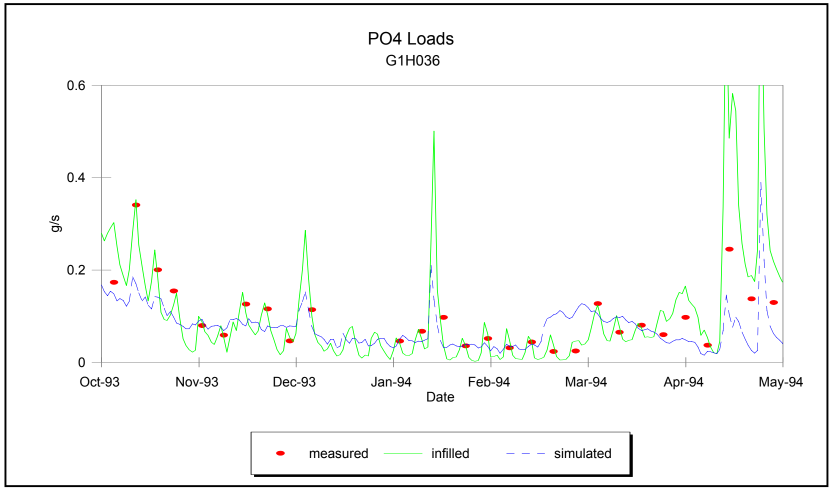

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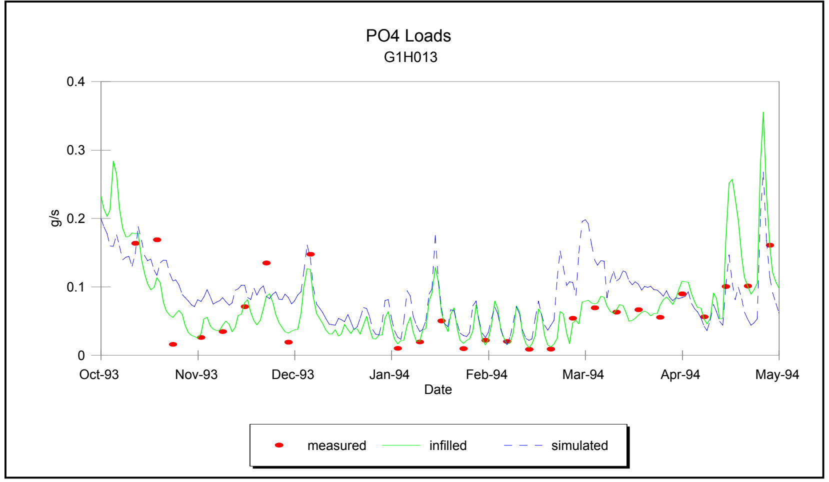

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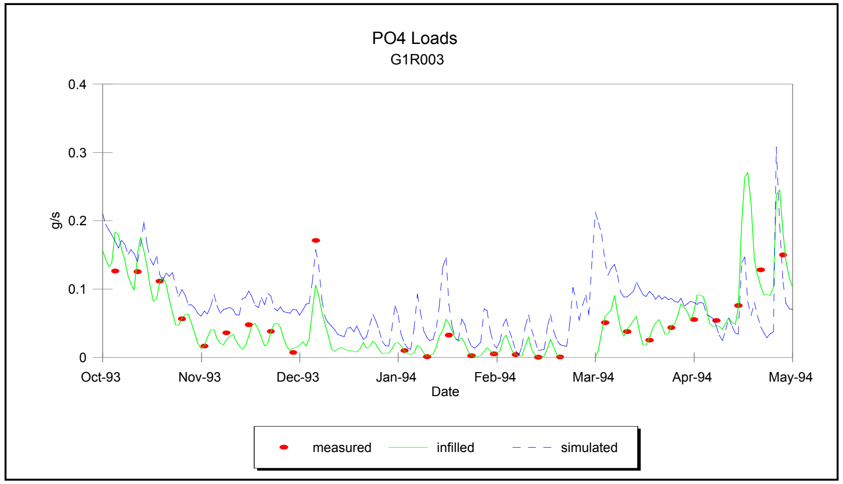

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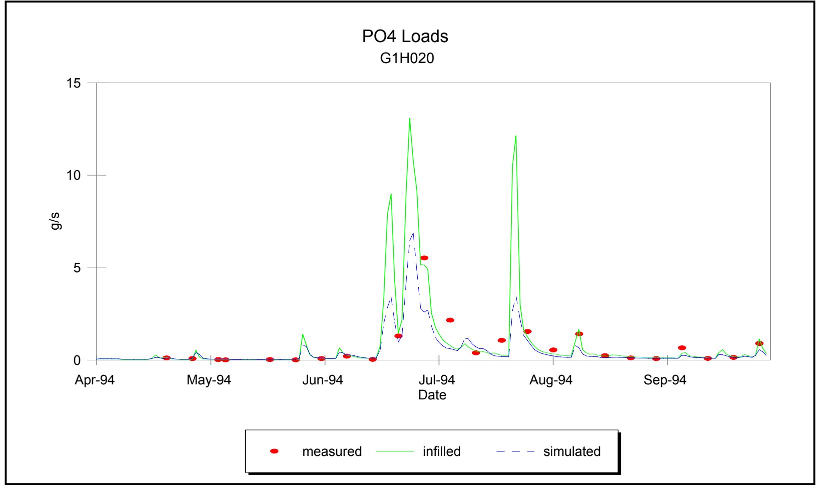

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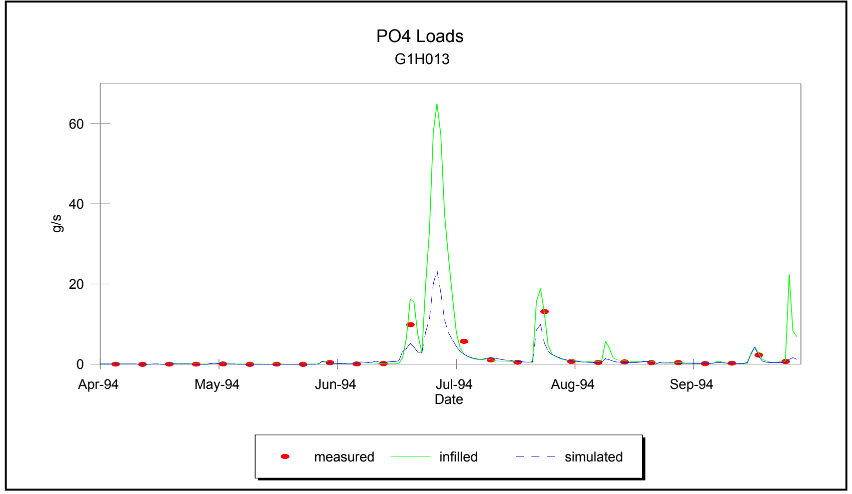

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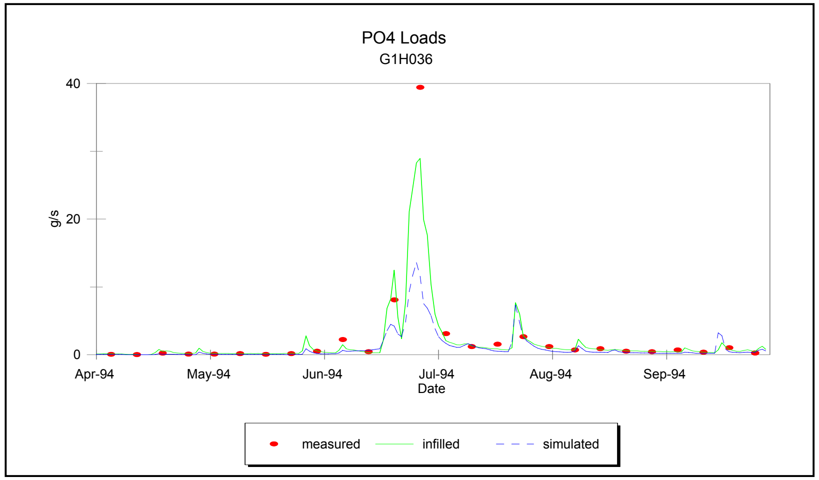

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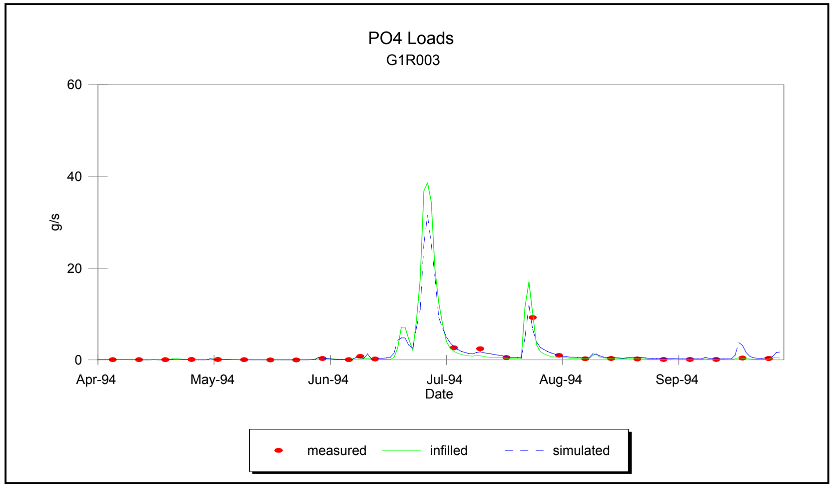

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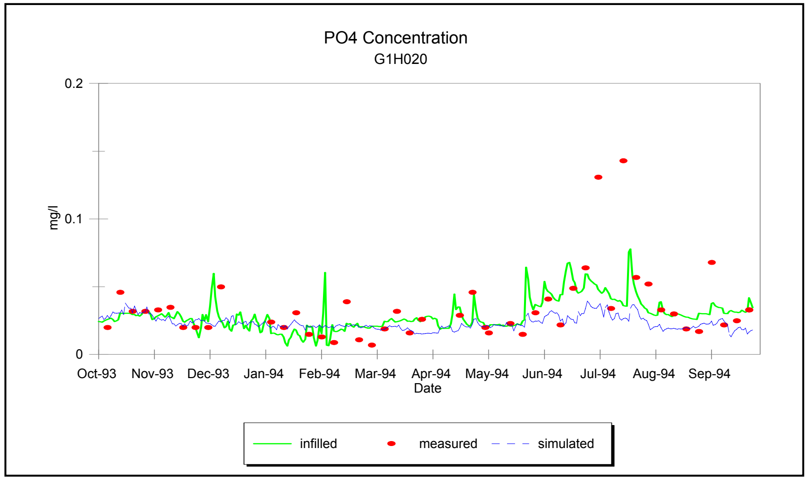

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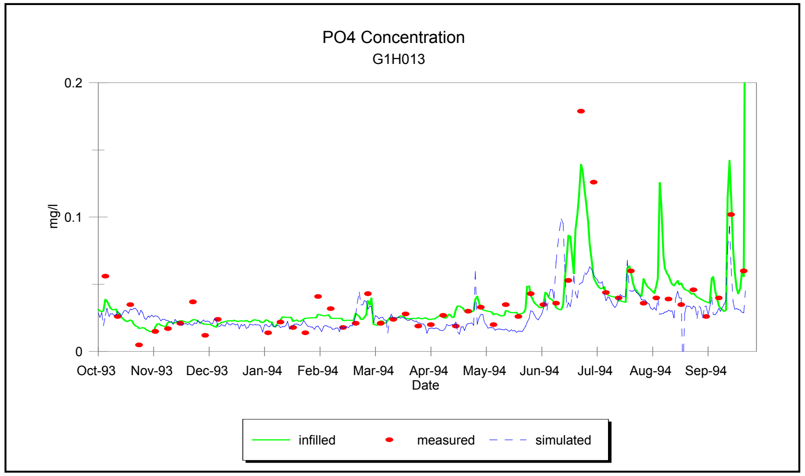

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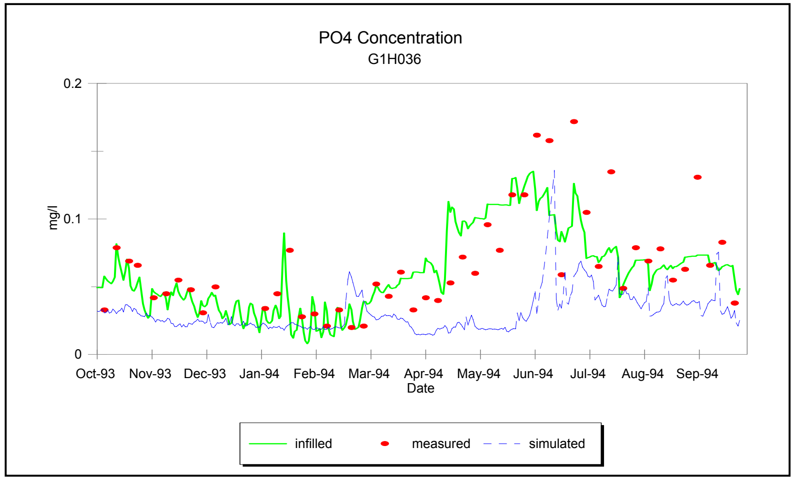

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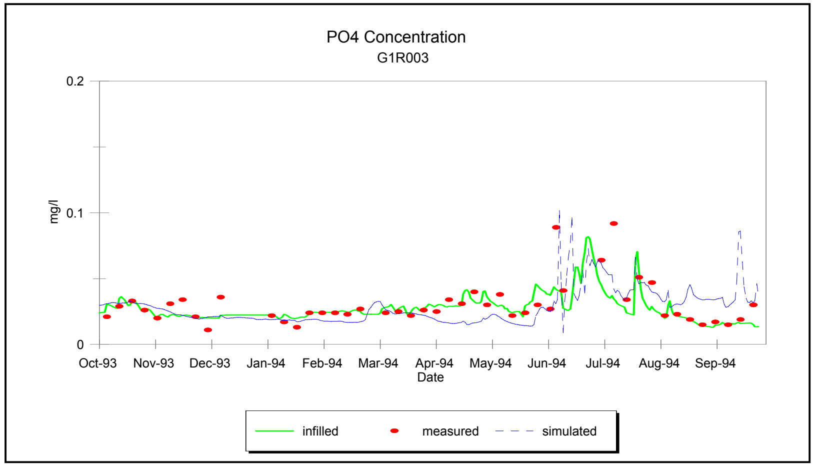

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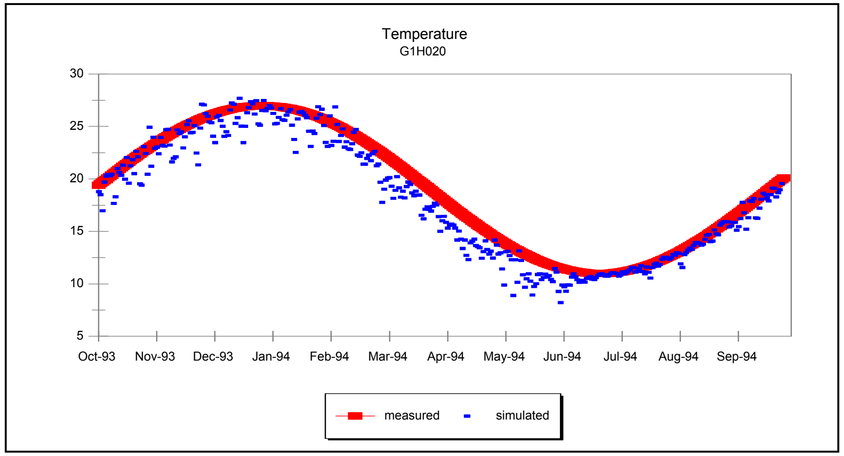

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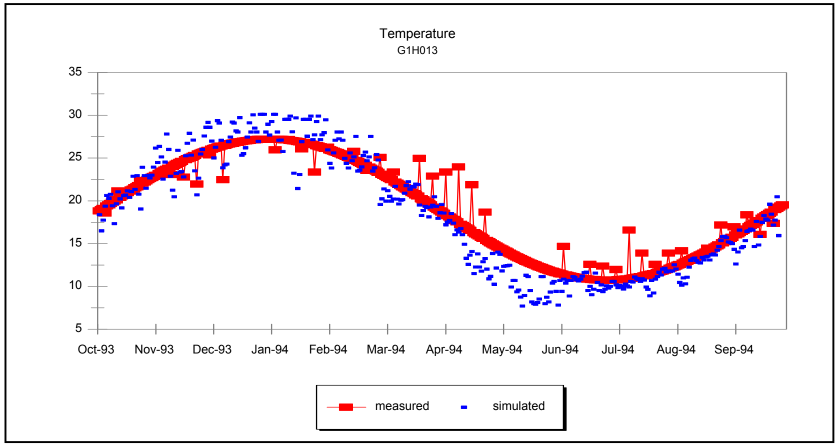

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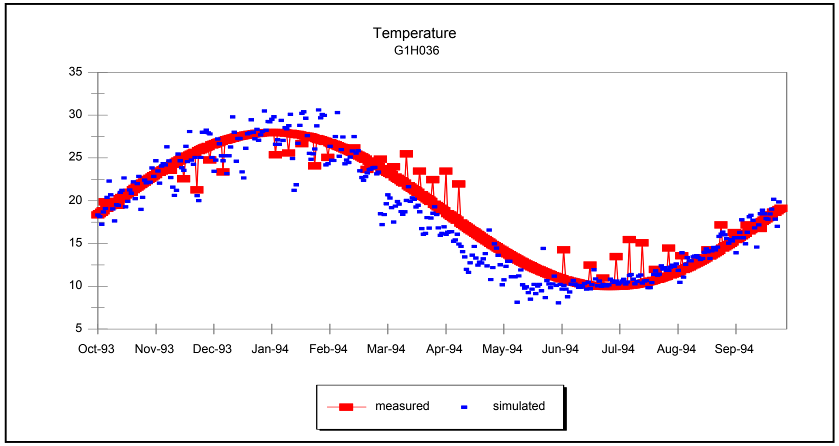

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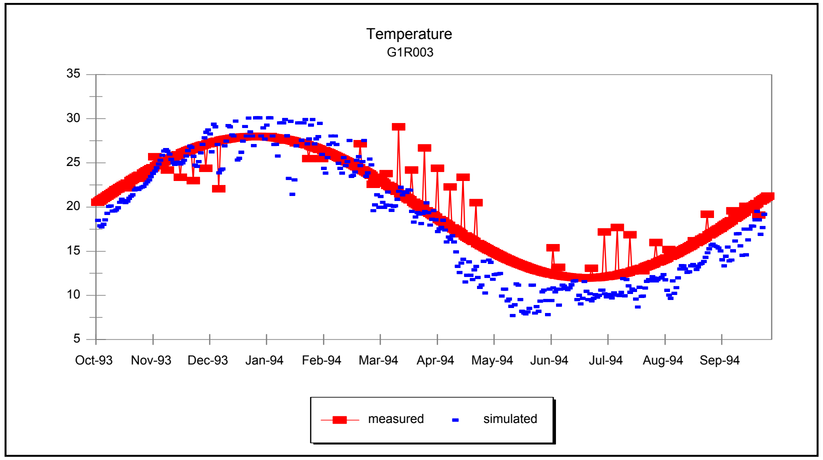

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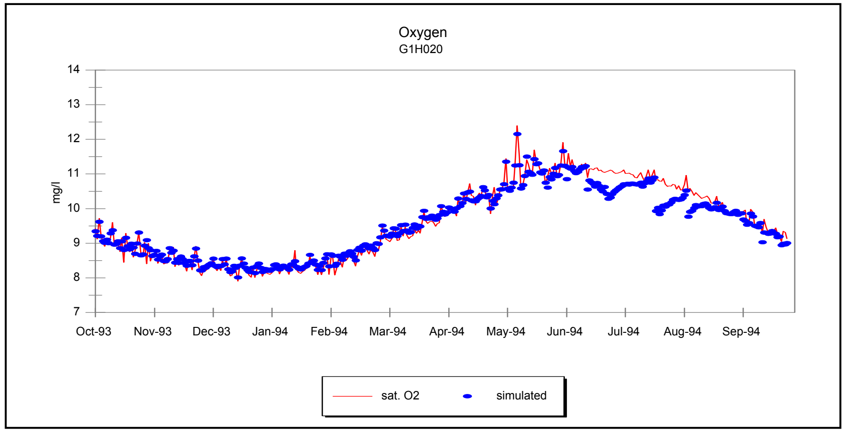

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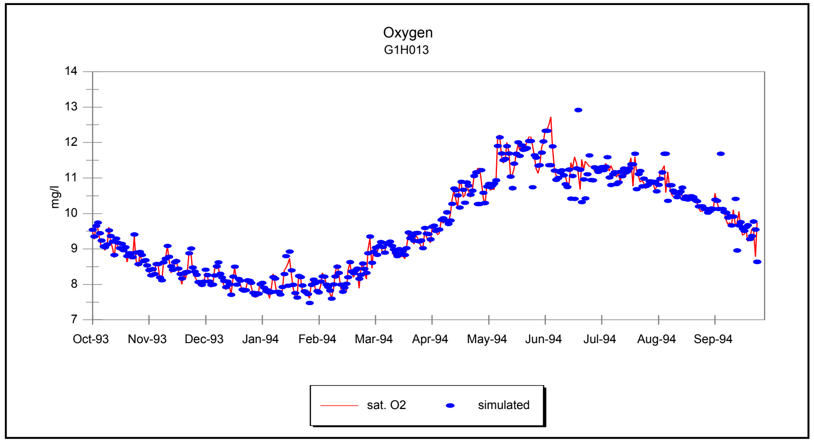

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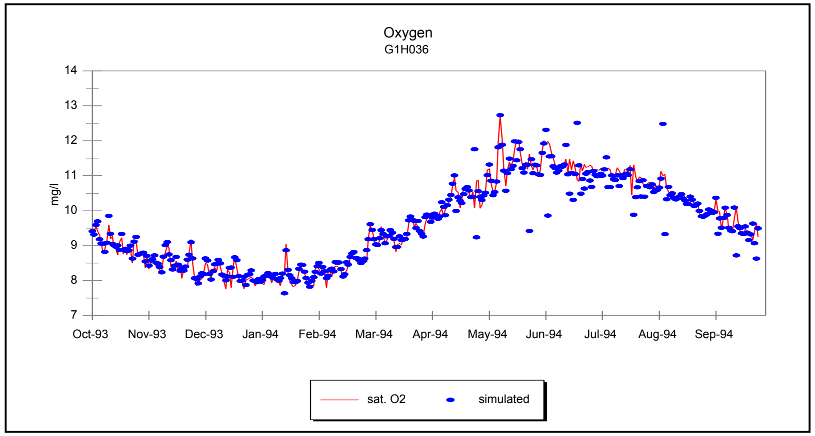

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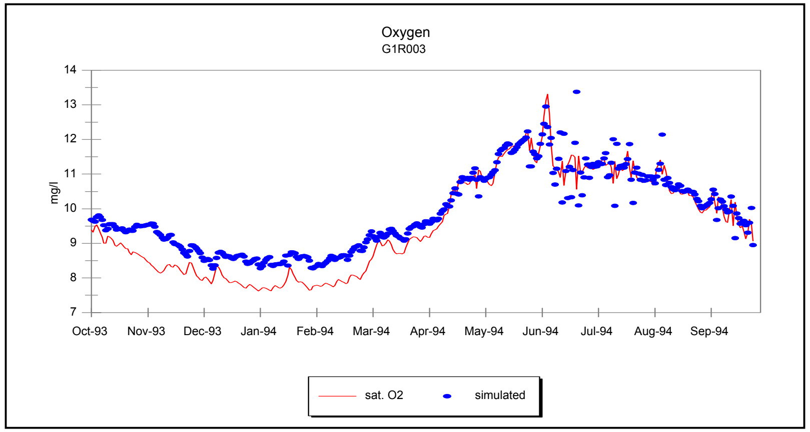

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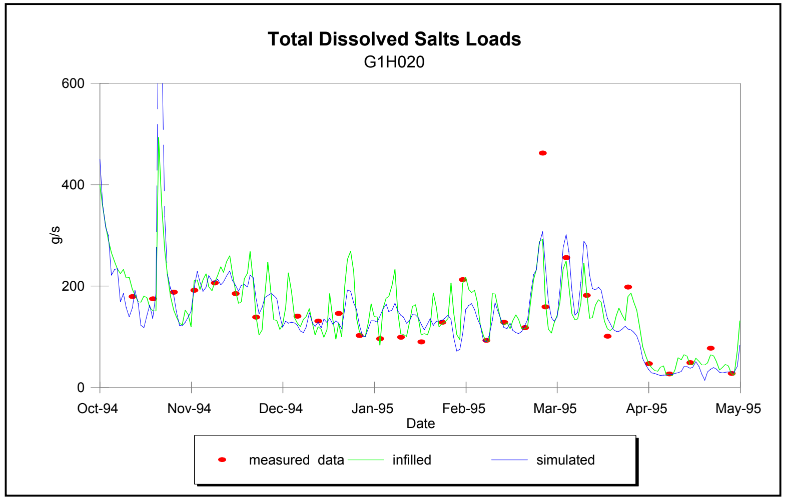

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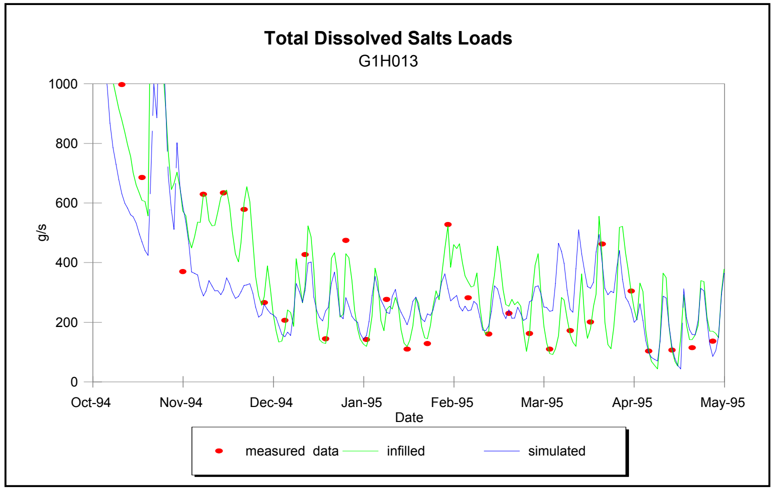

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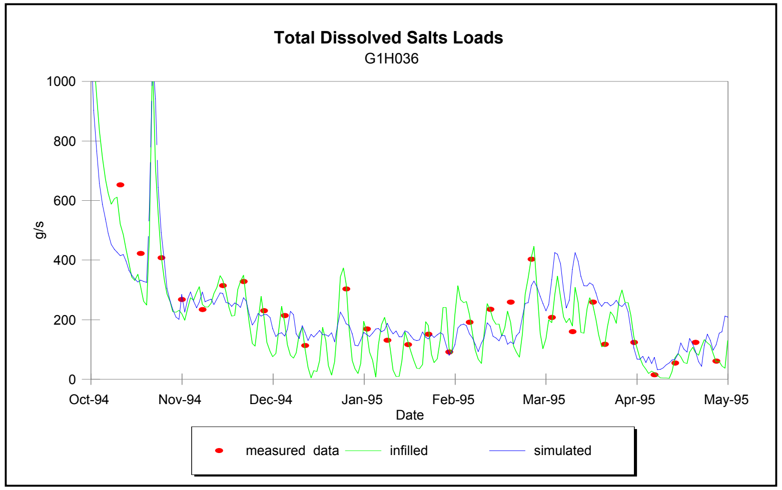

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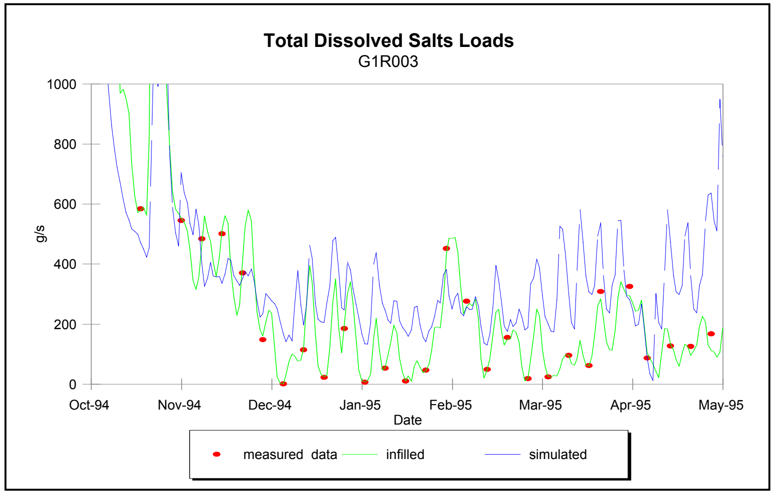

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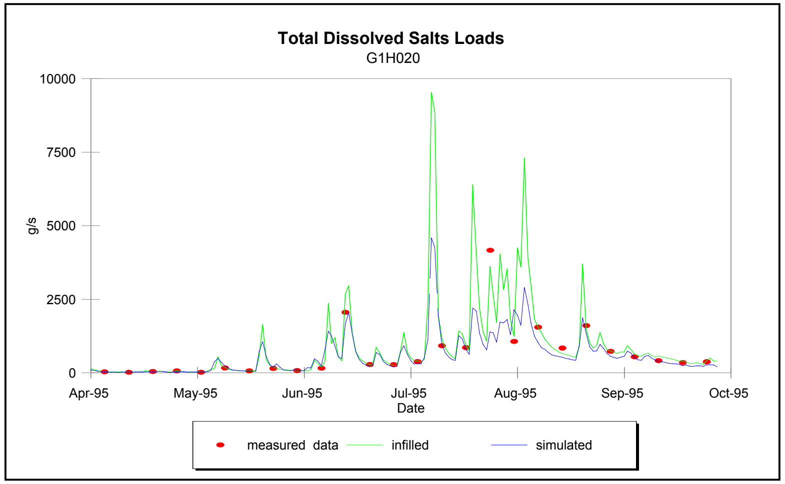

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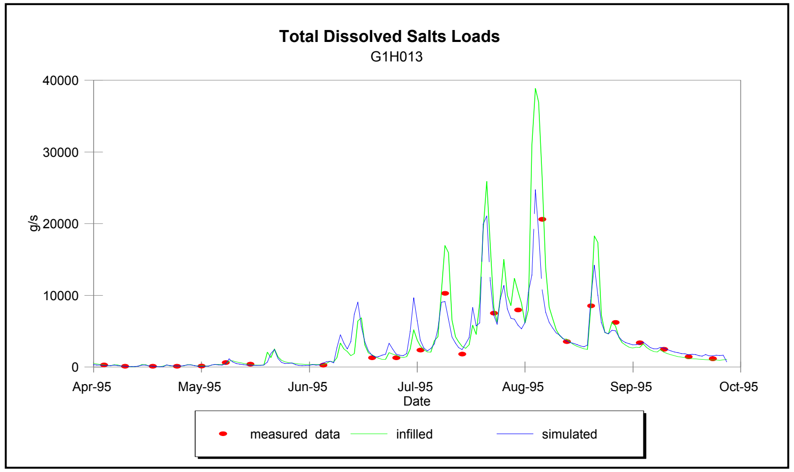

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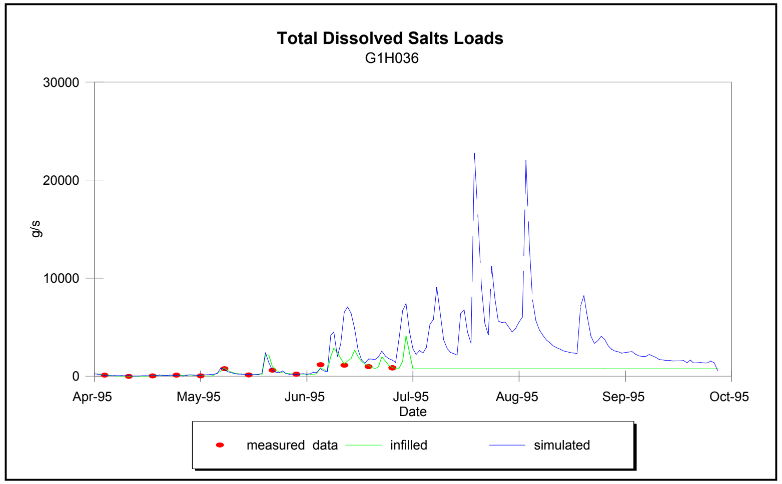

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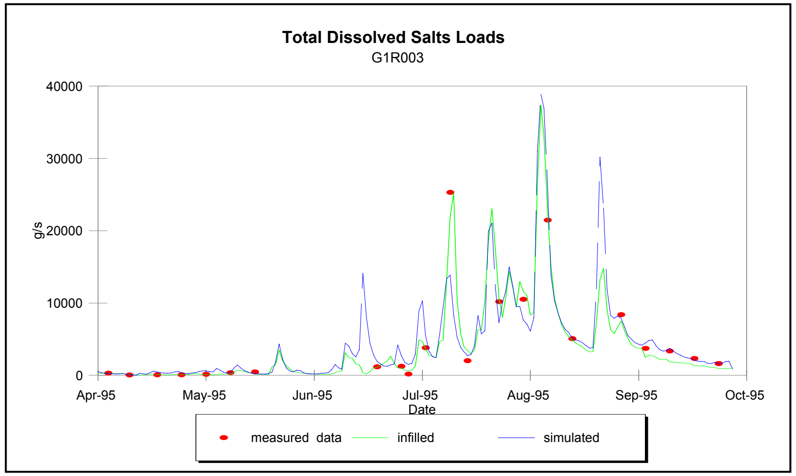

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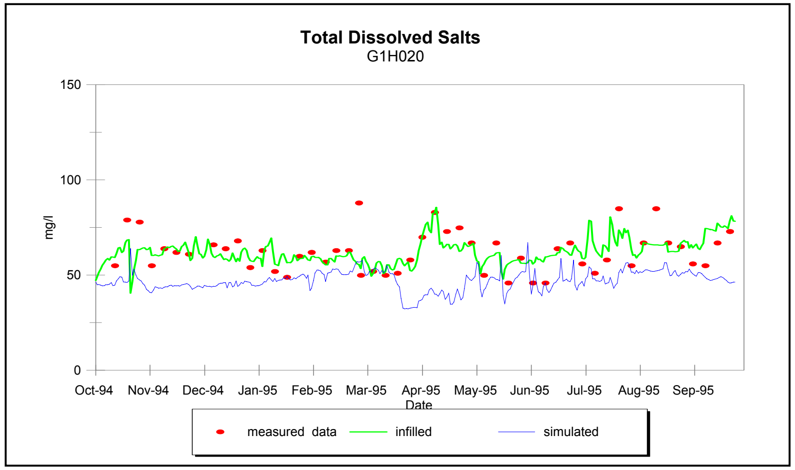

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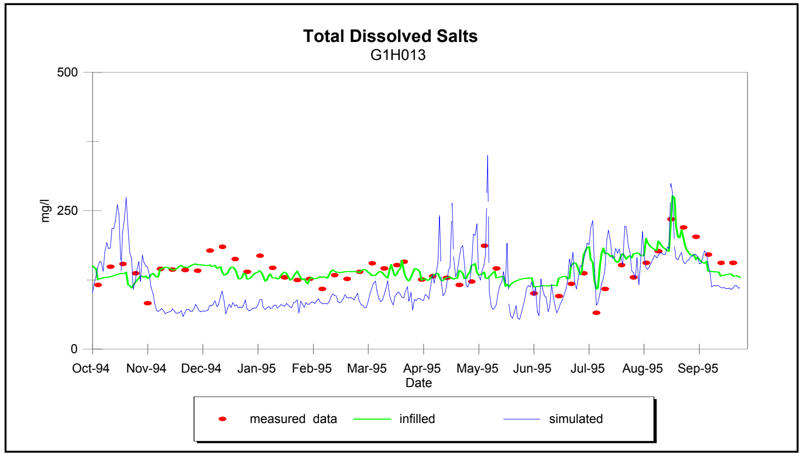

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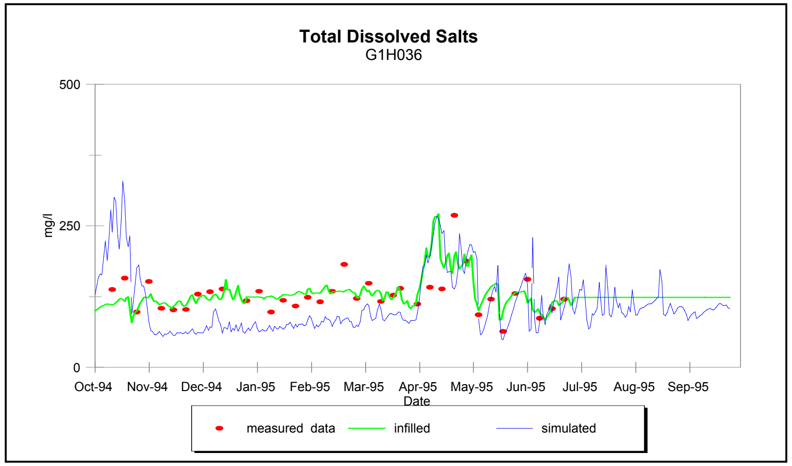

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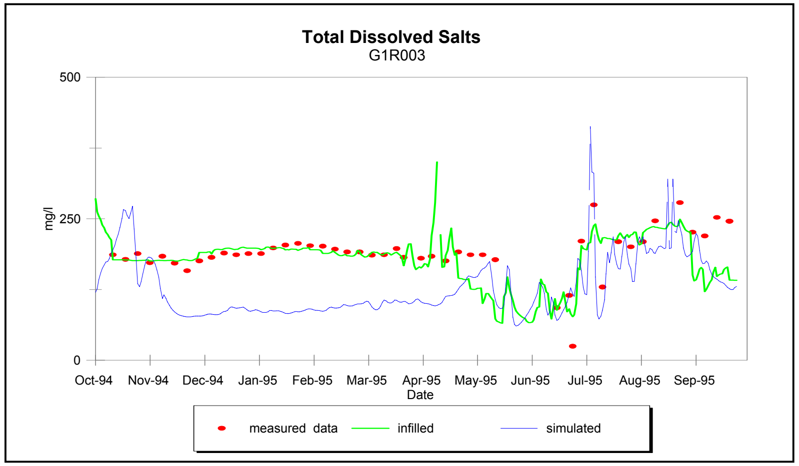

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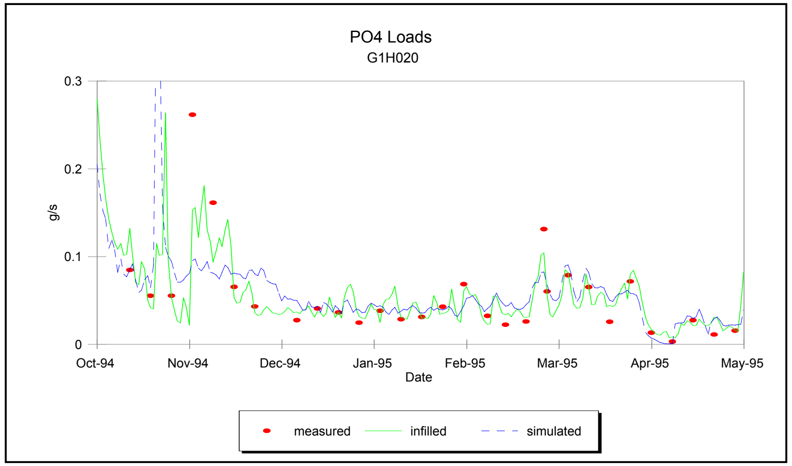

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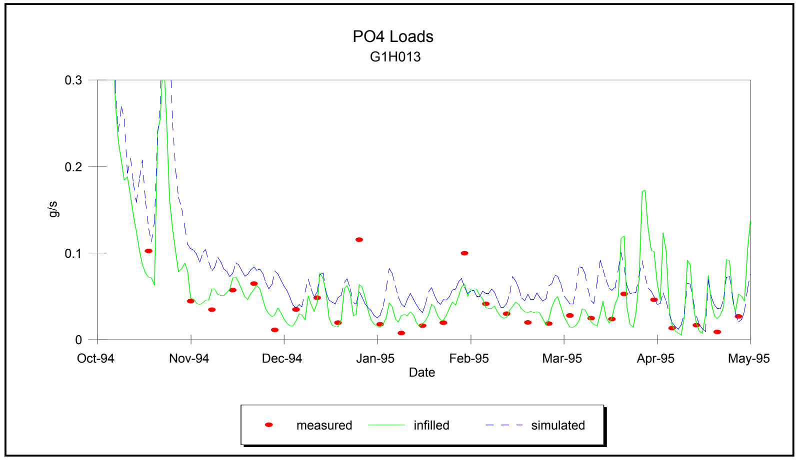

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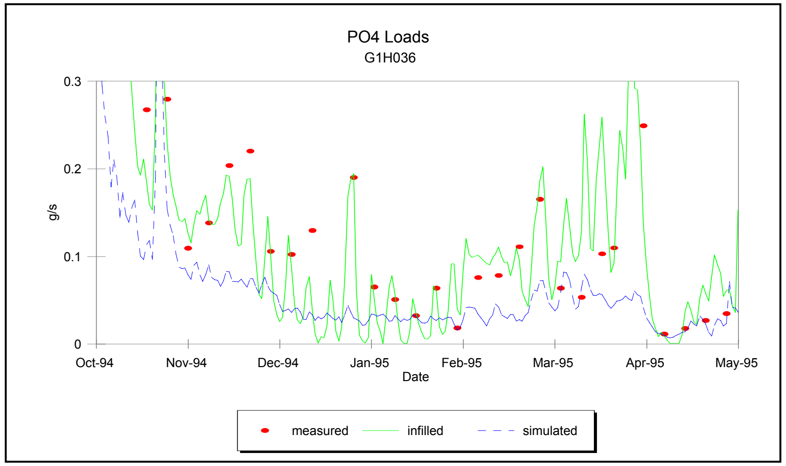

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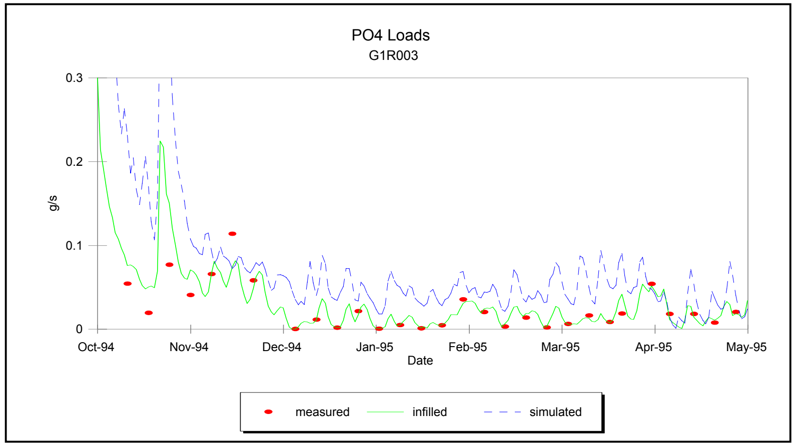

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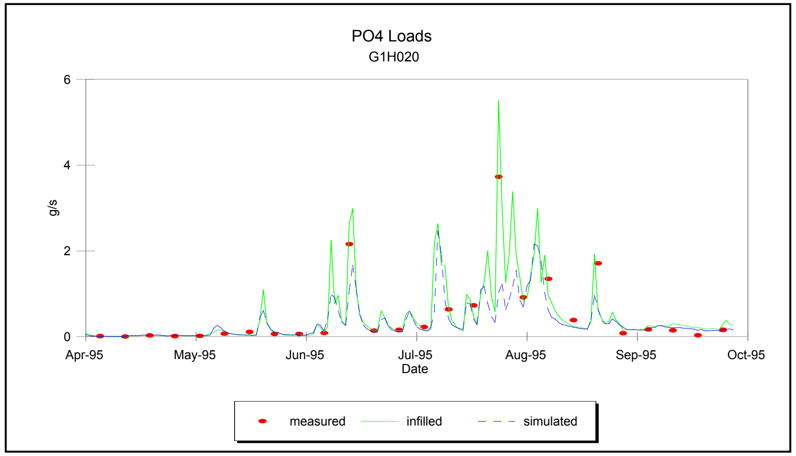

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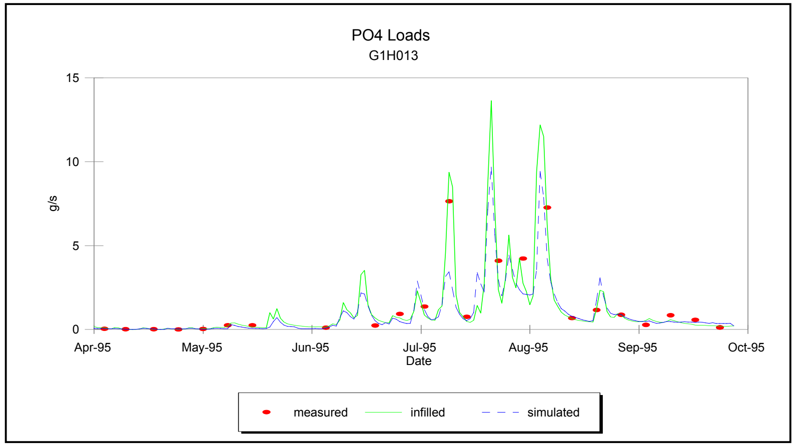

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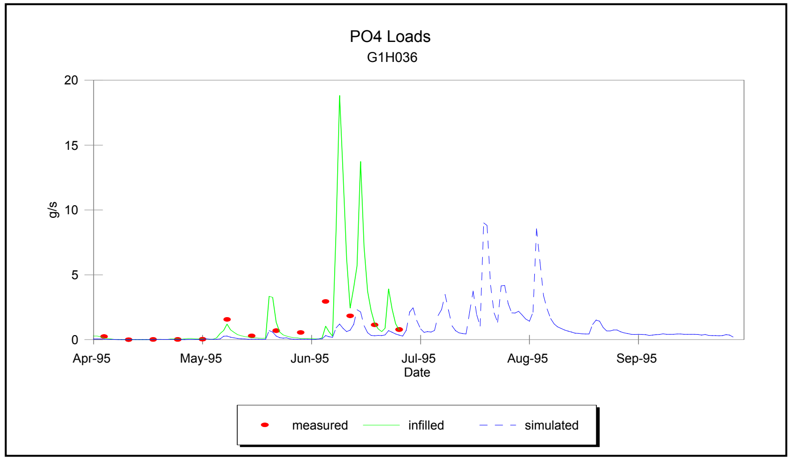

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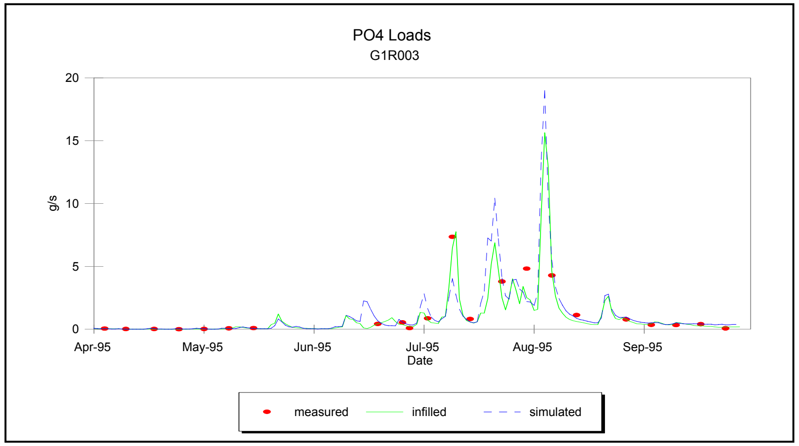

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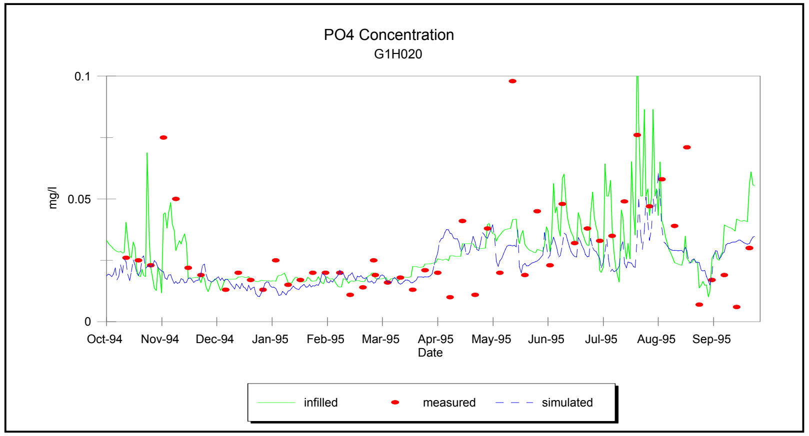

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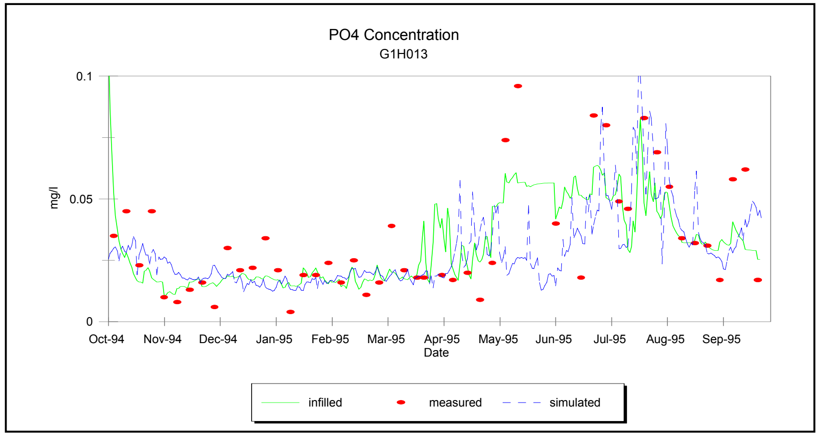

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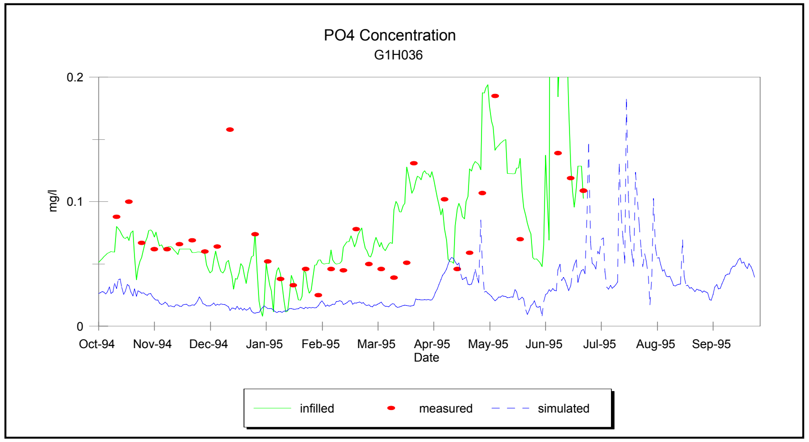

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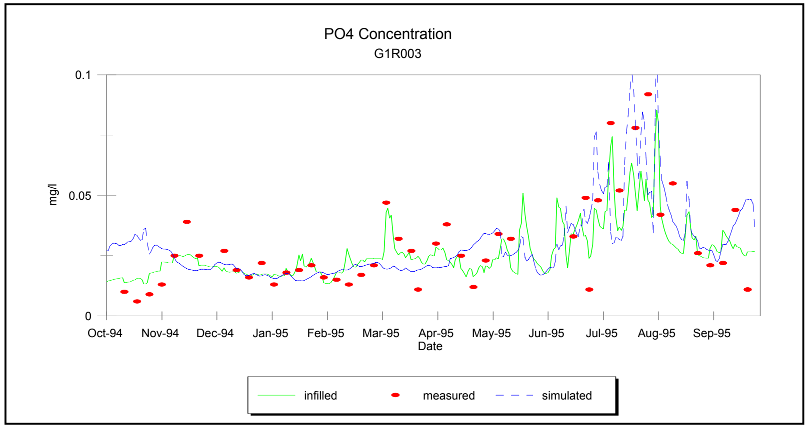

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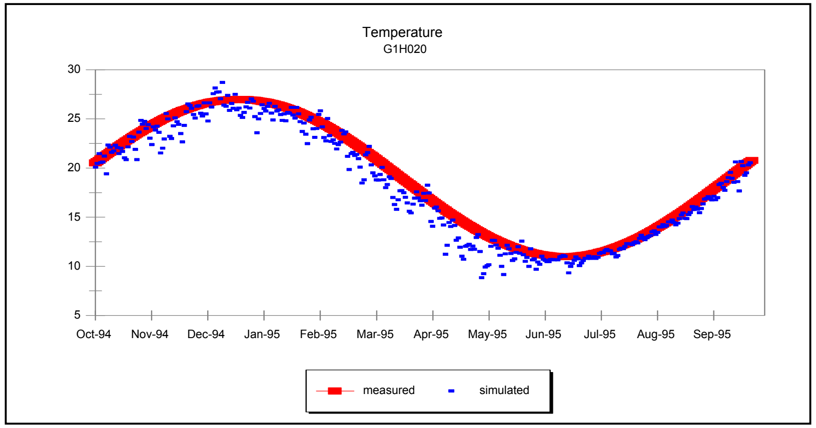

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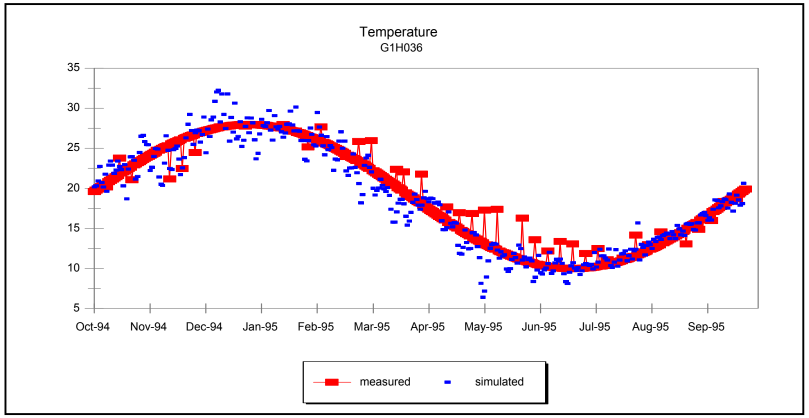

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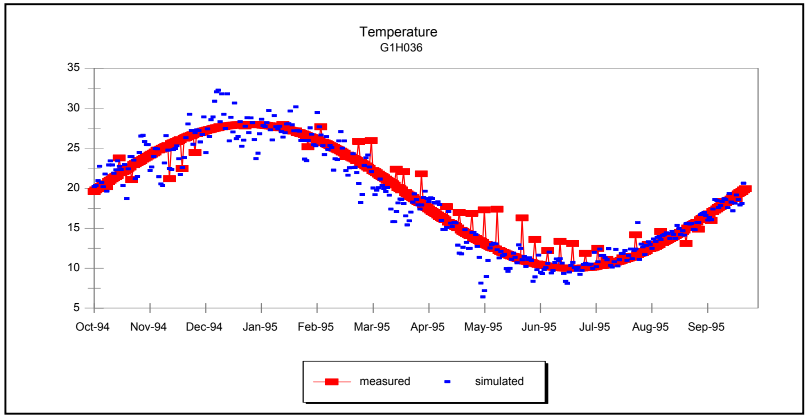

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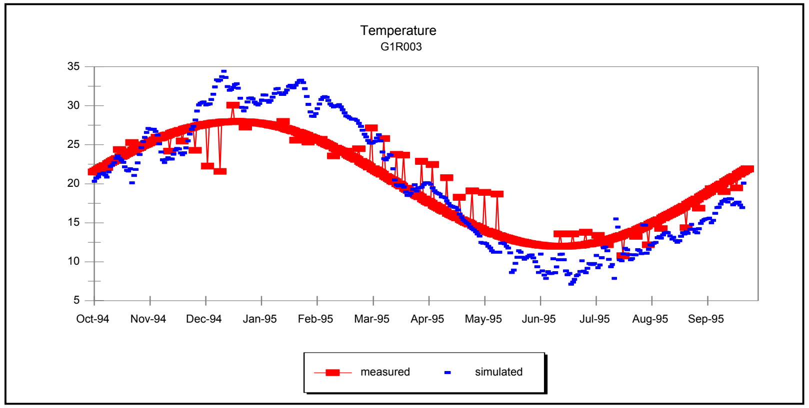

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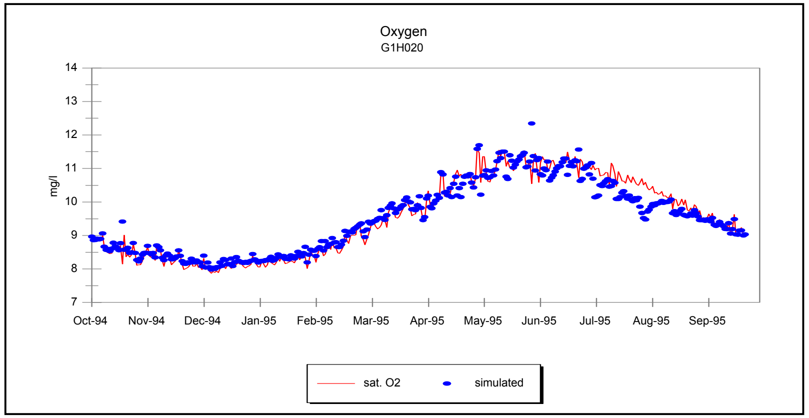

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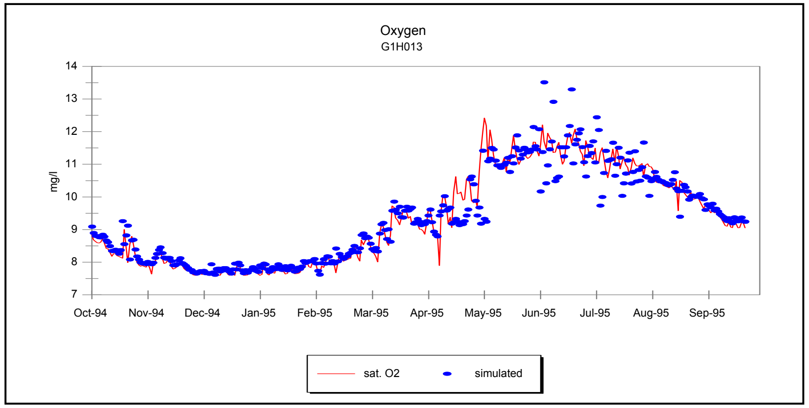

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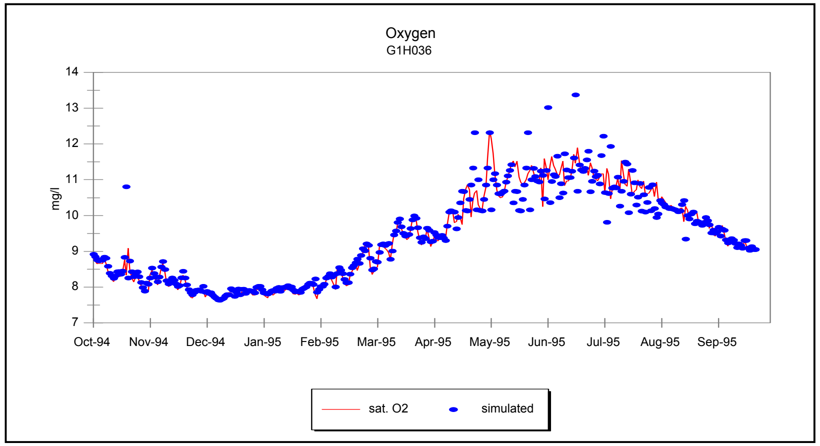

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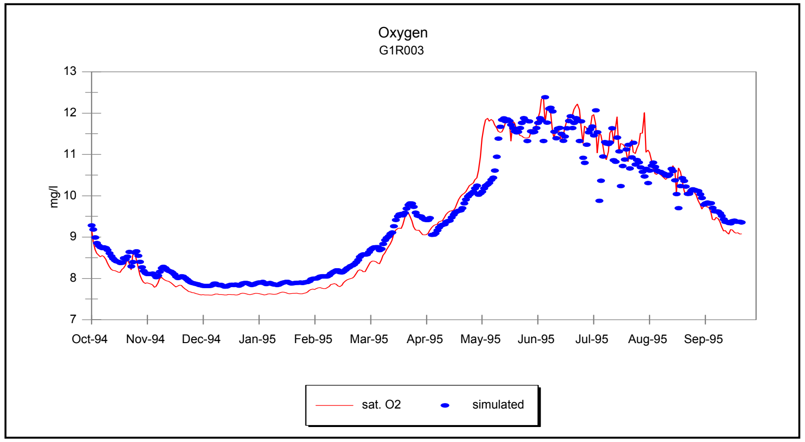

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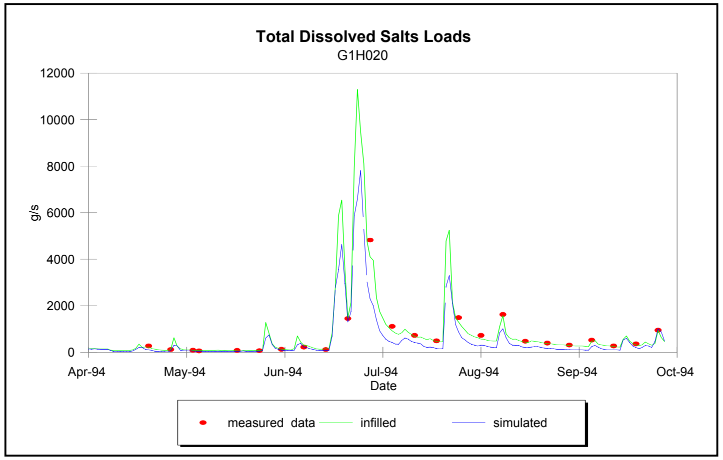

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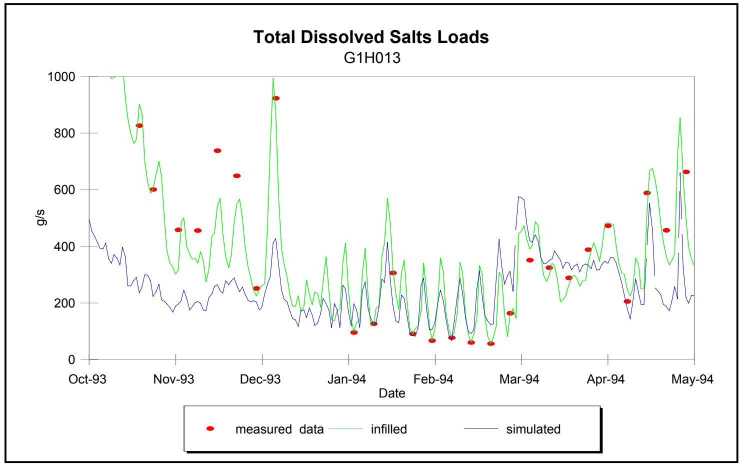

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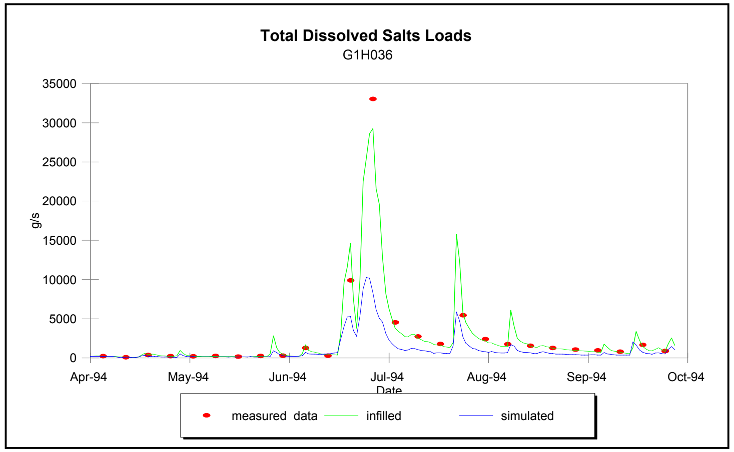

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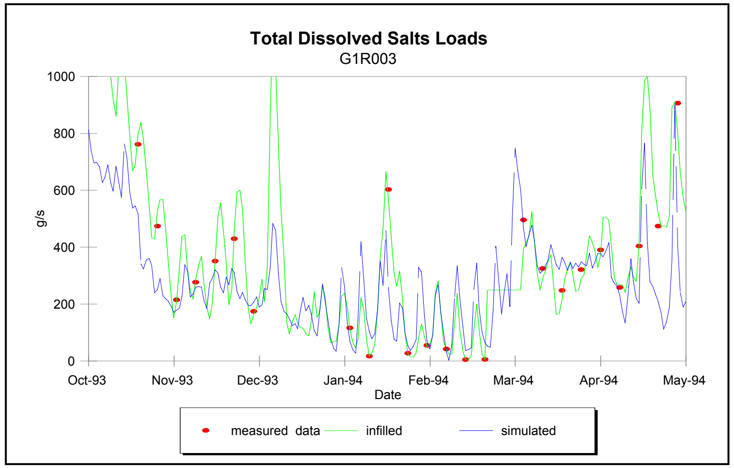

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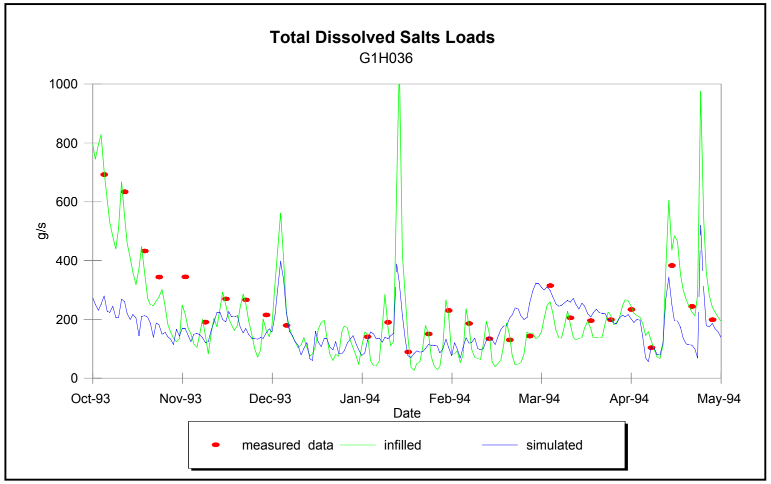

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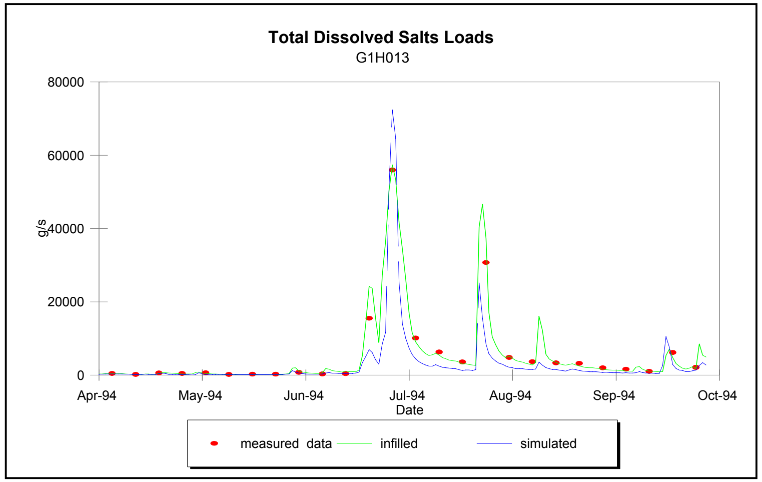

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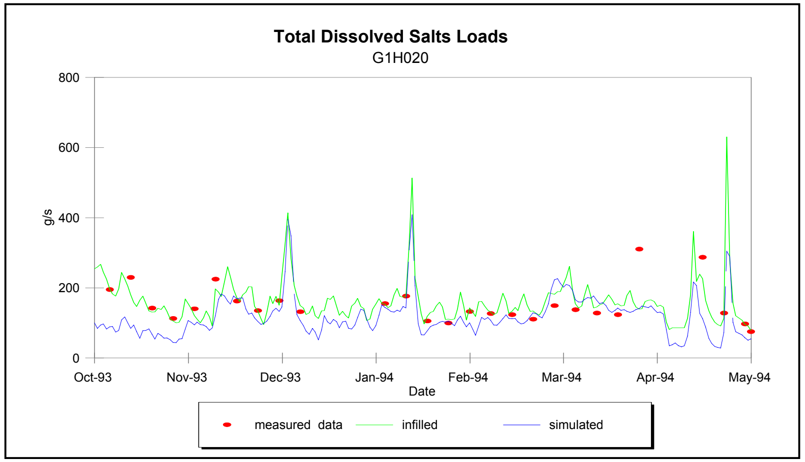

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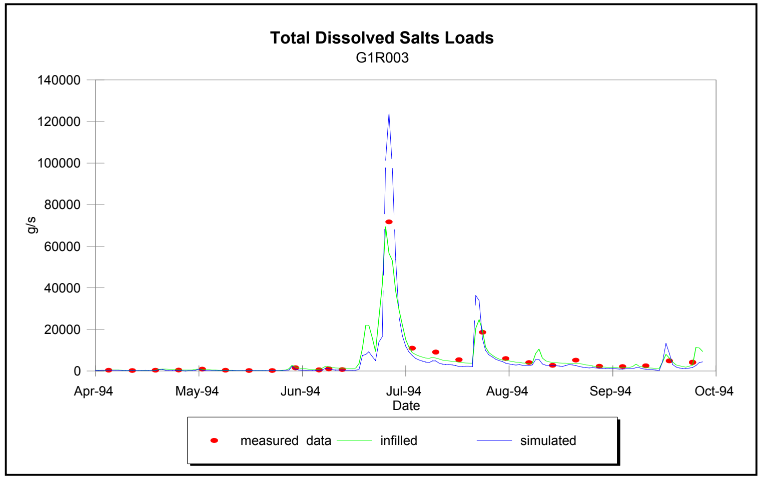

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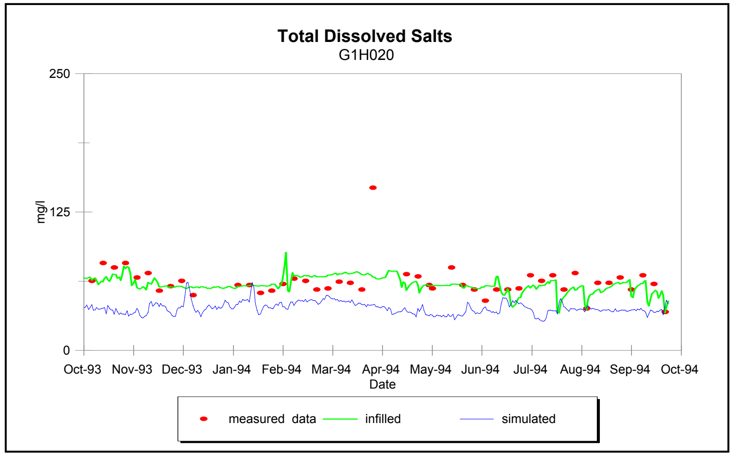

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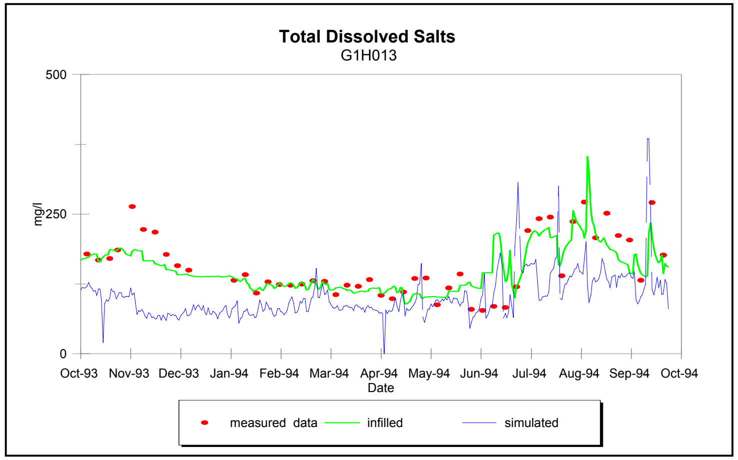

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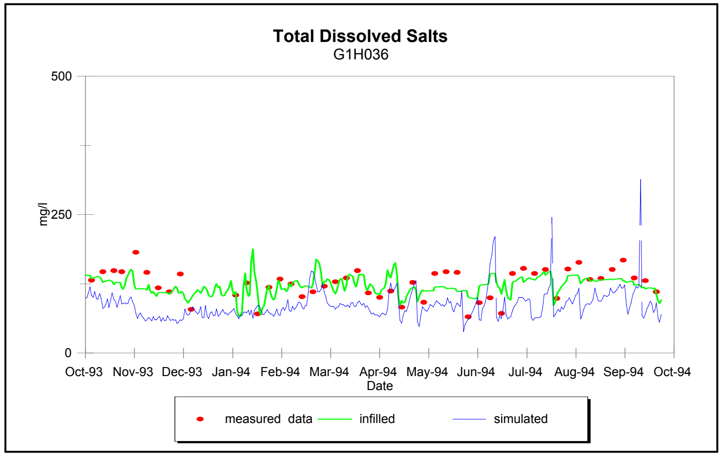

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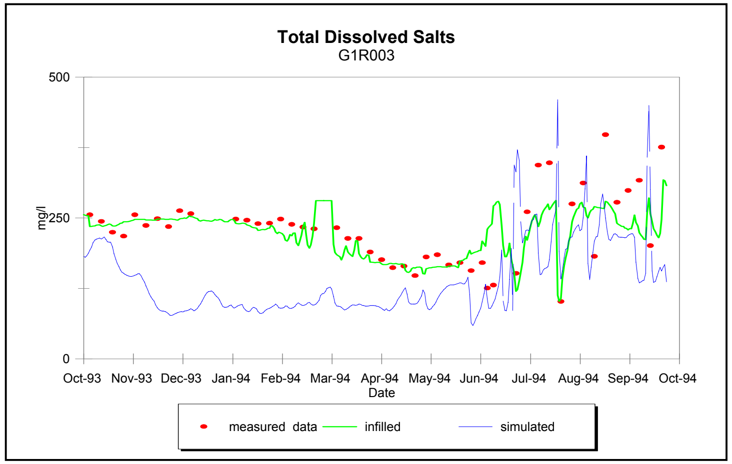

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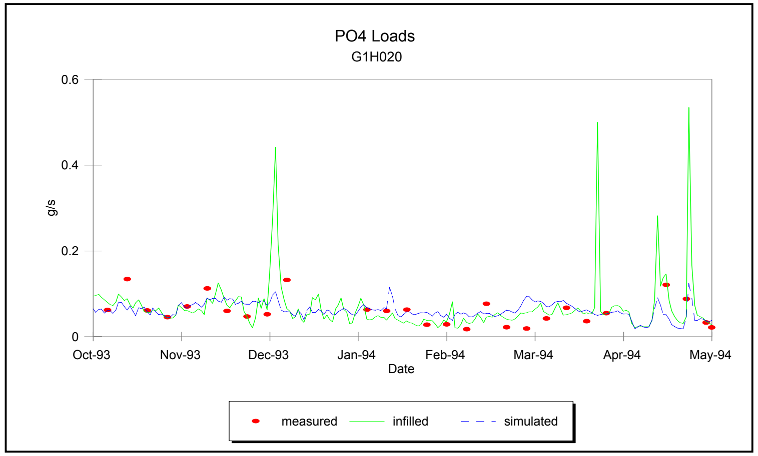

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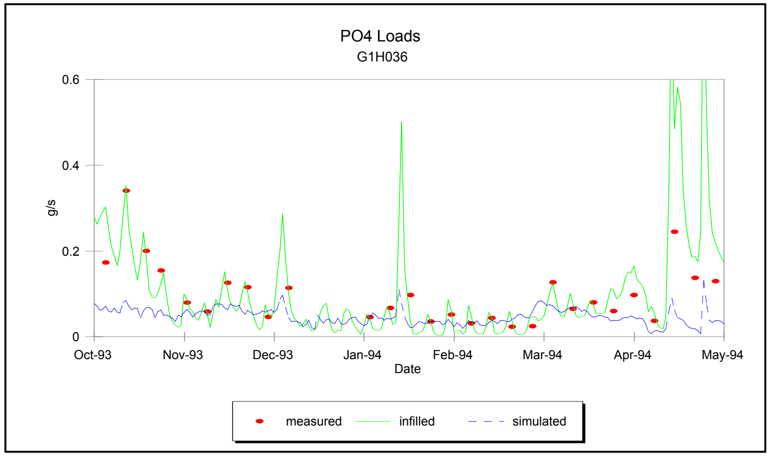

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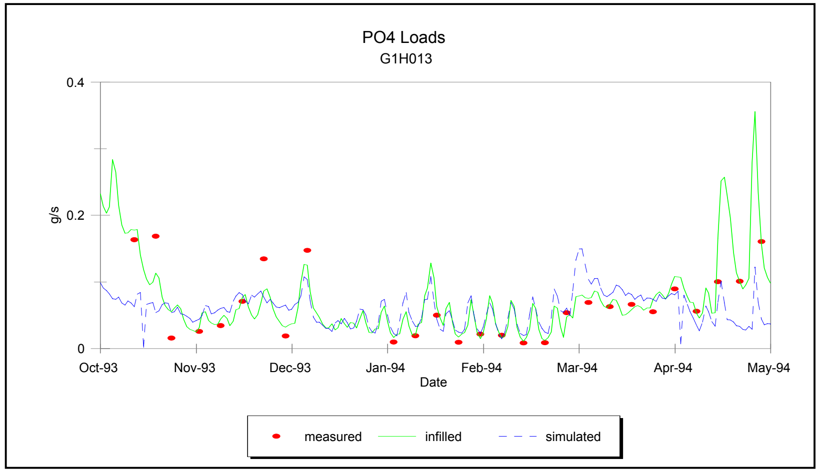

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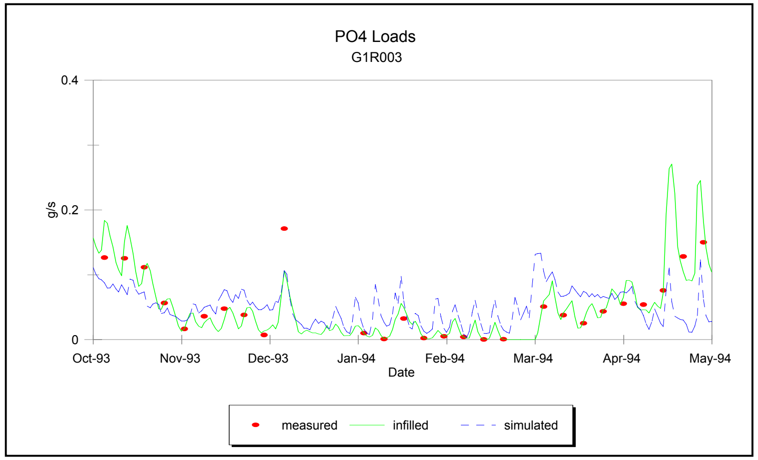

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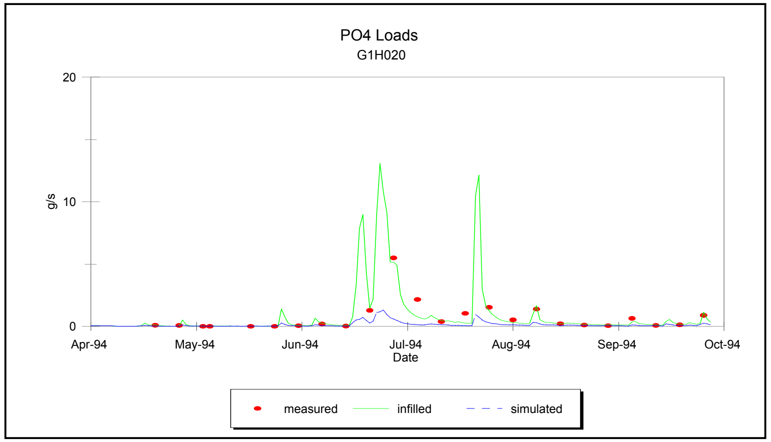

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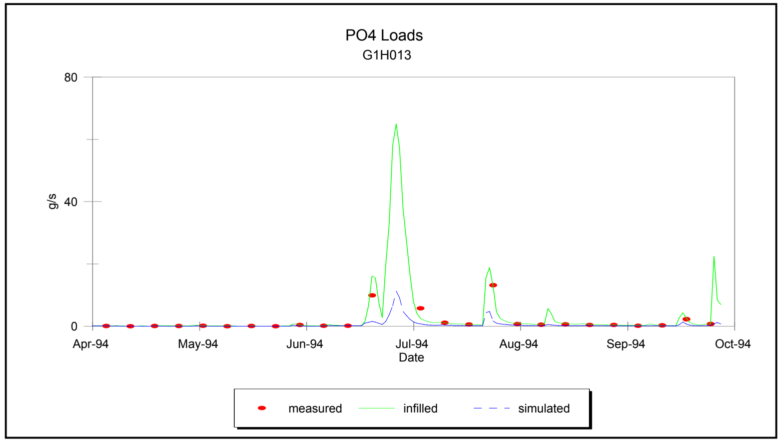

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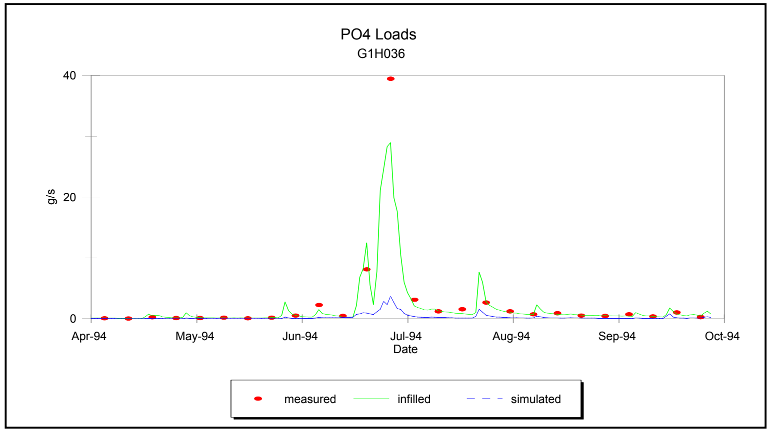

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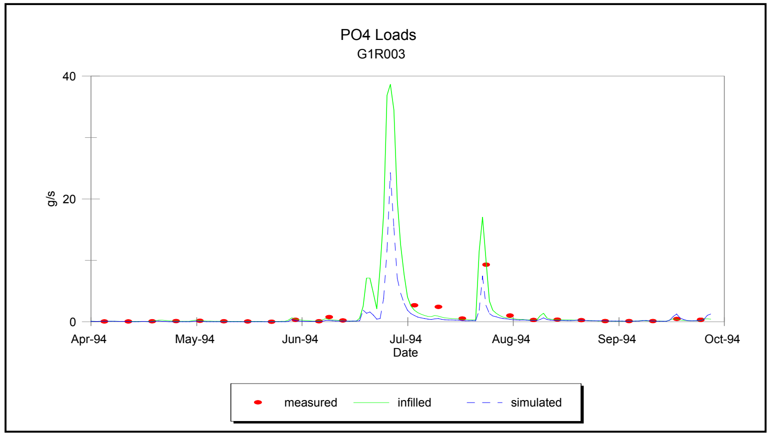

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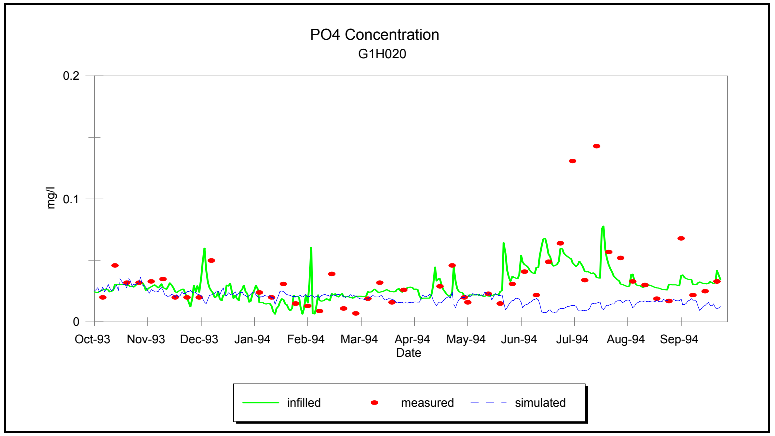

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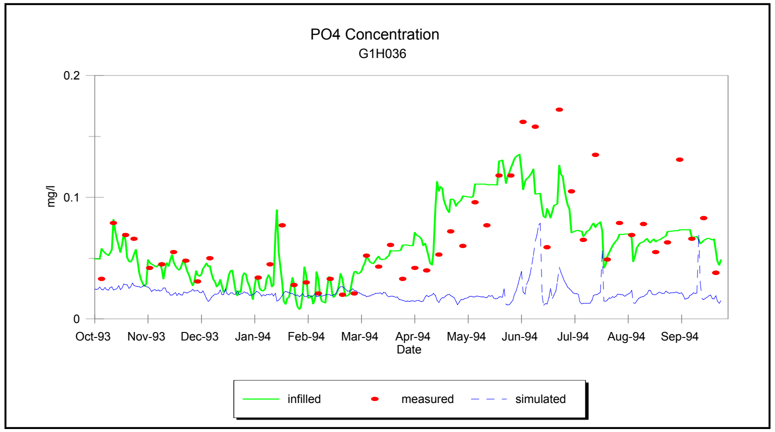

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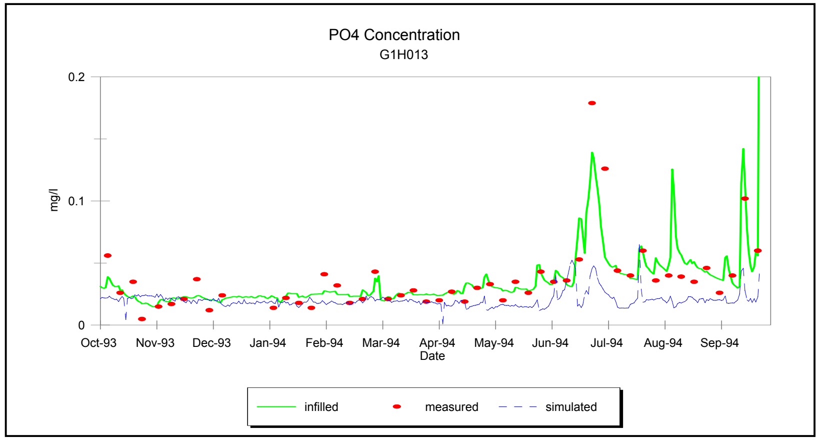

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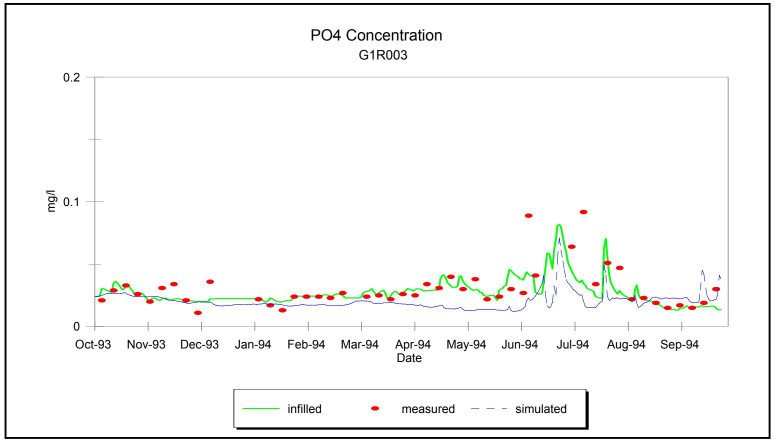

RESEARCH ON BERG RIVER WATER MANAGEMENT

VOLUME 2

(*Summarised*)

DEVELOPMENT OF THE WQIS (WATER QUALITY INFORMATION SYSTEM): APPLICATION TO THE BERG RIVER SYSTEM

by

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Departments of Civil Engineering and Soil Science,
University of Stellenbosch

EXECUTIVE SUMMARY
VOLUME 2

BACKGROUND

Impoundments and associated bulk water supply infrastructure are present in most South African river systems. Because of the disparate natural occurrence of rainfall and runoff, and its mismatch with water demand concentrations, many of these schemes have to incorporate inter-catchment transfers to meet demands in the face of inadequate local availability. Furthermore, water quality deterioration, because of human impacts through a wide range of land-uses and waste discharges, has for some time been recognised as a threat in South Africa, as it diminishes the utilisable part of the runoff in many catchments. These complexities increasingly offer challenges to water resource managers that require a response with integrative management philosophies and innovative management tools.

During 1997, in recognition of the aforementioned needs, the Department of Civil Engineering of the University of Stellenbosch, formulated a research proposal to the Water Research Commission (WRC) whose aim would be to serve the philosophy of Integrated Water Resource Management (IWRM), through the development of an integrated information system specifically for water quality – here abbreviated to "WQIS". To be useful to IWRM, this WQIS was to provide diagnostic and predictive utilities to serve technical planning and operational decision-making in a river system, but, simultaneously, provide appropriate information to support water managers in communication with technical stakeholders. It was also recognised that the project would need identification of a "prototype" catchment for development of appropriate WQIS approaches and to provide a relevant database.

Simultaneous with the research formulation process described above, the Department of Soil and Water Science[1] (DSWS) at the University of Stellenbosch, formulated a research proposal to the WRC to investigate the causes of and quantification of apparently increasing salinisation of the Berg River, one of the prime water sources to meet growing demands in the Greater Cape Town and West Coast Region. The WRC proposed that the two separate proposals be merged to form a single Terms of Reference and, ultimately, a single contract between the WRC and the University, with Prof Görgens as the Project Leader. It then also made sense to select the Berg River as the prototype for the WQIS development, partly because of the accent that the DSWS research would put on salinisation processes, which is one of the Berg River's most pressing issues, and partly because the Berg catchment contains all the general water resource management challenges and complexities referred to earlier

OVERALL PROJECT AIMS

The original aims of the project as specified in the WRC contract are as follows:

i) To develop Water Quality Information Systems to support both integrated management of a water resources system, and to support communication about water quality management with stakeholders and communities in the catchments of that system.
ii) To develop an understanding of the primary water quality responses, and their causes, of the Riviersonderend-Berg River (RSE-BR) System, which would serve as a case study for the Water Quality Information System implementation. (The Berg River is connected via a two-way tunnel to the Theewaterskloof Dam on the Riviersonderend River.)
iii) To evaluate the potential for operation of the future RSE-BR System to meet recently developed salinity guidelines for irrigation.

As the project planning unfolded, it became clear to the Steering Committee that the aims needed adjustment for two sets of reasons: On the one hand, they were too broad for the available budget and time-frame. On the other hand, parallel development of suitable approaches to community participation in IWRM, as part of DWAF's initiatives to implement the National Water Act (1998), was forcing a change in the focus of the project. The Steering Committee, therefore, agreed that most of the research focus would fall on Aims (i) and (ii), and that (iii) should be seen as a long-term objective of salinity-based research in the Berg River catchment.

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[1] Now called the Department of Soil Science.

Furthermore, the Steering Committee agreed that the WQIS would primarily be developed as a technical information tool aimed at supporting water resource managers and stakeholders on the technical domain, and that communication support for community participation in consultative water management processes would fall outside the ambit of the current contract.

TWO RESEARCH THEMES AND TWO SETS OF RESEARCH OUTPUTS

The background described earlier, as well as the stated objectives, imply that two related, but essentially different, research themes underlie this project:

- Theme One: Development and/or application of decision support and information management software for general water quality management in a river system with diverse components and human impacts. This Theme was the responsibility of the Department of Civil Engineering.
- Theme Two: Water quality-related research in the form of field-scale process studies and large-scale soils data interpretation and mapping, with a strong focus on salinisation processes. This Theme was the responsibility of the Department of Soil Science.

Each Theme yielded a separate set of research outputs and Reports. This document deals exclusively with the research methodology, results and findings produced by the Department of Civil Engineering under Theme One.

WATER QUALITY INFORMATION SYSTEM (WQIS) DEVELOPMENT

The following steps outline the approach and essence of this component of the Study:

i) The aim of the research conducted under this component of this Project was to develop an effective water quality decision support information system. To fulfil the aims of this project, complex communication and design challenges had to be resolved to produce an information system that satisfied the requirements of the intended technical users. Two crucial concepts that were featured were “interactive” and “integrated”.

ii) As part of the interactive communication process between the developer and users a questionnaire was distributed to potential users and those with valuable knowledge in the relevant fields. A prototype was then developed based on decisions made regarding software, methods of integration and technical feedback from the questionnaires. The prototype was then demonstrated at a series of interviews and demonstrations where further feedback was recorded and further software adjustments were made.

iii) For this project, a number of the basic system components had already been outlined in the project proposal. The components and required level of their integration that would appropriately meet user needs was optimised as part of the aforementioned interactive development process.

iv) The functionality and analysis offered by the WQIS is fairly comprehensive, but by no means covers all the requirements of every river/water resource manager or user. However, the development environment and design of the system are sufficiently flexible to allow the inclusion of other simulation models and analysis options to ensure that the WQIS fulfils its role as a decision support and information tool for a broad spectrum of users.

v) Future research and system developments needs were highlighted in some of the interviews and the Steering Committee meeting for this project. Some of these are discussed in the following section.

FUTURE RESEARCH AND DEVELOPMENT: WQIS

One of the main concerns expressed about the WQIS was, how to prevent this information system becoming just “another” system that is used for one project or application and then shelved. Therefore, in the research and development of the WQIS, numerous steps (listed below) were taken to avoid this occurrence.

- The system was developed interactively with the users to create a feeling of ownership and buy-in.
- Modelling capabilities were offered that produced meaningful results for a range of managers in the water management environment.
- The system design is simple and intuitive and offers comprehensive on-line help to cater for all levels of computer literacy.
- The system may be transferred to other river systems provided certain data naming and format conventions are followed.
- The information system is sufficiently generic to allow the inclusion of additional simulation and analysis tools.
- The WQIS may be used as an educational facility for catchment orientation, GIS exposure and map creation.

These precautions may, however, not be sufficient to ensure the continued use and applicability of the information system. The format of the input and output of this system needs to be compatible with that of the main water regulatory organisation, DWAF. In this way the input information of the system may be updated easily and the results may be distributed and used in other studies. We understand that DWAF is currently developing a data storage system based on the USA-EPA's WDM (Watershed Data Management) principles, for the purpose of standardising the format of their water resources data. Any future information systems should be required to conform to this standard.

However, the WDM-based development was not stable at the time this component of the Project had to be concluded (June 2001) and therefore no standards were available at the time. For this reason, the WQIS was developed with its own database, but created sufficiently flexible to ensure that future conversions to WDM format proceed smoothly.

Concern was also expressed that the water quality constituents modelled in the WQIS were not adequate to describe the quality of the Berg River water used for irrigation and the subsequent irrigation return flows and leaching. However, due to the paucity of measured data, the modelling of more specific water quality indexes (such as the Sodium Absorption Ratio rather than TDS), would require an extensive and lengthy gauging and data collection exercise. In the interests of improved modelling and decision support, any improvement in measured water quality and flow data is always encouraged and should be considered at the outset of any modelling or simulation project.

CONCLUDING REMARKS: WQIS DEVELOPMENT

One of the achievements of this research has been the creation of an Integrated Water Quality Information System for use in water resource operational and planning decision support. In addition, however, the interaction with water managers has developed a clearer understanding of the day-to-day operational needs of these managers and which tools would best fulfil their requirements. Greater insight has been gained concerning the type of analysis and simulation tools, which are suitable for integration into an information system and the benefits of using existing models and modules rather developing new tools from scratch.

If the considerable interest and discussion stimulated by the development of this system is an indication of the need for effective decision support, then this WQIS could form the building block of an efficient, workable tool to be used in a wide range of future water resource applications.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

DISA	-	Daily Irrigation and Salinity Analyses Model
DWAF	-	Department of Water Affairs and Forestry (South Africa)
ESRI	-	Environmental Systems Research Institute
GCTMA	-	Greater Cape Town Metropolitan Area
GIS	-	Geographical Information System
GUI	-	Graphical User Interface
RSE-BR	-	Riviersonderend-Berg River System
WDM	-	Watershed Data Management System
WQIS	-	Water Quality Information System
WRC	-	Water Research Commission

CHAPTER ONE
INTRODUCTION

1.1 BACKGROUND AND CONTEXT

Impoundments and associated bulk water supply infrastructure are present in most South African river systems. Because of the disparate natural occurrence of rainfall and runoff, and its mismatch with water demand concentrations, many of these schemes have to incorporate inter-catchment transfers to meet demands in the face of inadequate local availability. Furthermore, water quality deterioration, because of human impacts through a wide range of land-uses and waste discharges, has for some time been recognised as a threat in South Africa, as it diminishes the utilisable part of the runoff in many catchments. These complexities increasingly offer challenges to water resource managers that require a response with integrative management philosophies and innovative management tools.

During 1997, in recognition of the aforementioned needs, the Department of Civil Engineering of the University of Stellenbosch, formulated a research proposal to the Water Research Commission (WRC) whose aim would be to serve the philosophy of Integrated Water Resource Management (IWRM), through the development of an integrated information system specifically for water quality – here abbreviated to “WQIS”. To be useful to IWRM, this WQIS was to provide diagnostic and predictive utilities to serve technical planning and operational decision-making in a river system, but, simultaneously, provide appropriate information to support water managers in communication with technical stakeholders. It was also recognised that the project would need identification of a “prototype” catchment for development of appropriate WQIS approaches and to provide a relevant database.

One of the aims of this project was to develop Water Quality Information Systems (WQIS) to support both integrated management of a water resources system, and to support communication about water quality management with stakeholders and communities in the catchments of that system - In this study the Riviersonderend-Berg River (RSE-BR) System was used as the prototype catchment. To develop this WQIS, however, it was necessary to combine a suite of water quality models with a user interface so that the results of the modelling could be visually interpreted. **CE-QUAL-W2** (refer to section 3 of volume1), a two-dimensional hydrodynamic and water quality model, was used to simulate the flow pattern and constituent profiles in the proposed impoundment in the system while **DUFLOW** (refer to section 2 of volume1) a one-dimensional hydrodynamic river flow and water quality model was used to simulate the river. To amalgamate the two hydrodynamic and water quality models a **Graphical User Interface (GUI)** was used. The GUI consisted of a database for linking the input and outputs from the river and reservoir models, graphing and analysis tools as well as a Geographical Information System (GIS) for displaying spatial information. The development of the GUI is discussed in the ensuing chapters.

1.2 MOTIVATION FOR THIS RESEARCH

To demonstrate the principles and dynamics involved in creating a tool to assist with the water resources management of a complex river system, the Riviersonderend-Berg River System was selected as a suitable Case Study. This system contains many of the archetypal complexities, such as impoundments, bulk water supply infrastructure, limited water resources, and deteriorating water quality due to human impacts, that offer challenges to water managers and that require innovative management tools and philosophies.

A key objective of this study was to develop and apply a water management tool, referred to as *An integrated Water Quality Information System (WQIS)*, to the Riviersonderend-Berg River System. The aim of the WQIS and its linked simulation models was to offer supporting information, useful to the immediate planning of new water supply schemes or to water quality management decisions related to pollution incidents or licensing under the National Water Act (South Africa, 1998). Interaction with water managers raised the need to include facilities in the WQIS for devising short-term operating policies to ensure minimisation of water wastage or sudden quality problems.

It was intended that the framework created here would also be applicable to many other cascading type river-based bulk water supply systems in South Africa and provide sound information and decision support to water managers and other interested river users.

1.3 OBJECTIVES

The primary objective of this project was to combine existing simulation models through a consistent, user-friendly interface, incorporating Geographical Information Systems (GIS) and sound graphing and analytical capabilities in order to satisfy as many as possible of the information and modelling needs of the technical user or the water manager.

The sub-objectives of this research were:

- To interact with potential users to gain a good understanding of their information, modelling and decision support requirements.
- To integrate relevant simulation models in appropriate ways.
- To critically assess, based on management and potential technical user feedback, the ability of the simulation models originally chosen for integration into the WQIS to perform the different functions of planning and operational management.
- To research alternative methods or models for integration into the WQIS, where the simulation models did not provide the required management options.
- To apply the WQIS to the Berg River System.

1.4 OVERVIEW OF METHODOLOGY

To determine the requirements of the system, it was necessary to interview the potential users of the WQIS (as defined in Section 1.2) and establish their needs and preferences in terms of modelling (input and output), display of results and interface environment characteristics. These requirements, in turn, determine the software characteristics, methods of integration, operating step and types of output required when developing the WQIS.

1.4.1 Modelling Tools

The focus of this aspect of the research was to determine, by way of interviews, the key functions required of streamflow simulation and quality models, by water managers, to perform their every day operational and planning duties. Long-term hydrodynamic simulation/planning models were suggested/required for use in this project and their relevance, applicability to the users' requirements and methods of integration were investigated and compared with alternatives.

1.4.2 Interface Environment

When researching an appropriate interface environment, the aim of the software development was not to just fulfil new technical modelling requirements, but rather to develop a uniform environment into which existing, or still to be developed, models can be integrated.

As stated in the primary objective, the interface environment was required to incorporate GIS and good analytical and graphing facilities. Therefore, the numerous GIS and programming products available were also researched in order to choose the product or combination of products that would best address the needs of the project while also catering for various levels of expertise.

1.5 FRAMEWORK FOR THE WQIS

Effort spent on the technical development of the WQIS, although essential, was considered no more important than the gathering of knowledge about, and understanding of, user needs. Therefore, this document focuses on the process of interactive development and integration of a water quality information system that addresses the needs, comments and recommendations of the target user, throughout its development and in its final function, while still fulfilling the technical requirements for which it was designed. It also aims to provide a consistent environment for the user to view the results of the various function specific models.

The initial list for WQIS components is as follows:

- Hydrodynamic flow and water quality river model,
- Hydrodynamic flow and water quality reservoir model,
- GIS to store, analyse and display spatial information,
- One or more databases linking the input and output from the above components, and
- A User-friendly Graphical User Interface (GUI), which seamlessly interacts with all the components and provides the means to analyse and display data and the results of scenario testing with the models. This enables the user to become familiar with the conventions and environment rather than continually expose them to new technology and models, each with their own styles and look.

The actual mechanisms for interfacing the components, and the final component list were confirmed after reviewing the technical management and communication needs of the target groups (see Figure 1.1). This will hopefully develop the WQIS into an indispensable tool in constant use, rather than being a one off modelling exercise.

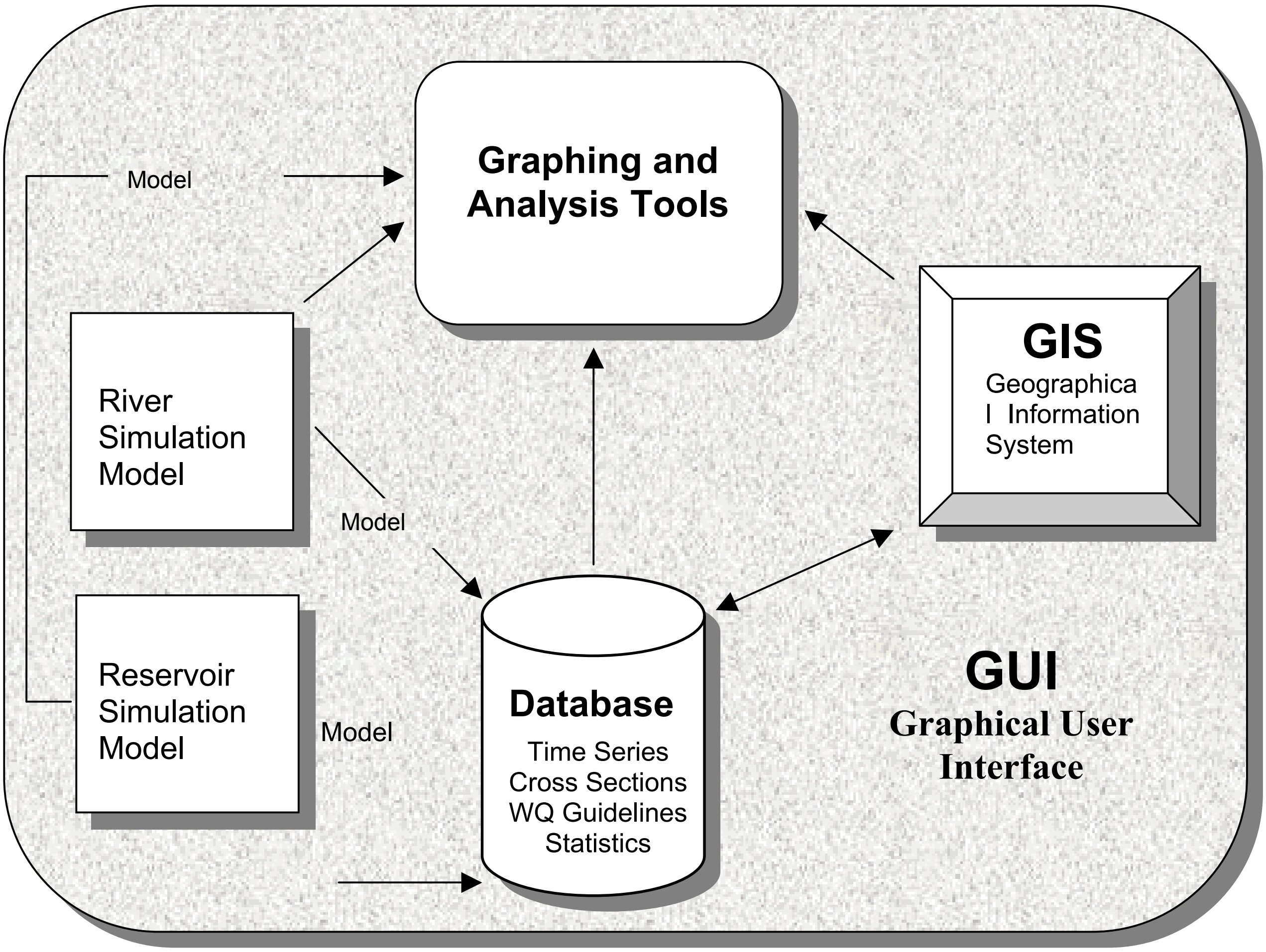


Figure 1.1: Conceptual Model

CHAPTER TWO
THE BERG RIVER CATCHMENT AS A CASE STUDY

As mentioned in Chapter 1, the Berg River catchment has been used as the study area for the application and development of a Water Quality Information System. The biophysical characteristics of the catchment are described below and their unique interrelationships and management issues are discussed.

2.1 PHYSICAL CHARACTERISTICS

The Berg River has its source in the mountainous area of the Groot Drakensteinberge. The upper region of the Berg River basin is surrounded by high mountain ranges to the south, east and west. The river basin is fairly narrow (10-15km) between the source and Wellington. North of Wellington, the Limietberge bound the valley to the west, and in the east the basin levels out and the river valley widens to approximately 25km.

From the source the Berg River flows north and joins the Franschhoek River in the Franschhoek Valley. It is joined by two more tributaries, the Wemmershoek River to the east and the Banhoek River to the west, halfway between Franschhoek and Paarl. The Berg River then flows through Paarl and Wellington where it is joined, from the east, by the Krom River. This tributary has its source in the Limietberge and drains the valley above Wellington. North of Wellington, the Berg River is joined by various other tributaries including the Klein Berg River, Kompanjies River and the Twenty Four Rivers. The Klein Berg has its source in the high lying Winterhoek Mountains in the north-east of the Tulbagh Valley. Further southwards it is joined by the Boontjies River. From there, it flows westwards between the Obiekwa and Voëlvlei mountains into the Berg River Valley and joins the Berg River to the west of Saron. Approximately 3km north, is the confluence of the Twenty Four Rivers and the Berg River.

After a further 10 to 15km, the Berg River flows over the Misverstand Weir. Upstream of the weir, it is joined by the tributaries that drain the areas north of Porterville and Moorreesburg. The river flows in a northwestward direction and drains into the Atlantic Ocean at Velddrift (DWAF, 1993).

2.2 CLIMATE AND HYDROLOGY

The climate in the Berg River catchment is typical of the Western Cape Region. This region is classified as the humid zone and experiences winter rainfall and high summer evaporation. Precipitation occurs as a result of the cold fronts approaching from the northwest.

In the high lying areas of the Groot Drakenstein, the Mean Annual Precipitation (MAP) is above 1500 mm but reduces steadily to under 500mm further northwards where the Berg River levels out. The MAP then drops further to below 300mm at the mouth (Midgley *et al*., 1994). The Mean Annual Evaporation (MAE) in the southern and western regions of the catchment is between 1400mm and 1500 mm and increases to over 1600mm in the northeast. There are significant seasonal variations in monthly evaporations which fall typically between 40 and 50 mm in winter and 230 – 250 mm in the summer months (Midgley *et al*., 1994).

The number and distribution of flow gauging stations recording runoff in the upper and middle reaches of the Berg River is adequate for water resource purposes. The Misverstand Weir is the most downstream site where a reliable continuous runoff record is available.

2.3 RESERVOIRS

There are three existing reservoirs within the Berg River catchment. Voëlvlei and Wemmershoek are relatively large dams and Misverstand Weir is considerably smaller. These have already been discussed in Volume 1, Section 2.

2.4 IRRIGATION

There are numerous, formal irrigation schemes in the Berg River catchment which, for the most part, fall under the operation of the Upper Berg River Irrigation Board. Irrigation is predominantly during the summer months with the exception of the Paarl Municipality which irrigates throughout the year when necessary. The main types of irrigated crops are vines, fruit and vegetables (Midgley *et al*, 1994). Each irrigation scheme has limited annual quotas.

2.5 CATCHMENT MANAGEMENT ISSUES

The demand for water in the Greater Cape Town Metropolitan Area (GCTMA) is increasing as a result of population growth, improved living standards and irrigation expansion. This sustained growth will necessitate expansion of the Riviersonderend-Berg River (RSE-BR) system in the near future.

The combined impoundments of the RSE-BR catchment system currently contribute more than 80% of the total annual water yield of 450 million m^3 available to the bulk water supply system of the GCTMA. In order to overcome potential shortages of water and to minimise adverse impacts caused by continued development of new water sources, strategies to augment supplies and moderate the demand for water are required. The following schemes are being investigated for imminent implementation in the Berg River:

- Skuifraam Dam in the Upper Berg and
- Skuifraam Supplement Pump Scheme downstream of Franschhoek and Lorelei Diversion to an enlarged Voëlvlei Dam in the Middle Berg.

These schemes also aim to provide improved water supply and sanitation to a number of disadvantaged communities as part of numerous RDP projects. Development of irrigation schemes for emergent farmers from these communities will also be made possible. In addition, irrigation extensions by currently established farmers will also be possible.

The implementation of these schemes is likely to remove an additional 20% of fresh water from the Berg River main stem and will lead to a strongly regulated river system between Skuifraam and Misverstand. The real possibility that these planned developments will go ahead has caused concerns about the water quality fitness for use and ecological deterioration.

New irrigation areas will receive fresh water from the water supply developments mentioned above. However, these extended irrigation areas will increase the saline irrigation return flows reaching the Middle to Lower Berg system and possibly exacerbate the moderately high salinities already recorded in those reaches. An understanding of the soil types, their distribution and their leaching characteristics would prove useful to demarcate “salinity hazard zones” where new irrigation development should be restricted. This issue is being investigated in a concurrent WRC study conducted at the University of Stellenbosch.

High summer releases for irrigation are made from Voëlvlei Dam (and Skuifraam in the future) which stratifies during summer. These large volumes of cool water are unusual for a winter rainfall area and may also cause river temperatures and oxygen levels to be unacceptably low. In addition, the volumetric In-Stream Flow Requirements (IFR) of the river system, particularly the wetlands near the Berg River Mouth and the tidal zone of the estuary, need to be considered.

Another potential water quality risk is the increase in nutrient levels. Due to the increase in population in the catchment, increased volumes of treated wastewater effluents and non-point source loadings are augmenting nutrient levels in the Middle Berg River. This, in turn, may lead to eutrophication hazards in Voëlvlei and Misverstand Dams.

2.6 DISCUSSION

The unique characteristics of the Berg River catchment and the numerous, on-going and planned developments within the catchments require collaborative and continual management from all interested parties. The development of a single decision support or information tool that can be used by all those involved in the management and use of the river catchment, is an intuitive way of stimulating discussion, offering solutions and reaching consensus.

This tool needs to be developed with the continual input of the relevant managers and users so that it becomes a workable, well-used system. The components of the system also need to be considered carefully to ensure that they correctly describe the processes occurring in the catchment. A number of components may be integrated into an information system to offer the best solution.

These processes of interactive development and system integration are discussed in general, and in terms of their application to the current project, in Chapters 4 and 5, respectively.

CHAPTER THREE
DESIGN PRINCIPLES OF MANAGEMENT INFORMATION SYSTEMS

There are many processes that act and interact in our everyday business, government and environment. These processes rely on “resources” in their various forms (staff, time, finance, water etc.) as driving forces. However, there are almost always limitations on these resources, as they are generally unevenly distributed in space and time. The management of these resources within an atmosphere of continual change is a very complex task and research and expertise are often specialised or focussed on selected aspects of resource management. This ‘modular’ approach is losing popularity as an effective management strategy and new methods of integrated resource management are being sought.

A similar pattern has occurred in the development of the software tools that have resulted in or corresponded with, the type of research discussed above. The rapid progress in computing capability produced a plethora of computer simulation models to simulate many aspects of the business world or environment. As Dent (1993) remarks, computer simulation models formalise, in a quantitative manner, the knowledge that we have about a process. Many of these models have been very successful in providing insight into specific processes, but rarely address the significant impacts that these processes may have on any number of related aspects.

There is a drive to develop information and decision support tools that will enable knowledge seekers and concerned individuals to make informed decisions based on large volumes of information on a wide range of aspects at the same time. Turban (1993) suggests that these technologies have the potential to create a synergy that greatly impacts on the effectiveness of managerial decision making. However, there is an on-going debate concerning the kinds of information, the structure and major components required by the decision support or management information system. Wijers (1993) states that in such a multi-faceted environment, the concerned parties need to be in a position to see the whole picture, to assess the current needs and future aspirations of all users and to make decisions in the interests of all concerned.

To this end, some of the many challenging tasks in the implementation of an information system are listed below and discussed in the following sections.

- Data and information collection.
- Design of a database structure to suit the information requirements of all disciplines involved.
- Design of data capture and data management facilities.
- Population of the database
- Incorporation of models and other management tools.
- Incorporation of analysis and graphical tools.
- Creation of a user friendly interface and menu system
- Creation of an organisational structure responsible for information maintenance.

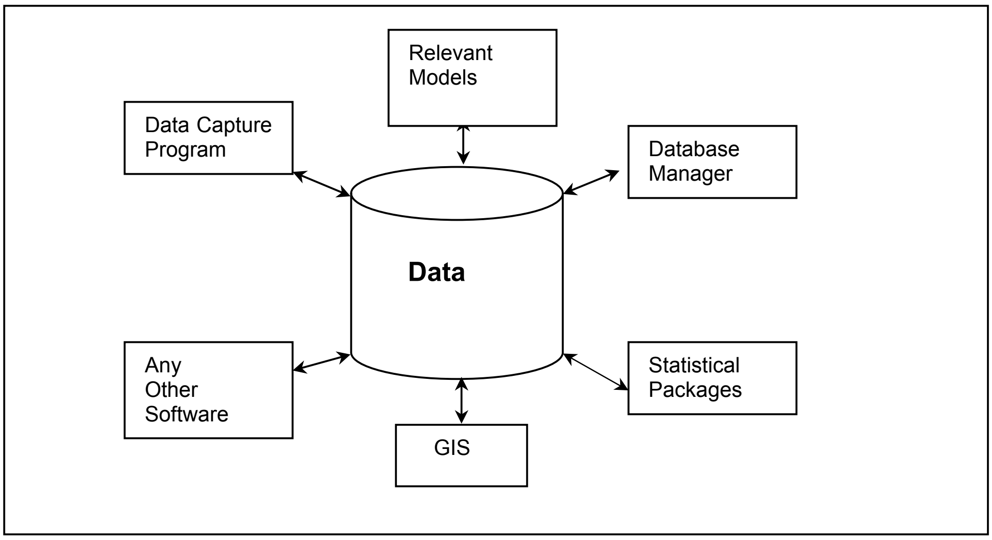


Figure 3.1: Simplified Structure of a Management Information System (after Wijers (1993))

A management information system is a formal, computer-based system, intended to retrieve, extract and integrate data from various sources in order to provide timely information necessary for decision making (Turban, 1993). Figure 3.1 illustrates the typical, simplified structure of an information system, the aim of which is to satisfy the decision support, modelling and general information requirements of as many users as possible. To provide these functions, the structure of the information system needs to be flexible enough to accommodate a variety of components that cover the wide spectrum of disciplines involved. The main components that would ideally form the basis of an effective management information system are discussed below.

3.1 DATA MANAGEMENT

The effective management of any resource, process or organisation relies to a large degree on the availability and accessibility of adequate and accurate data and information. Rob and Coronel (1993) agree that organisations usually prosper when their managers act on the basis of efficiently generated, relevant information. Although data is the fundamental building block of most modelling and information systems, it rarely receives the attention it requires. More often than not, incomplete and outdated data is used for modelling exercises, the results of which are used to make fundamental decisions.

The consistent and conscientious collection of data should be encouraged and a database structure that accommodates easy access by a wide range of applications and users should be devised to store the data and information. Efficient data entry facilities need to be developed to facilitate, firstly, the initial population of the database and then any subsequent updates, in a consistent format.

Once established, the database needs to be continually maintained. For this reason, a data manager should be included in the system to run quality checks and backups and maintain a data dictionary or metadata. Another important function of the data manager would be data conversion, i.e. provision of data in a suitable format to other system components or to other information users.

3.2 MODELS

The type and nature of the models required (if any) by a management information system will obviously be dictated by the system's ultimate function and the environment it aims to represent. No matter which models are used, there should be an efficient and effective way of converting the model output to and from the database format so that the information can be accessed and used by any of the other models and components that make up the information system.

Before the models are integrated into the information system, they should be well researched, concentrating on issues such as:

- software platform compatibility,
- nature and size of model input and output,
- licence agreements and portability,
- setup and running time,
- model purpose.

3.3 ANALYSIS

Tools for analysing data and the results of the various modelling components are essential elements of an information system. These tools provide the facility to convert vast amounts of data into meaningful information which in turn can be used to make essential management decisions.

Standardising these analysis tools in the information system precludes the need for a variety of stand alone applications, each with its own data formats, operating procedures and visual environment. The user will become familiar with a single analysis environment and, therefore, will easily understand the graphical results of each model. Inconsistencies in analysis methods will be eliminated.

3.4 GEOGRAPHICAL INFORMATION SYSTEMS

According to the ESRI President, J Dangermond, “Knowing where things are and why is essential to rational decision making”. In all areas of decision making, a visual representation of the process often provides a good overview of the situation and can highlight points of significance. A few examples of this are:

- Business: office floor plan for most effective/least disruptive staff communication
- Government: location and distribution of voters within constituencies
- Environment: geographical map showing the distribution of rainfall and runoff gauges
- Systems: layout and interconnectivity of PC stations within a network

Although GIS is a fairly new addition to most information systems, it is relatively easy to integrate and has enormous potential for describing the system and processes about which decisions need to be made.

3.5 RESPONSIBILITY AND OWNERSHIP

The concepts and motivation behind implementing an information system may seem exciting, productive and even essential for future decisions and operations. However, even after successful design and implementation phases, the information system needs to be “maintained”. This requires an organisation or department within an organisation to assume responsibility for the new system, i.e. provide user support, implement upgrades, monitor backups and design and develop new features based on user feedback, new technology and new procedures. A well-maintained system will become an indispensable and well-used application, if the data, tools and technology are kept current and operational.

3.6 DISCUSSION

Effective management requires the definition of clear goals and objectives, an efficient organisation and a reference framework for decision support. To this effect, effective management requires an information system which provides (at least) the following list of functions:

- Contains and allows easy access to large volumes of data concerning a multiplicity of themes and disciplines,
- Provides relevant information at an appropriate level of detail in a user friendly format,
- Provides an information platform flexible enough to accommodate a wide range of applications.

These information systems couple the intellectual resources of individuals with the capabilities of the computer to improve the quality of decisions (Turban, 1993). It is essential to make information systems as generic as possible for ease of transfer to other scenarios and simulation cases. Systems should be transparent and always evolving, based on user’s comments. In this way, information systems are a means of stimulating discussion and new ideas, making good use of data and detecting areas where new information is lacking and hence may need research effort (Dent, 1993).

CHAPTER FOUR
PROCESS OF INTERACTIVE DEVELOPMENT

The development of an effective decision support information system involves complex communication and design challenges. To fulfil the aims of this project, both sets of these challenges had to be dealt with effectively to produce an information system that satisfies the requirements of the intended users. Two crucial concepts that feature here were “interactive” and “integrated”.

Interactive development comprises ongoing communication between the developer and users and mutual inputs and responses regarding the conceptual and general design of the required information system. Integration refers to the linkage and communication between the actual components of the system. The components and level of their integration required to appropriately meet user needs should be agreed upon as part of the interactive development process.

Both interactive development and system integration are crucial objectives (see Section 1.3) of this project and as such have been researched and implemented. Interactive development is discussed in this chapter and integration is dealt with separately in Chapter 5.

4.1 INTERACTIVE DEVELOPMENT

4.1.1 Learning from Past Experience

“We developed a system for them – so why don’t they use it?”

Shepherd (1997) admits that this is probably a question asked by many developers and even managers, after a new system has been designed and implemented. The key to the success or failure of any system is the level of communication between user and developer during the entire analysis, design and implementation of the system. Dearnley and Mayhew (1983) agree that the conventional approach to systems design is one in which the user is passive, only being interviewed during the fact-finding investigation, and the analyst or developer is active, doing the design and development. This approach concentrates on technological development, creating a ‘new’ system, and neglects the process of interactive development and implementation.

A contrasting approach is one in which the user takes an active, or participative role in the system design process. In this way, not only is the process of technological development examined, but the critical interactions between the system developer, the technology and the user are also analysed. It is important that the developer engages in a process of ‘interactive development’ with the user rather than just for the user. A system’s acceptance by a user depends not only on system attributes, but also on the process by which it is integrated into the user’s work routine (Shepherd, 1997).

Dearnley and Mayhew (1983) list numerous tools that can be used during the different stages of the participative design process to achieve a system that satisfies as many requirements as possible. These include surveys, field tests, prototypes and simulation.

As a first step, a process of initial knowledge acquisition should be performed, where the developer would observe and interview the experts and users to gain insight into the basic requirements and processes required. This could be done by means of surveys/questionnaires or interviews.

Once the basic requirements and components of an information system have been established the process of development begins. Shepherd (1997) warns that the mere development of, or decision to adopt, a new information system does not necessarily guarantee that the target users will make use of the system. Although there may already have been extensive negotiations as to the type of system required, a constructive process of iterative, interactive development should be re-enforced.

Interactive involvement promotes acceptance of the product and creates a sense of ownership, responsibility and commitment. This interactive, adaptive approach to development and implementation will create a better system, as the expertise, feedback and needs of the user will be incorporated, thereby increasing the acceptance of a system that was developed with input from the user. Using a prototype of the final system is a good way to stimulate interest and feedback. A prototype is an approximation of the required system and contains certain essential aspects of the final system that need to be tested in some manner (Tate, 1990). The prototype is by nature, incomplete, unreliable and has limited functional capabilities, but has value in that it reduces project risk that arises from incomplete knowledge of what is required, or how to achieve it. Tate (1990) states that the primary reason for prototyping is to buy knowledge and thus reduce uncertainty, and increase the likelihood of success of the software project. The knowledge gained from demonstrating the prototype (running test cases and scenarios) can provide vital clarification of requirements, feasibility, user acceptance, marketability, system behaviour and critical performance factors (Tate, 1990). The system would then be modified and demonstrated again in an iterative process (within a given budget) until the users are satisfied (Shepherd, 1997).

If an attempt is made to follow the steps outlined above, there is a greater chance that the new system will ‘include’ the user in its operation and will function using the user’s knowledge and not disregard it totally by imposing new methods. The system will incorporate the user’s familiar methods, but hopefully also facilitate progress if the user’s “comfort zone” is outdated. Increased user acceptance would also occur if the developer focused more on ways to support users in the way they make a decision rather than on sophisticated algorithms to make the decision for them.

The system should be critically assessed throughout the development process. The many small loop back steps shown in the Systems Life Cycle diagram in Figure 4.1 illustrate the iterative nature of the investigation, analysis and design steps.

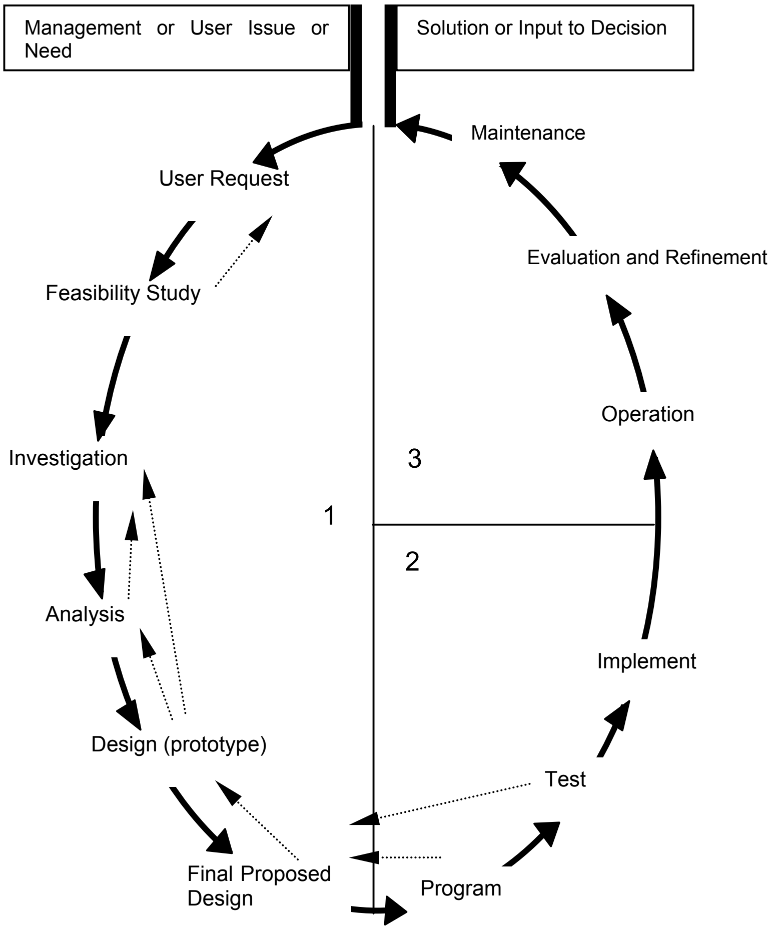


Figure 4.1: Systems Life Cycle - Stage 1: study and design, Stage 2: implementation, Stage 3: operation (Dearnley and Mayhew (1983) modified)

An enforced change or discovery of shortcomings in any one step may result in a loop back to another step. Some of the questions that should be posed during this iterative procedure are listed below, modified from Shepherd (1997). To make the system truly successful and to avoid excessive revisiting of the System Life Cycle steps, the answers to a majority of the following questions should be positive.

For the user: Does the system

- help the user to be actively involved rather than be a passive observer,
- help to improve and refine the user's skills,
- focus on the user's needs,
- let the user carry out practice as usual,
- improve the quality of the user's operating decisions ?

General system: Does the system

- provide reliable decision support,
- improve the efficiency of decision making,
- provide trustworthy advice,
- promote positive innovation in the work place,
- incorporate good teaching tools,
- incorporate good learning tools,
- function as a tool for regular use,
- provide useful feedback,
- allow flexibility ?

4.1.2 Implementing Past Experience for this Study

For this project, a number of the basic system components had already been outlined in the project proposal. To gain insight into how these components would best be linked, operated and displayed, a questionnaire was distributed to potential users and those with valuable knowledge in the relevant fields. A prototype was then developed based on decisions made regarding software, methods of integration and technical feedback from the questionnaires. The prototype was then demonstrated at a series of interviews and demonstrations where further feedback was recorded and further software adjustments were made. Finally, a comprehensive demonstration of the near-final WQIS was undertaken for a Steering Committee for this project, comprising persons in management or scientific roles. Their comments and requests were incorporated to produce a final version of the WQIS.

4.2 METHODS FOLLOWED IN WQIS

The steps taken as part of the participative approach to the design and development of the WQIS in this project are discussed in detail in the following sections.

4.2.1 Questionnaires

A questionnaire was drawn up and distributed to a number of knowledgeable persons who could provide valuable input and have experience in any of the following project related fields: management of water quality, planning of water resources, model/software development, model/software use. The questionnaire outlines the research project and stipulates the intention and aims of the WQIS.

The time spent on the questionnaires by those who responded (approximately 50%) is much appreciated and the replies provided valuable input and guidelines for the development of the information system. The information provided in each response varied according to the particular area of interest of the respondent. However, the general agreement concerning water quality modelling in rivers was that a short time step, preferably daily (dependent on data constraints and monitoring programmes), would best provide the information required to highlight and manage point and non-point pollution sources. The water quality information (concentrations and loads) should be displayed in time series (compare time frames), spatial graphs (compare river reaches) and box and whisker plots for a statistical overview of the catchment.

4.2.2 Interviews

The aim of the interviews was to speak to a broad spectrum of "water managers" with operational, water quality, planning or decision support interests. Organisations that were visited were: Cape Metropolitan Council, Department of Agriculture, Elsenburg, WAM Software Solutions, DWAF (Belville), DWAF (Pretoria), Ninham Shand, University of Stellenbosch, Department of Geography and Environmental Studies and University of Stellenbosch, Department of Civil Engineering.

A prototype of the WQIS was used during the interviews to facilitate discussion and stimulate suggestions and modifications necessary to enhance the WQIS within the project limits. Each interviewee was asked to comment on a number of specific issues and also to provide feedback on personal preferences. The specific issues included:

- Display environment
- Graphical display format and content,
- Input and output resolution,
- Simulation model output representation.

The prototype version of the WQIS aimed at giving the interviewees an idea of what was envisaged from the WQIS and also provided an opportunity for them to challenge or agree with the processes, concepts and specifications used in the WQIS.

4.2.3 Responding to Steering Committee Comments

A near-final version of the WQIS was demonstrated to the Steering Committee for this project. The members of the committee had further comments and suggestions, some of which were implemented and are discussed in the description of the WQIS in Chapter 7 and in Chapter 9. Other issues such as the future connectivity of WQIS to a Watershed Data Management file system (WDM) developed by the US Geological Survey (Lumb *et al*., 1988) and the need for further research into more detailed water quality constituent modelling, are discussed in the Chapter 10 in the section on future research.

4.3 DISCUSSION

The prototype demonstrations and accompanying discussions provided valuable insight into the preferences and expectations of those most likely to use, or manage the use of, the WQIS.

4.3.1 General Display and Presentation

There was some concern that information systems are too often written by technical experts for users with technical competency. As a result, the graphics, tools and language used in the applications are too technical and clinical. Screens with many buttons and toolbars might be somewhat alienating. An alternative would be to provide a much simpler interface where the user is guided from a main menu, through a series of screens by clicking one of very few, larger buttons on the screen. This approach is used for public participation exercises with non-technical persons.

The prototype falls primarily into the first category and, on the assumption that potential users would be highly computer literate, uses Windows type menus and toolbars and a fairly standard GIS interface. However, a few screens were developed to represent and test the interest in the less technical approach.

These two options were presented at each interview and, in all but one case, the more technical approach was preferred. The reasoning behind these decisions was that, in most cases, the users of the WQIS would be computer literate and would therefore be familiar with the Windows environment. The procedure of moving through screens would be intuitive and would not require large ‘leading’ buttons. It was agreed that the simpler interface had merits as a display or discussion tool, to be used in meetings with community Forums for conveying summarised technical information in a simplified and more understandable format.

4.3.2 Level and Resolution of Data and Information Required

It was agreed that information and data should be available at multiple levels, i.e. raw data through to processed statistics. This builds confidence and trust in the information presented by the WQIS and therefore offers the potential for wider and more appropriate application.

The results of statistical analysis are often presented without a description of the methods used for calculating them. This could lead to scepticism or misuse of the results. If the raw data is supplied, the users may perform their own statistical analyses to verify the results and satisfy their mistrust. In addition, if the results are explained fully, or “de-mystified”, as one interviewee put it (O’Bree, 1999), there is no need for double-checking, and the results become dependable and useful for decision-making.

The purpose of the WQIS dictates the level and resolution of input and output information required. If the WQIS is being used for day-to-day operational management of the river or reservoir system, then reliable, measured data is necessary, usually at a fine resolution (daily). However, if the WQIS is being used for long-term planning such as statutory or water allocation decisions, a more broad-brush approach is required. Here, several months, or even years, of data can be summarised to extract trends, long-term averages, minimums and maximums.

4.3.3 Identifying the Purpose of the WQIS

The purpose of the WQIS prescribes the relevant models required for integration into the WQIS. From the discussions it became clear that most managers and operators are concerned with the day-to-day operational management of rivers, or with responses to water quality changes. Their primary focus is short-term decision support and management of urgent situations such as water quality spills, irrigation releases or flood management. Therefore, simulation models with short setup and run times would be required to produce the necessary decision support results. This analysis is discussed in Chapter 9.

CHAPTER FIVE
INFORMATION SYSTEM INTEGRATION

According to the research objectives described in Section 1.3 of Chapter 1, the overall configuration of the information system required by this project, necessitated the integration of various simulation models to investigate the management of processes in main stem river systems and impoundments. These models would be required to transfer information to and from a database and operate within a graphical and spatial display environment. A Geographical Information System (GIS) offers a suitable environment for handling and displaying the information and data.

Integration, as mentioned in Chapter 4, refers to the linkage and communication between the components of the system. The process of integration is discussed in this chapter, as are the characteristics of a GIS and the benefits of its inclusion in the current information system.

5.1 INTEGRATION

Integration describes the method by which all the system components are joined, including how each component interacts with each other and the interface environment. The integration of simulation and analytical models has been a common way to combine the individual functionalities of two or more systems (Lilburne *et al*, 1997). Modellers can take advantage of extended functionality by integrating analytical, graphical, spatial and simulation tools in one of two general approaches: loose or tight coupling.

Coupling (or linking) suggests the extent to which the components are integrated within the information system. Loosely coupled modelling is primarily for taking advantage of database and visualisation tools, which can be improved by capitalising on analytical tools and techniques. The GUI and interface software is used to construct input files that a simulation program can read and the results of the simulation are then read back into the GUI for display and analysis (Bennett, 1997). Tightly coupled models are completely encapsulated within the interface environment and take full advantage of its analysis capabilities (Karimi and Houston, 1996). Once integrated, the information system then offers a virtual environment within which decision-makers and scientists can explore the interaction of simulated processes and evaluate competing management strategies (Bennett, 1997).

The way in which simulation models exchange input and output may also vary. Models can be integrated either in series or in parallel. Parallel linking is fairly complex and involves using the output from one model as input to another, in the same time step. This method would be appropriate when "real-time" exchange of data is required. However, the simpler and more common method of integrating simulation models is in series which involves allowing the first model to complete a run and then using its output as input for the next model (Jewitt, 1998).

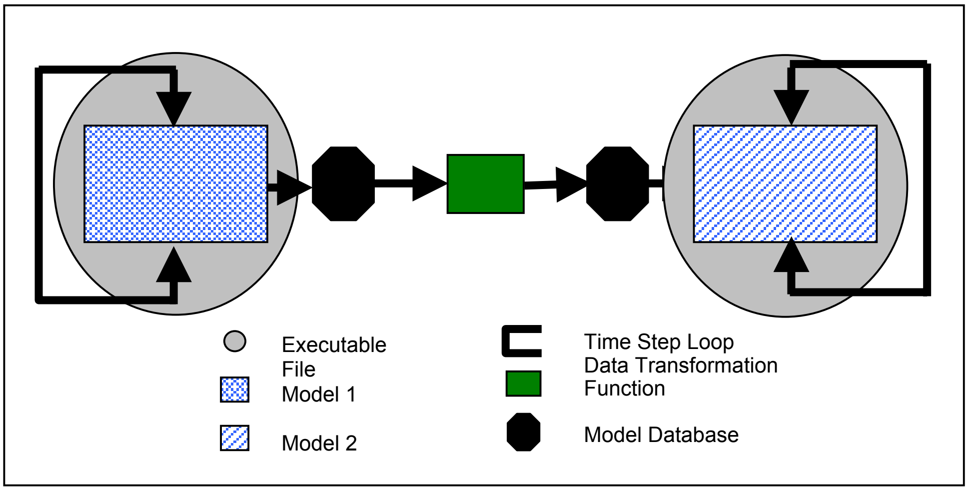


Figure 5.1: Linking models in series (after Jewitt (1998))

For this project, the loose coupling approach, as illustrated in Figure 5.1, was adopted which enables the user to view and analyse the simulation model output, graphically and spatially, using the functionality provided by the interface environment and incorporated GIS. Originally, the simulation models were designed to operate in series, but due to output and input constraints, this information exchange was adjusted.

5.2 INITIAL SIMULATION MODEL SELECTION

As stated in Chapter 1, one of the primary objectives of this study was to combine various, existing models within a consistent, user-friendly environment. The aim of creating this tool was to satisfy as many as possible of the technical user's or water manager's information and modelling needs, using the Berg River as a case study.

Most of South Africa's regulated river systems are operated on a time resolution of days to weeks, i.e. distinctly sub-monthly. Some of these systems have relatively high gradients and shallow soils which result in fast runoff response to rainfall and unsteady flows during the wet season. The models currently used for water resource planning in South Africa operate primarily on a monthly time step, assume steady flow and do not satisfy the water quality simulation requirements of the aforementioned objectives (BKS and SSO, 1988). The daily models in use cater only for the salinity component of water quality (DWAF, 1990) and because of their requirement to be intensively calibrated, may be seen to be too site-specific.

It was therefore clear that typical South African rivers, of which the Berg River is no exception, require simulation models that adhere to numerous criteria:

- The information system should operate at a daily or sub-daily time-step.
- The information system should cater for river flow hydrodynamics and simulate a range of water quality processes such as salt and nutrient transport, eutrophication and temperature and oxygen variation. A range of water quality guidelines (DWAF, 1996) should also be provided to check water quality compliance of the output of this multi-constituent model for particular management scenarios.
- Simulation of reservoir hydrodynamics and stratification.
- The information system should provide a uniform, user-friendly interface that would allow interactive access to a range of catchment data and physical characteristics. These would include historical water quality data and flow time series and extra quality data collected under this project, cross sections, photographs, land-use, soils information, monitoring sites, infrastructure and climate.
- The information system should be easily transferable and affordable.

The reasoning behind the selection of the simulation models for this study is outlined in the following sections.

5.2.1 River Model

In Volume 1 Section 1, various models were considered for inclusion into the over-riding WRC project and were compared on the basis of their dimensional characteristics, hydraulics, equations used, numerical solution, water quality transport and variables supported, cost, availability, user-friendliness and user support facilities. DUFLOW was selected for its good user support, sound modelling principles and cost effectiveness (Volume 1 Section 1). DUFLOW is under the joint ownership of the Faculty of Civil Engineering at Delft University of Technology and the Public Works Department (Rijkswaterstaat), International Institute for Hydraulic and Environmental Engineering (IHE), the Delft University of Technology, the Agricultural University of Wageningen and STOWA.

5.2.2 Reservoir Model

For the reservoir simulation, a hydrodynamic model was required that could model density stratification and consequent water quality profiles in the impoundment. Two models were considered suitable for this purpose - the water quality version of the daily model 1D-DYRESM (Centre for Water Research, 1992) and CE-QUAL-W2 (Cole and Buckak, 1995). CE-QUAL-W2 was accepted as the simulation model for inclusion into information system (Volume 1, section 3).

5.3 GEOGRAPHICAL INFORMATION SYSTEMS

A Geographical Information System can be defined as a computer-enhanced information system that aids decision-making by referencing data to spatial or geographical co-ordinates (Schoolmaster and Marr, 1992). The Environmental Systems Research Institute (ESRI) defines a GIS as “a computer-based tool for mapping and analysing things that exist and events that happen on earth”.

GIS were initially developed for functions such as simple mapping and computerised cartography. Further enhancements have provided GIS with greater capability and the ability to store and manipulate large volumes of spatial and associated data and to present this data in summarised and analysed form in a useable and accessible way. According to ESRI, GIS technology integrates common database operations such as query and statistical analysis with the unique visualisation and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make them valuable to a wide range of public and private enterprises as a decision support for explaining events, predicting outcomes, and planning strategies.

Until recently, the analysis, storage, organisation and presentation of spatial data have been the primary functions of a GIS, but the rapid development of the object orientated programming genre and associated GIS components have broadened the capabilities of the GIS. Barandela (1997), suggests that to fulfil GIS’s potential as a suitable aid to environmental monitoring, the introduction of knowledge-based concepts and methods into GIS software should be encouraged, as well as improved integration with other techniques such as river and reservoir simulation and washoff models.

It has become increasingly viable to create organised databases, manipulate the data using various models which can be accessed through a simple Graphical User Interface (GUI) and then to present the updated information or results graphically, or in tabular form, using customised interfaces and components. According to Karimi and Houston (1996), using GIS as part of an environmental modelling framework allows modellers to use databases, data visualisation, and analytical tools in a single integrated environment.

5.3.1 Benefits of GIS for model results/display

A GIS provides the potential for powerful geographical analyses and interpretation of data (e.g. hydrological) in a spatial context (Cobban and Silberbauer, 1993). Most information can be related to a spatial index in some way (Mingins, 1996) and the amount or type of information that is required is not limited. Huge databases can be attached to points on a ‘map’ which, when recalled, can display a wealth of information, thereby turning facts and figures stored in a database into an informative summary of data linked to a geographical reference point (Mingins, 1996).

5.3.2 Decision to use a GIS

As discussed previously, once linked to simulation models and analytical tools, a GIS has the potential to provide focused information in terms of which operational, planning and management decisions can be made. Once it is established that GIS can add value to an information system, the correct level of complexity and integration must be found. Certain applications may provide too much information or complexity, which in turn leads to misuse and frustration. On the other hand, an oversimplified system may not provide the required technical focus on reliability of output.

The need for, and requirements of, the system should be well researched to ensure that the product achieves what is expected and is not just “window dressing”. The temptation is often to add all the extra features, which generally do not enhance the basic operation of the system and, in many cases, slow down processing and hamper the efficient output of results. If the environment where the system is to be used is well researched and the exact needs are identified, the integrated GIS can prove to be an asset.

Once it is established that GIS is a necessary component of the system, the choice of which product to use, needs to be made. There are numerous software products available and those considered for this project are discussed in the following section.

5.3.3 Product Comparison

There are numerous GIS products available on the market, each with their own specific features, functionality and merits. To narrow the comparison down and because of the general use among the government departments in South Africa, ESRI products were considered a good standard to commit to.

Within the ESRI suite of products there is also a wide range of useful products to choose from. Each product requires a different level of user proficiency, training, hardware, integration etc. Some of the products considered relevant to this project were Arcview, ArcExplorer, MapObjects and MapObjects Lt.

For this project, a GIS with limited capability was required to display general orientation information and access results linked to spatial locations. Advanced spatial analysis tools were not required as the bulk of the data and information analysis would be performed by the interface environment. The GIS needed to be easily portable/transferable and easy to use. The full version of MapObjects was therefore chosen to serve the GIS function.

According to van Rensburg and Dent (1997), GIS layers are fundamental requirements of any water resources analysis in which land use is critical to the generation of runoff, as is the use and abuse of water. For this purpose and for general catchment orientation and understanding, the GIS associated with this WQIS, consists of a predefined set of spatial layers containing relevant, catchment information.

5.4 INTERFACE ENVIRONMENT

Historically, many simulation and analysis models have been developed using traditional, DOS based programming languages such as FORTRAN and Pascal. Subsequently, a need has arisen for more sophisticated and visual pre- and post-processors and even total development environments for these models to facilitate the input, output and display functions. With the introduction of the object-oriented genre of programming languages, the rapid development of these processors has been made relatively easy.

Visual Basic and Delphi are two such object-oriented programming languages which offer very similar functionality and capabilities. The differences are only in their technical structure. The decision of which one to use is usually down to personal preference. The author was familiar with Delphi and in particular, applications that included MapObjects in their functionality. Therefore, Delphi (Borland, 1997) was selected as the programming environment to use for the development of the GUI, all the relevant interfaces, analytical and graphing functionality. Using MapObjects within Delphi allowed the development of the appropriate level of spatial capability combined with efficient database access and graphing facilities.

5.5 DATABASE

The decision of which database structure/tables to use was all but prescribed by the choice of the GIS component. MapObjects uses spatial layers, called shapefiles, which are the standard ESRI layer format. These shapefiles store the layer attributes in dBASE tables (i.e. with a ‘dbf’ file extension) and therefore for ease of information transfer dBASE was selected as the preferred choice of database for the storage and access of information and data.

5.6 DISCUSSION

The choice of which components to integrate in to the Information System is a complex task as the requirements of the various users may vary considerably. Each component, be it a simulation model or a GIS, is included for its specific features or functionality. However, this may, for example, be at the expense of software platform compatibility or portability. To overcome or eliminate some of these concerns, each component should be well researched before it is considered for integration, and the Information System should be designed to be as generic as possible to allow the inclusion or removal of components at a later stage to accommodate any required functionality adjustments. Chapter 8 examines some of the problems encountered when integrating the river and reservoir models into the WQIS.

CHAPTER SIX
WATER QUALITY INFORMATION SYSTEMS

Catchment models are used to simulate water quantity and quality in order to examine the outcomes of scenarios of changes in land use, land-use management practices, and water-management operations. Analysing and managing the high volumes of input and output of complex river and catchment models is a major task. Various models have been developed to deal with the task of managing a river catchment and storing and displaying its sizeable input and output in an integrated system. Individual models have their own unique focus, strengths and weaknesses. Some of the currently available models that also incorporate GIS are described below and are discussed in terms of their relevance to this study.

6.1 EXISTING WATER QUALITY RELATED DECISION SUPPORT INFORMATION SYSTEMS

There are numerous water quality information systems available, each with its own merits. To narrow the selection and provide a good base for comparison, only the water quality models that have been developed with a GIS component were chosen for discussion and comparison.

6.1.1 ICIS (Jewitt, 1998)

The integrated catchment information system (ICIS) is a prototype software system designed to assist the meaningful participation of stakeholders in integrated river management. The ICIS system provides a framework of tools to assess impacts of change in a catchment in a spatial context. The system also aims to provide a management tool that can be used to compare different catchment development scenarios.

6.1.2 BASINS 2.0 (Lahlou *et al*, 1999)

Better **A**ssessment **S**cience **I**ntegrating Point and **N**onpoint **S**ources (BASINS) is a system developed to meet the needs of environmental agencies, particularly in the USA. These agencies are increasingly emphasising catchment and water quality-based assessment and integrated analysis of point and nonpoint sources of pollution. The BASINS model was therefore developed to integrate a GIS, catchment data, and environmental assessment and modelling tools into one convenient package.

6.1.3 GENSCN (Kittle *et al*, 1998)

GENeration and analysis of model simulation SCeNarios (GenScn), is an interactive computer program that facilitates the catchment management process by the creation of simulation scenarios, analysis and comparison of the scenarios and their results. GenScn provides an interactive framework for analysis built around an established and adaptable catchment model.

6.2 DISCUSSION

All the above decision support packages, although relevant, useful and aiming to achieve a similar goal as the WQIS, have features that are not applicable to the current study or defeat the main objectives. All the reviewed models can simulate conditions at a daily time step and adequately describe the river flow and quality conditions using their various hydrodynamic models. However, to describe the impoundments in the river catchment, both BASINS and GenScn use the HSPF simulation model which is incapable of simulating density stratification and water quality profiles in impoundments as required by this project.

In both the ICIS and BASINS models, ARCVIEW is used to provide GIS capabilities and at the current price of around R9000, is not an affordable option for many of the local councils, authorities and DWAF Regional Office who are targeted to benefit most from the development of the WQIS. ARCVIEW also requires considerable computer literacy and training as well as a software lock key for each user which makes distribution difficult. GenScn has many features that would be useful and relevant to this project as it is user-friendly and can be easily installed on any machine without licence or software keys. However, it also uses MapObjects LT, which will limit future Web enablements.

BASINS, and to a lesser extent GenScn and ICIS, require a fairly comprehensive set of supporting databases. The BASINS system includes a variety of databases that are extracted and formatted to facilitate catchment-based analysis and modelling. Four types of data are required for the BASINS analysis system, namely:

- Base cartographic data
- Environmental background data
- Environmental monitoring data
- Point sources/loading data

This data is, however, pertains to catchments in the USA. To apply BASINS to South African catchments, data in the correct format, in all four of the above categories would have to be assembled. This task, even for catchments where monitoring infrastructure is in place, could prove to be an onerous and time-consuming task.

CHAPTER SEVEN
WATER QUALITY INFORMATION SYSTEM FOR THE BERG RIVER

A prototype version of the WQIS was developed and aimed at demonstrating a preview of what processes, concepts and specifications were envisaged for inclusion in the WQIS. The prototype is described below, is followed by a detailed description of the WQIS functionality.

7.1 DEVELOPMENT PROTOTYPE

On startup, the prototype presents the user with a standard GIS interface (see Figure 7.1) consisting of

- a Map View area,
- a legend describing the coverages,
- an overview box for orientation and
- a toolbar containing general mapping tools and customised functionality.

General mapping tools were provided, e.g. zoom in, zoom out, pan, zoom to coverage extent, zoom to full extent to allow focus of the spatial data as required. The overview box indicates, using a red rectangle, the area displayed in the Map View in relation to the full extent. The legend allows the users to select spatial coverages to display. Labels of coverage features may be displayed and coverage properties such as colour, style and line thickness may be set using the "properties" button on the tool bar, or the drop-down box activated by right clicking on the legend.

The customised tools are divided into those dealing with the river modelling and those focused on the reservoir modelling. Where possible, this information was linked spatially to points on the map to allow the user to physically locate points of interest or concern. Once these points have been located, the data and model output can be interrogated and used to form an opinion, or make a decision for operational management, planning or interest.

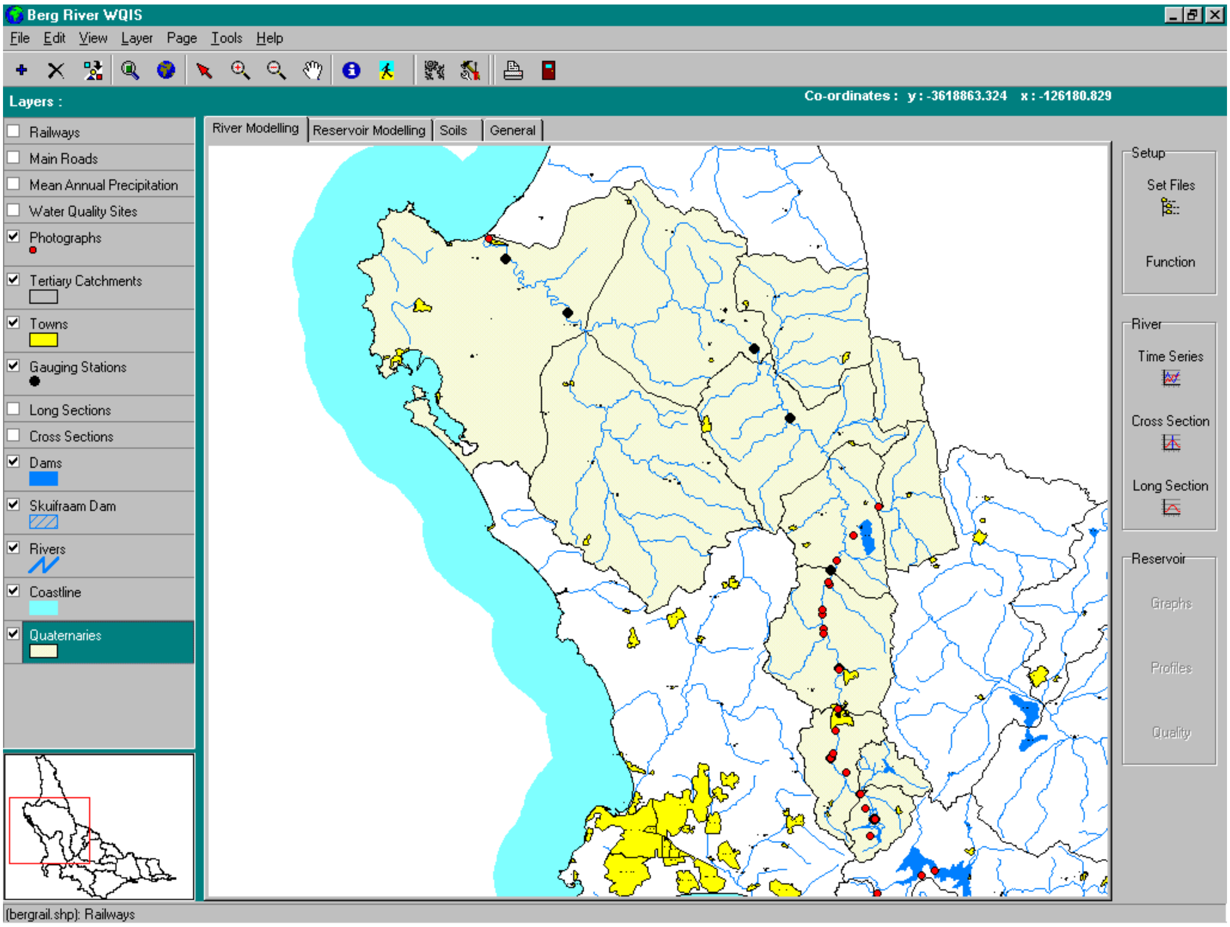
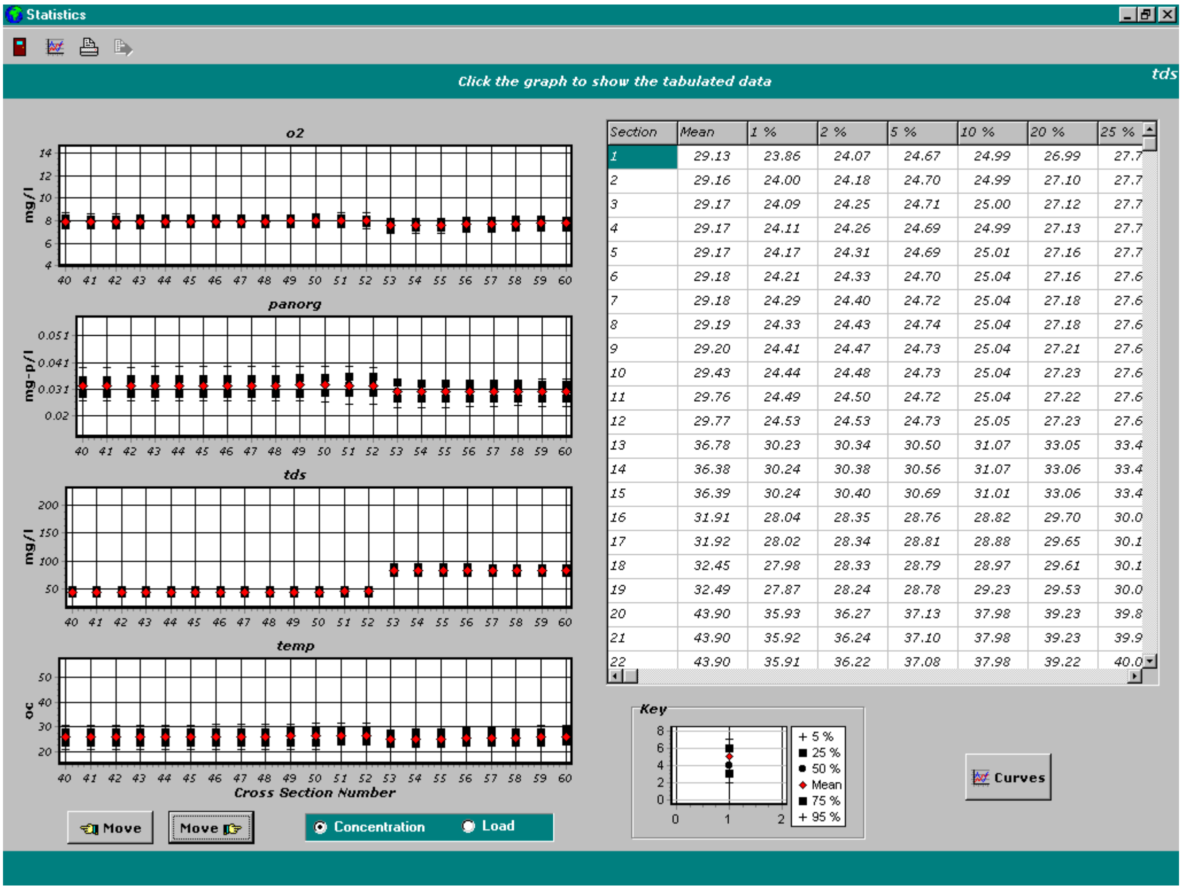


Figure 7.1: WQIS Prototype Main Screen

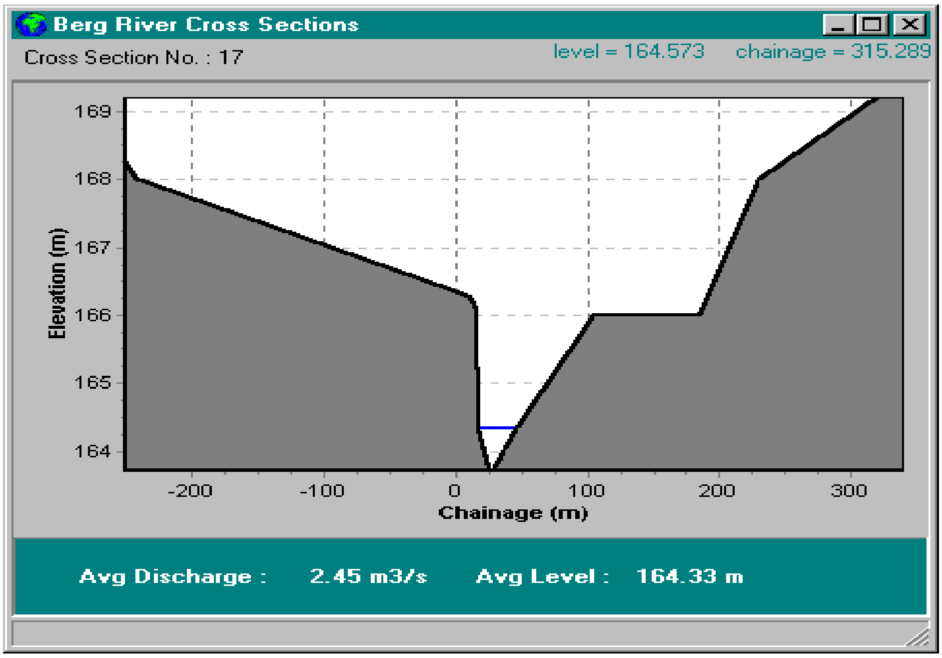
For the river modelling, various graphing tools have been created,

- time series at a point,
- output variables along a reach for a specified time step,
- box and whisker plots of output variables (Figure 7.2), or
- percentile (duration) curves,
- cross section and long section diagrams (Figures 7.3 and 7.4).



Section	Mean	1 %	2 %	5 %	10 %	20 %	25 %
1	29.13	23.86	24.07	24.67	24.99	26.99	27.7
2	29.16	24.00	24.18	24.70	24.99	27.10	27.7
3	29.17	24.09	24.25	24.71	25.00	27.12	27.7
4	29.17	24.11	24.26	24.69	24.99	27.13	27.7
5	29.17	24.17	24.31	24.69	25.01	27.16	27.7
6	29.18	24.21	24.33	24.70	25.04	27.16	27.6
7	29.18	24.29	24.40	24.72	25.04	27.18	27.6
8	29.19	24.33	24.43	24.74	25.04	27.18	27.6
9	29.20	24.41	24.47	24.73	25.04	27.21	27.6
10	29.43	24.44	24.48	24.73	25.04	27.23	27.6
11	29.76	24.49	24.50	24.72	25.04	27.22	27.6
12	29.77	24.53	24.53	24.73	25.05	27.23	27.6
13	36.78	30.23	30.34	30.50	31.07	33.05	33.4
14	36.38	30.24	30.38	30.56	31.07	33.06	33.4
15	36.39	30.24	30.40	30.69	31.01	33.06	33.4
16	31.91	28.04	28.35	28.76	28.82	29.70	30.0
17	31.92	28.02	28.34	28.81	28.88	29.65	30.1
18	32.45	27.98	28.33	28.79	28.97	29.61	30.1
19	32.49	27.87	28.24	28.78	29.23	29.53	30.0
20	43.90	35.93	36.27	37.13	37.98	39.23	39.8
21	43.90	35.92	36.24	37.10	37.98	39.23	39.9
22	43.90	35.91	36.22	37.08	37.98	39.22	40.0

Figure 7.2: Box and Whisker Plots and Percentile Values



Cross Section No. : 17

level = 164.573 chainage = 315.289

Avg Discharge : 2.45 m3/s Avg Level : 164.33 m

Figure 7.3: Cross Section

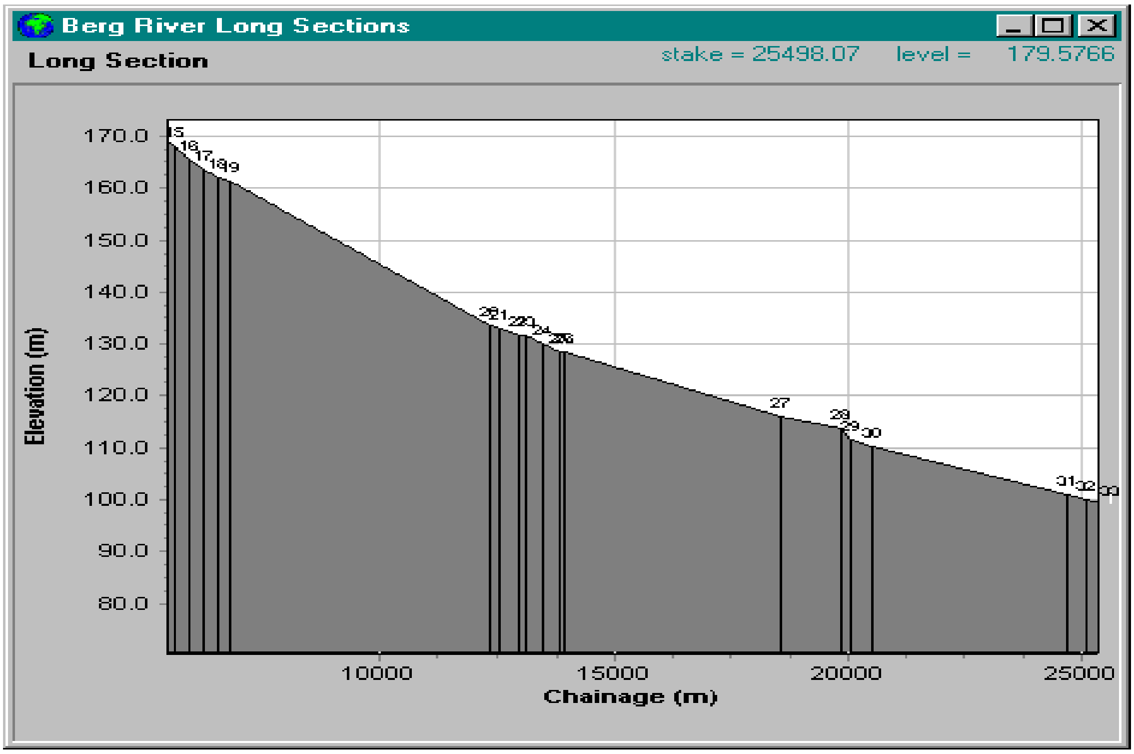


Figure 7.4: Long Section

For the reservoir modelling, sample graphing facilities have been developed, such as:

- a cross section view of the dam showing the concentration of a variable for a time step(s),
- a horizontal view of the dam at a certain depth showing the concentration of a variable for a time step(s) or time series plots of various constituents at a point in the dam.

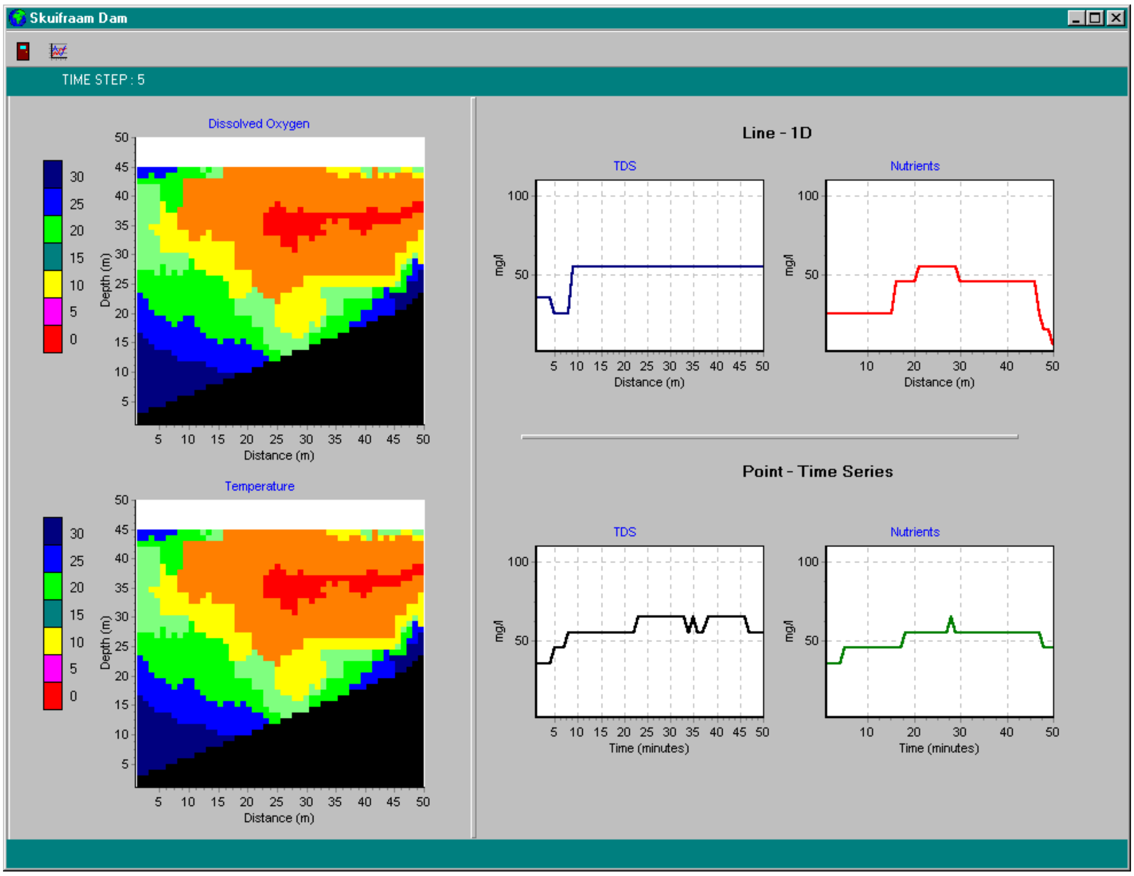


Figure 7.5: Reservoir Sample Graphs

7.2 WATER QUALITY INFORMATION SYSTEM FOR THE BERG RIVER

The WQIS model configuration developed for this project, offers the user access to information in three main categories, namely River, Reservoir and GIS. These are described in Figure 7.6. The reader is encouraged to launch the WQIS demonstration CD that is enclosed and follow the descriptions of the screens that follow in the next sections. A detailed schematic description of the links between, and processes occurring in, the WQIS screens, and printed copies of some the screens, not shown in this chapter are included, for completeness, in Appendix B of the complete Volume 2.

On startup, the Water Quality Information System presents the user with a standard GIS interface consisting of a Map View area, a Legend describing the layers, an Overview Box for orientation and a Tool Bar containing general mapping tools and customised functionality tools. In addition, there are various other buttons on the right-hand panel that provide access to the simulation results. Each model component is discussed in detail in the following sections.

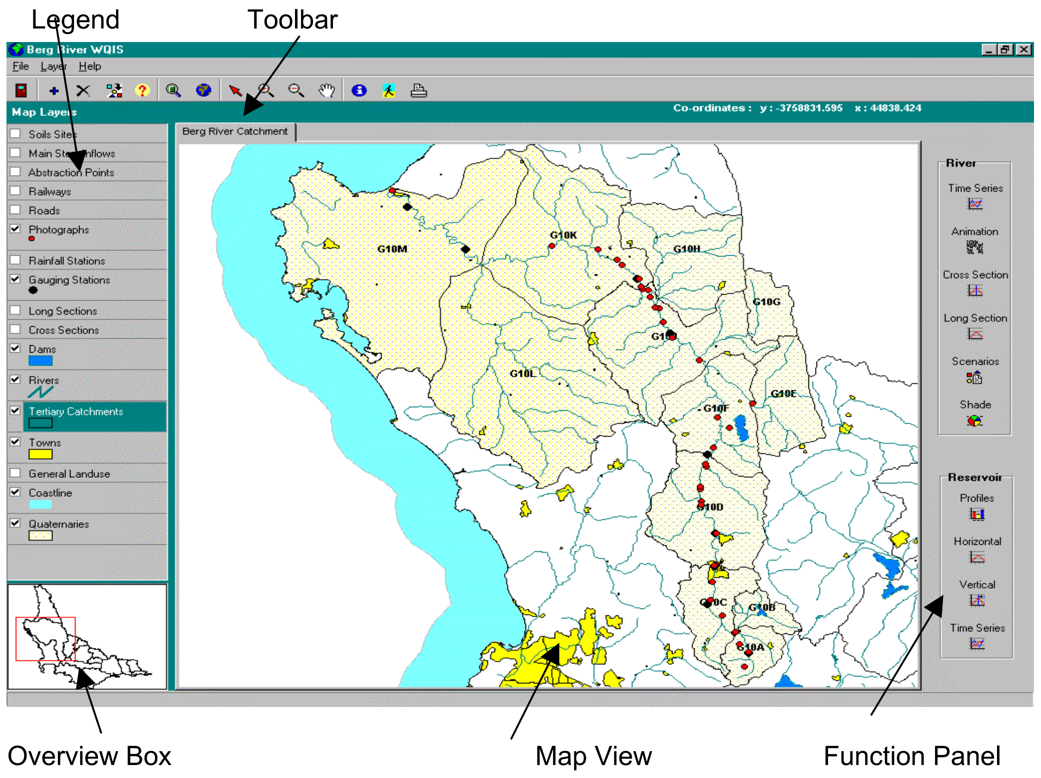


Figure 7.6: Main Screen

7.2.1 Map View

The Map View displays numerous layers, such as roads, railways etc., that are relevant and aid the decision making process. A list of the included layers and their relevance is shown in Table 7.1 below.

These layers can be switched on and off as required, depending on the level of detail required in the display (see Legend description). To change the extent of information displayed in the Map View the general mapping tools should be used. The Overview Box indicates, using a red rectangle, the area displayed in the Map View in relation to the full extent.

7.2.2 Legend

The Legend is used to select layers or to access their properties. To switch a layer on or off, the user may click on the small check box to the left of each layer name. By right clicking on a specific layer in the Legend, a drop down property box is activated. The labels of the layer features may be displayed and layer properties such as colour, style, line thickness and gradings may be set using the Property Box. The order of the layers may also be rearranged by dragging the layer name up or down in the Legend while holding down the right mouse button. The Legend reverts to the default settings once the program is closed down.

7.2.3 Toolbar

The toolbar has a selection of general mapping tools that allow the user to specify the extent or focus of the spatial data required.

Figure 7.7: Toolbar buttons (properties, layer extent, full extent, pointer, zoom in, zoom out, pan, information, photograph)

The properties tool activates the Property Box and allows the user to change the attributes of the currently active layer. The zoom in tool allows the user to trace a rectangle in the Map View, to which the Map View is then zoomed. When zooming out, the displayed extent doubles each time the user clicks on the Map View. The layer extent tool changes the display extent to that of the highlighted layer and the full extent tool zooms to the maximum extent of all the layers. The pointer tool allows the user to select specific layer features when using the customised tools.

Additional information tools, specific to WQIS, provide access to project specific information not normally available in ‘off-the-shelf’ GIS applications. These tools are spatially linked to features of interest in the layers.

- *Identify Tool*: The Identify tool allows the user to click on and identify any spatially represented feature in the Map View. The layer that describes the required feature should be switched on and highlighted in the Legend.

- *Photograph Tool*: A photograph box is activated that shows numerous photographs taken at points of interest down the river, which offer a means of comparing current water levels and river flow and channel conditions with historical conditions.

7.2.4 Function Panel

The Function Panel to the right of the Map View allows the user to connect to the simulation models, read in output information and open results screens. The Function Panel is divided into two sections for River and Reservoir.

River

- *Time Series*: This option enables the user to access the flow or quality time series and statistical analysis of the DUFLOW simulation runs.

- *Animation*: This option enables the user to access the flow or quality spatial simulation and statistical analysis of the DUFLOW results.

- *Cross Section*: Cross Section graph boxes are activated by clicking on the Cross Section tool button and then on the relevant cross section feature in the Map View. The cross section graphs show the cross section profile and the average water level calculated using DUFLOW. The average discharge is provided as additional information below the graph. The date and source of the cross section information is also displayed.

- *Long Section*: The Long Section graph box is also activated by clicking on the interactive map and shows the profile of the river through the lowest points of each cross section. The position of the cross sections and the water level calculated in DUFLOW are also visible.

- *Scenario*: A scenario manager is displayed, which allows the user to choose the event month, spill or release characteristics and then run the DUFLOW model.

- *Shade*: The Berg River layer in the Map View is shaded based on the results of the most current scenario run. A water quality constituent, or river flow condition, as well as the minimum, mean or maximum value should be selected.

Reservoir

- *Profile*: This option displays the two-dimensional graphs of the results of the reservoir analysis for all the modelled constituents.

- *Horizontal*: The variations in time, on a selected horizontal plane, of the concentration of the modelled constituents are displayed.

- *Vertical*: The variations in time, on a selected vertical plane, of the concentration of the modelled constituents are displayed.

- *Time Series*: This option allows the user to view the time series for each modelled constituent for each active cell in the reservoir configuration.

7.2.5 River Model Results Screens

The user is required to choose which quality or flow results to view: simulated, observed, or scenario.

If water quality results are required then the necessary Water Quality Target Limits must be set. Four options for water quality user group standards are available, namely, agriculture, domestic, recreation and user defined. The options are provided as guidelines and may be changed by the user on the **Water Quality Limits** screen. The **Time Series Results** screen has an interactive map showing the Berg River, a set of cross sections and the main channel streamflow gauges for which observed data is available (see Figure 7.9). The standard mapping tools are again available for this map.

The toolbar on this screen offers various options and these are described below.

- *Times Series Tool*: Time series graphs, for a selected time period, are displayed by clicking on the relevant cross section on the interactive map. For the flow option, water level and discharge are displayed and for the water quality option, graphs are displayed for Dissolved Oxygen, Phosphorus, TDS and Temperature.
- *Comparison Tool*: The user may select up to four different cross sections on the interactive map for which they wish results to be compared.
- *Statistics*: A new screen displays box and whisker plots for each cross section and tabulated percentile values that may be exported to a database file for further analysis. The Curves tool on this screen offers the functionality to display the duration frequency curves for each cross section.
- *Violations*: This option is only available for the water quality results and counts the number of water quality “target” violations. A new screen displays a table showing, for each cross section, the start and end dates of the violation period and the number of actual violations within the time frame.

The **Spatial Simulation Results** screen allows the user to animate the results of the DUFLOW simulation through time. The spatial graphs show the water level and discharge or constituent load and concentration at all the cross sections for a particular time step. The progress through the time steps may be speeded up or slowed down using the slider bar and paused, resumed or aborted using the relevant buttons.

The toolbar on this screen offers the user various display options and these are listed below:

- *Abstraction Points*: The locations of the various abstractions are indicated on the spatial graphs using red triangles.
- *Inflow Points*: The location of the various tributary inflows and return flows are indicated on the spatial graphs using green inverted triangles.
- *Statistics*: A new screen displays box-and-whisker plots for each cross section and tabulated percentile data that may be exported to a database file for further analysis. The Curves tool on this screen offers the functionality to display the duration curves for each cross section.

- *Violations*: This option is only available for the water quality results. A new screen displays a table showing, for each cross section, the start and end dates of the violation period and the number of actual violations within the time frame.

NB: Each of the River Model Results screens has printing facilities for hardcopy reproductions.

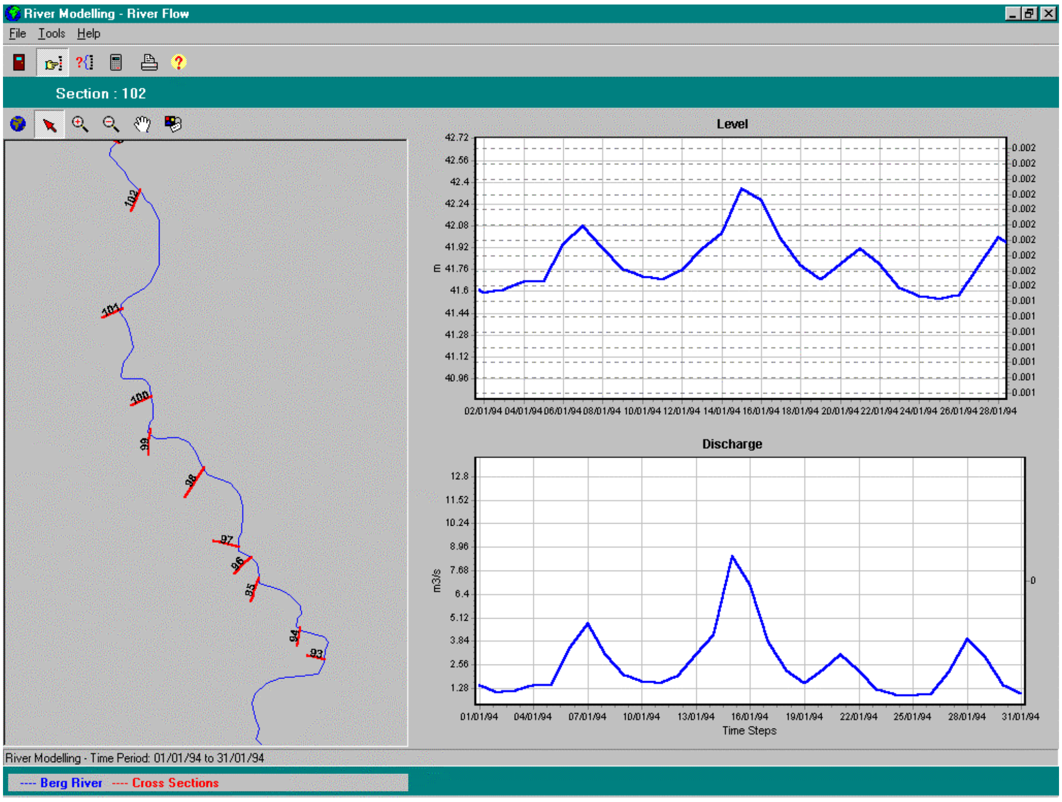


Figure 7.8: Time Series Results Screen for January 1994

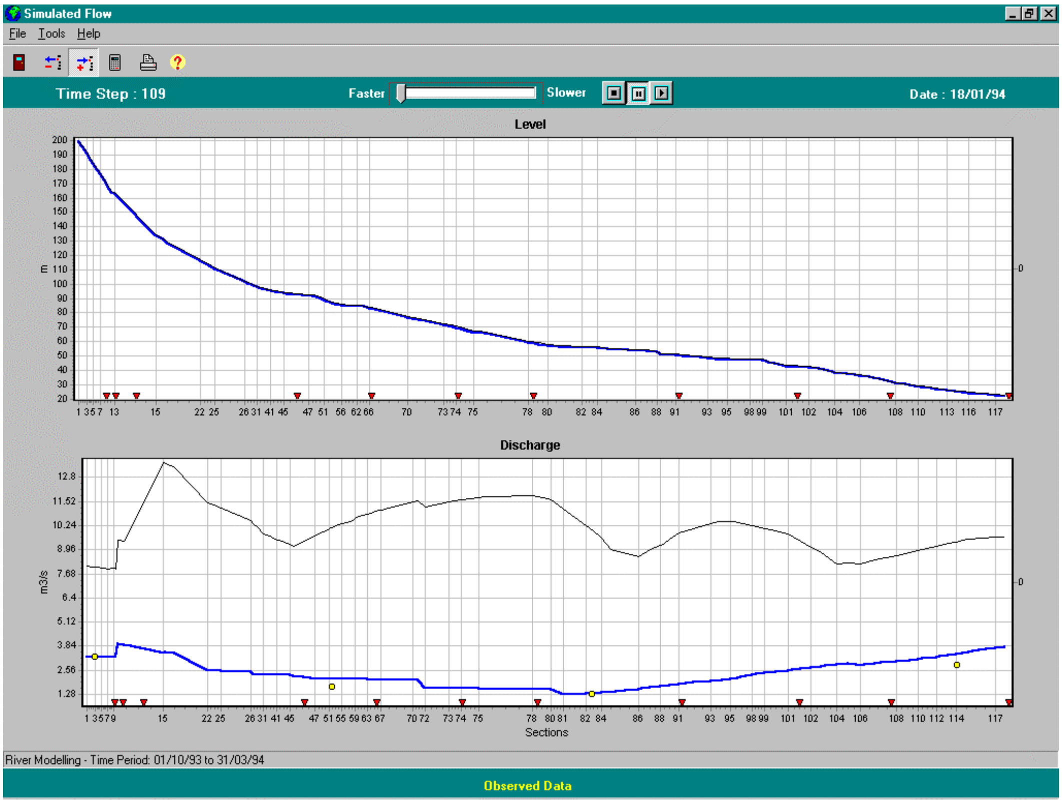


Figure 7.9: Spatial Animation Results Screen for 18 January 1994

7.2.6 Reservoir Model Results Screens

The bathymetric input requirements of CE-QUAL-W2 require that the reservoir be divided into segments along the reservoir length and layers across the profile, effectively describing the reservoir in term of “cells”. The reservoir simulated in this project, Skuifraam Dam, was divided into 10 segments and 30 layers. The first and last segments and layers are considered “boundary” cells and are as such, not included in the output (Volume 1, section 3).

The **Profile Animation** screen presents a map depicting the reservoir and the demarcated finite difference segments used for the reservoir modelling. There are four graph boxes for the concentration results of the modelled constituents (Temperature, Phosphorus, TDS and Dissolved Oxygen). The coloured blocks represent the constituent concentration in each active reservoir cell and the black blocks represent the inactive cells or reservoir bed. The results are animated by running through the time steps. The variations in each constituent concentration may be observed through the length and depth of the reservoir, simultaneously. A snap shot of the animation is shown in Figure 7.11.

On the **Horizontal Simulation** screen, a grid is presented, depicting the cell configuration of the reservoir (Skuifraam Dam). The cells containing the characters ‘****’ are the inactive cells and the numbered grid cells represent the active reservoir cells. There are also four graph boxes for the modelled constituents, Temperature, Phosphorus, TDS and Dissolved Oxygen. For each time step in the model simulation run, the concentration of the constituents, at a specified depth, for the length of the reservoir, are plotted. The longitudinal variations in constituent concentration between the inlet and the dam wall can be noted.

The same grid depicting the cell configuration of the reservoir is shown on the **Vertical Simulation** screen. The four graph boxes display the concentration of the modelled constituents listed above. For each time step in the model simulation run, the concentration profile of the constituents, for a specified vertical slice, for the depth of the reservoir, are plotted. The variations in constituent concentration (stratification) between the reservoir surface and bed can be clearly seen in Figure 7.13. Again, on the **Time Series** screen there is a reservoir grid and four graph boxes depicting the concentrations of the modelled constituents. The time series, for the full simulation period, for a cell in the reservoir, are displayed by clicking on that cell in the grid (see Figure 7.14).

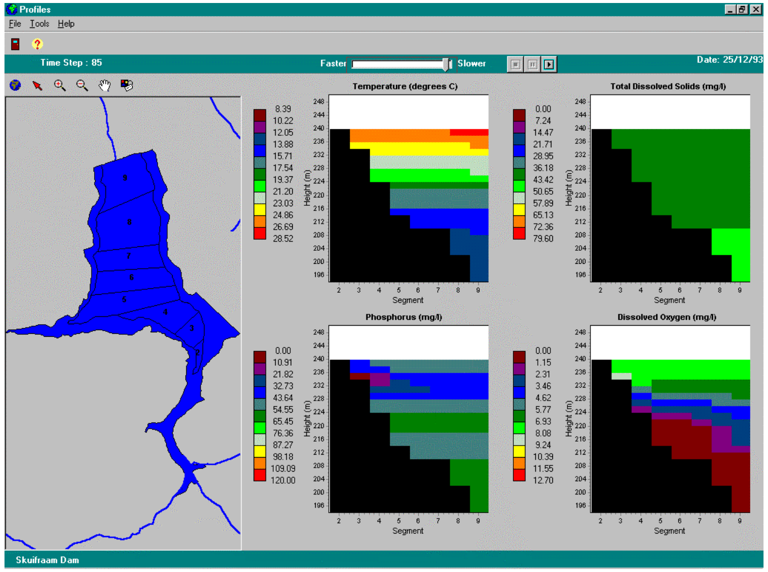
The above three screens have facilities to print hardcopies of the graphs and view a map of the reservoir.

7.2.7 Help Facilities

Intuitive On-line Help facilities have been created for each screen and there are key words and a contents page to assist in locating the required advice or description.

7.3 DISCUSSION

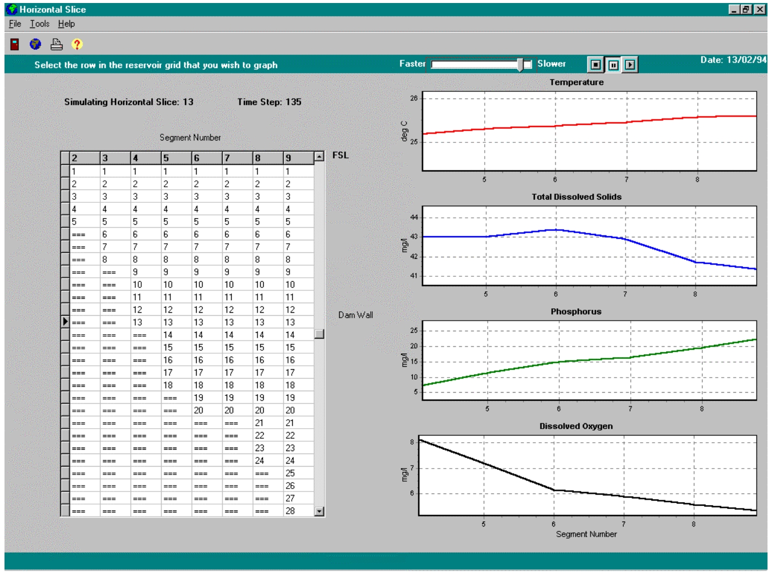
The functionality and analysis offered by this information system is fairly comprehensive but by no means covers all the requirements of every river manager or water resource analyst. However, the development environment and design of the system are sufficiently flexible to allow the inclusion of other simulation models and analysis options to ensure that the WQIS fulfils its role as a decision support and information tool for a broad spectrum of users.



Time Step : 85

Date: 25/12/93

Figure 7.10: Profile Animation Results Screen

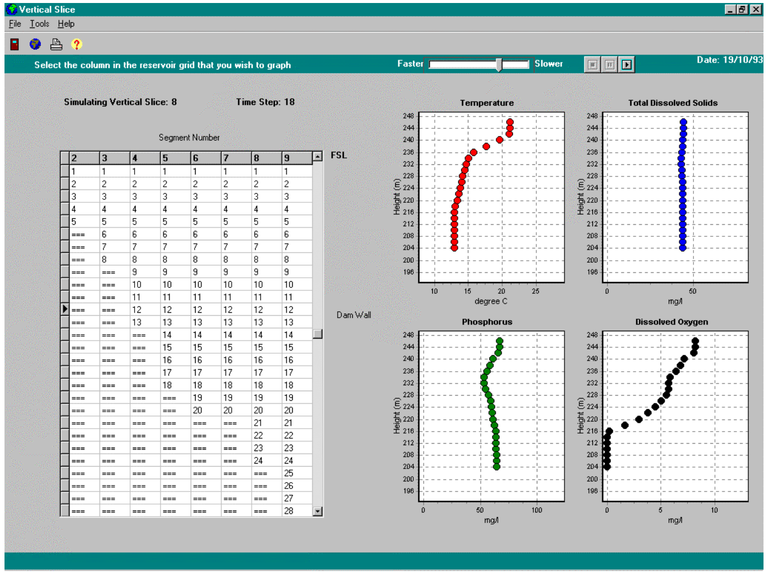


Date: 13/02/94

Simulating Horizontal Slice: 13   Time Step: 135

2	3	4	5	6	7	8	9
1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5
===	6	6	6	6	6	6	6
===	7	7	7	7	7	7	7
===	8	8	8	8	8	8	8
===	===	9	9	9	9	9	9
===	===	10	10	10	10	10	10
===	===	11	11	11	11	11	11
===	===	12	12	12	12	12	12
===	===	13	13	13	13	13	13
===	===	===	14	14	14	14	14
===	===	===	15	15	15	15	15
===	===	===	16	16	16	16	16
===	===	===	17	17	17	17	17
===	===	===	18	18	18	18	18
===	===	===	===	19	19	19	19
===	===	===	===	20	20	20	20
===	===	===	===	===	===	21	21
===	===	===	===	===	===	22	22
===	===	===	===	===	===	23	23
===	===	===	===	===	===	24	24
===	===	===	===	===	===	===	25
===	===	===	===	===	===	===	26
===	===	===	===	===	===	===	27
===	===	===	===	===	===	===	28

Figure 7.11: Horizontal Simulation Results Screen

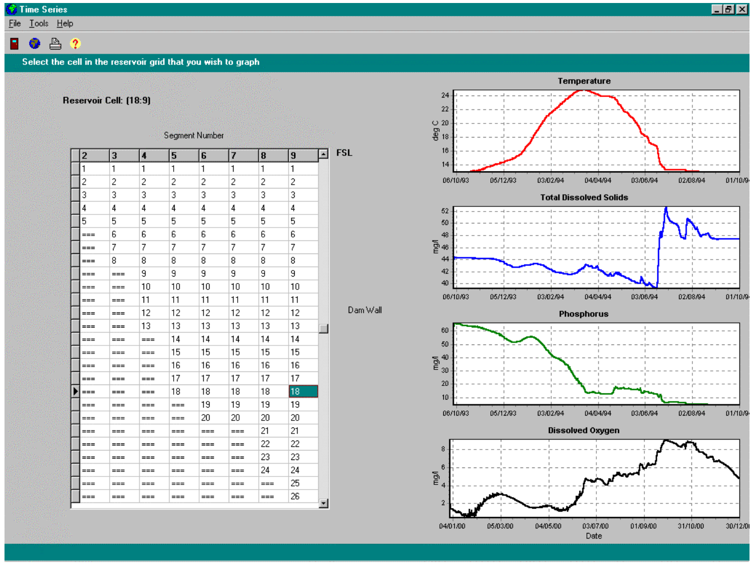


Date: 19/10/93

Simulating Vertical Slice: 8   Time Step: 18

2	3	4	5	6	7	8	9
1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5
===	6	6	6	6	6	6	6
===	7	7	7	7	7	7	7
===	8	8	8	8	8	8	8
===	===	9	9	9	9	9	9
===	===	10	10	10	10	10	10
===	===	11	11	11	11	11	11
===	===	12	12	12	12	12	12
===	===	13	13	13	13	13	13
===	===	===	14	14	14	14	14
===	===	===	15	15	15	15	15
===	===	===	16	16	16	16	16
===	===	===	17	17	17	17	17
===	===	===	18	18	18	18	18
===	===	===	===	19	19	19	19
===	===	===	===	20	20	20	20
===	===	===	===	===	===	21	21
===	===	===	===	===	===	22	22
===	===	===	===	===	===	23	23
===	===	===	===	===	===	24	24
===	===	===	===	===	===	===	25
===	===	===	===	===	===	===	26
===	===	===	===	===	===	===	27
===	===	===	===	===	===	===	28

Figure 7.12: Vertical Simulation Results Screen



Reservoir Cell: (18:9)

2	3	4	5	6	7	8	9
1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4
5	5	5	5	5	5	5	5
===	6	6	6	6	6	6	6
===	7	7	7	7	7	7	7
===	8	8	8	8	8	8	8
===	===	9	9	9	9	9	9
===	===	10	10	10	10	10	10
===	===	11	11	11	11	11	11
===	===	12	12	12	12	12	12
===	===	13	13	13	13	13	13
===	===	===	14	14	14	14	14
===	===	===	15	15	15	15	15
===	===	===	16	16	16	16	16
===	===	===	17	17	17	17	17
===	===	===	18	18	18	18	18
===	===	===	===	19	19	19	19
===	===	===	===	20	20	20	20
===	===	===	===	===	===	21	21
===	===	===	===	===	===	22	22
===	===	===	===	===	===	23	23
===	===	===	===	===	===	24	24
===	===	===	===	===	===	===	25
===	===	===	===	===	===	===	26

Figure 7.13: Time Series Results Screen

CHAPTER EIGHT
EVALUATION OF SIMULATION MODEL INTEGRATION

All too often, the integration of simulation models may sound viable in theory, but the practical implementation of many of the components, although possible, may not be cost or time effective. A good understanding of the numerous model characteristics needs to be achieved before integration is attempted. These include:

- the optimal application of the model (medium to long-term historical or trend analysis, or short term operational management), which determines,
- the frequency of simulation runs,
- the sensitivity or robustness of the simulation models,
- the consistency, nature and size of the model output,
- necessary input modifications for future runs,
- the analysis and display features required from the information system into which the models are integrated.

All these aspects affect the way the information is converted, stored, accessed, updated and displayed.

8.1 RIVER MODEL

The selection, setup and testing of DUFLOW formed a component of Volume 1, section 2.

8.1.1 Project Timing

The information system development and river simulation projects were run concurrently. As a result, the simulation model was being continually modified, which resulted in unnecessary re-coding.

8.1.2 Model Purpose and Operation

The management questions or decisions for which DUFLOW is appropriate should also be carefully considered. A model such as DUFLOW is usually set up infrequently, using numerous years of historical data, and not updated daily or even weekly for use in operational management. The Berg River DUFLOW model is more suited to simulating medium to long-term, historical conditions, the results of which can be used for statistical and trend analysis useful for future long-term planning.

8.1.3 Pre-processing – Input Files

To run DUFLOW for current conditions, a number of input parameters and data needed to be updated each time a new model run was required. The observed inflows from tributaries, return flows and the various abstractions volumes, would need to have time frames and time steps corresponding to the release flows (reservoir release) that drive the simulation run.

8.1.4 Post-processing – Output Files

DUFLOW output is written to flat text files that vary in size. Much of the code required to read flat files needs to be hardwired and is often specific to the current set of run parameters. To produce code that is generic and has the ability to read the resultant output of any permutation of parameters is time consuming and duplicates much of the post-processing already supplied within DUFLOW itself. The output files are read in once after each model simulation run and stored in a database tables (Figure 8.1).

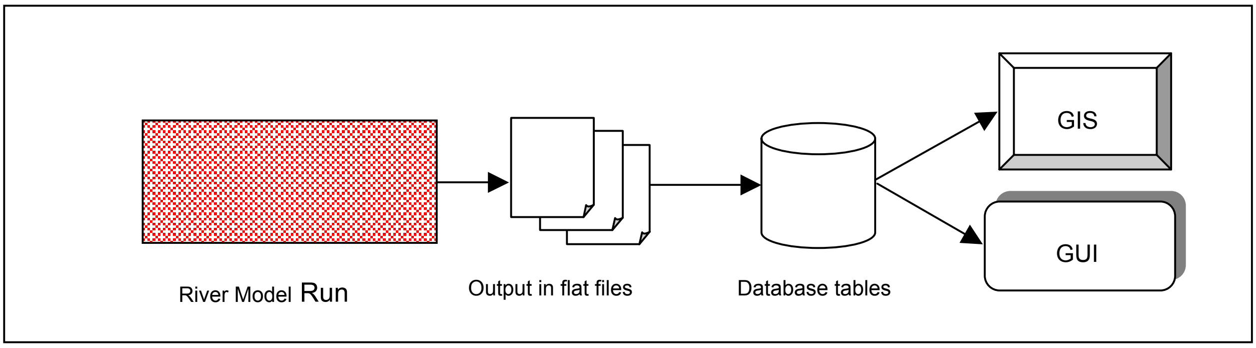


Figure 8.1: River Model Output

8.1.5 Software Platform Compatibility

DUFLOW operates on a Windows95 platform which is compatible with the WQIS environment and therefore the launching and operation of DUFLOW from within WQIS is suitable and seamless.

8.1.6 Portability

DUFLOW is distributed under licence and therefore not portable unless a new copy of DUFLOW is purchased for each installation (STOWA/EDS, 1998

8.2 RESERVOIR MODEL

CE-QUAL-W2 was selected to perform the reservoir analysis of the future (Volume 1, Section 3).

8.2.1 Project Timing

The reservoir modelling exercise was initiated late into the project, due to resource and data constraints. Consequently, a clear understanding of the interface requirements was achieved before the coding process began.

8.2.2 Model Purpose and Operation

Reservoir simulation usually involves the long-term or seasonal analysis of the physical and chemical processes occurring in the reservoir.

8.2.3 Pre-processing – Input Files

Due to the pre-processing constraints of the river model, as discussed in the earlier sections, it was unnecessary to re-run the reservoir model for scenario analysis and therefore no pre-processing facilities were required.

8.2.4 Post-processing – Output Files

The flat text output created by the CE-QUAL-W2 model must be read sequentially, in a format specific manner. The output format is well suited to the display requirements of WQIS and therefore very little data manipulation was required to produce informative graphic results.

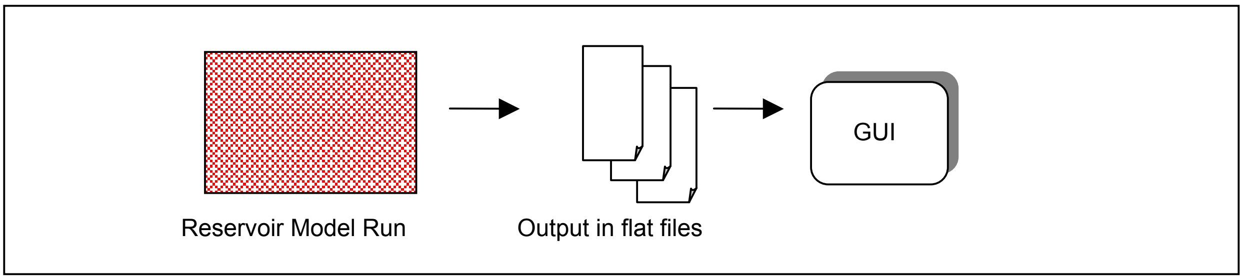


Figure 8.2: Reservoir Model Output

8.2.5 Software Platform Compatibility

CE-QUAL-W2 is a DOS based model with flat text, input and output files and is therefore not compatible with the WQIS environment. Only the output files produced by CE-QUAL-W2 are used as input to the WQIS.

8.2.6 Portability

CE-QUAL-W2 is available free of charge and may be downloaded from the Internet.

8.3 DISCUSSION

The increasing use of spatial methods in simulation models for creating input and displaying output will eventually eliminate many of the integration and incompatibility problems currently experienced when integrating various simulation models into an information system. In the future, hopefully, most models will construct their input information from a standardised set of GIS layers or an object-oriented network diagram. This will preclude the need for the development of multiple pre- and post-processors thereby ensuring that the Information System is generic and flexible, i.e. there are no limitations on the type (operational or long-term) and as all the required information will be stored in a similar format the set-up mechanisms will be comparable. However, there will still be certain constraints such as the volumes of information required and stored, and the time taken for a simulation run.

CHAPTER NINE
SCENARIO ANALYSIS USING DUFLOW

Irrigated areas are expanding, and there is no guarantee that future saline return flows will not render certain river stretches unusable as a means of supply. The RSE-BR catchment, chosen as a case study for this project, is no exception and is becoming increasingly susceptible to water quality issues that need urgent solutions.

The river simulation model, DUFLOW, accepted for inclusion in the WQIS, is effectively used for medium-term trend analysis and planning over a period of a few months or years. This information is useful for seasonal comparisons and an overview of conditions in the river system. However, if near real-time results are required for short-term operational decisions, a method for scenario analysis was required.

9.1 POTENTIAL SCENARIO ANALYSIS REQUIREMENTS

Following the interviews with the various water managers described in Chapter 4, it became clear that short-term water quality remediation was a high priority management issue in the Berg River catchment. In particular, managers expected the information system to provide decision support information on point and non-point pollutant spill remedies and irrigation releases, such as:

- the extent and magnitude of the spill,
- when to make releases,
- what volume to release,
- release period, and
- possible downstream effects.

The answers to these questions are typically required within hours and therefore a model with a short set-up and calculation time is necessary to perform the simulation and produce valuable decision support information. The scenario set-up is adequate to provide answers to a range of operational management issues as discussed in the following sections.

9.2 DUFLOW SCENARIO CONFIGURATION

In order to model river quality hazards and remedies effectively, DUFLOW needed to be configured to shorten the model run time and to facilitate easy methods for the user to stipulate water quality hazards and remedial measures.

For this purpose, a pre-processor or Scenario Manager was developed as part of the information system to allow the user to stipulate various spill and consequent freshening release characteristics, as well as the month in which they occur. The water quality and quantity characteristics may be set for separate model runs to simulate their individual impacts, or simultaneously to assess the remedial effect of the freshening releases on the spill event.

The following characteristics of the spill event are required:

- location,
- constituent,
- start and end day,
- peak concentration and
- hydrograph shape (Figure 9.1)

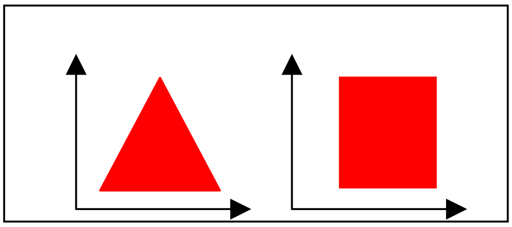


Figure 9.1: Spill Hydrograph Shapes

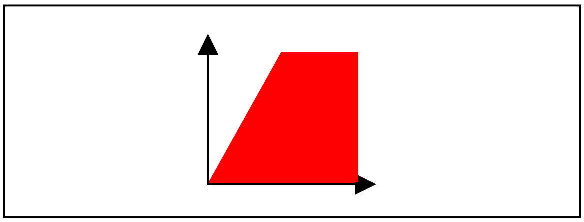


Figure 9.2: Release Hydrograph Shape

For the freshening release, the following characteristics are required:

- location,
- start and end day and
- peak volume.

The release hydrograph shape is set to increase uniformly from zero to the required peak value half way between the start and end day (Figure 9.2).

To shorten the model run time the DUFLOW model was configured to run for one month only and the user may select the appropriate month, depending on the time of year in which the spill occurs, using the scenario manager. The user may also set water quality limits that vary upstream and downstream of a specified target location. Once these characteristics have been set, the DUFLOW input files are updated to reflect the changes. DUFLOW is then re-run to simulate the adjusted quality and flow values. The application of the various scenario options are discussed in the following sections.

9.3 SCENARIO ANALYSIS OPTIONS

9.3.1 Release Management

Releases from Voëlvlei and the future Skuifraam reservoirs are required for purposes such as irrigation, spill hazard freshening and for the maintenance of the environmental flows and water quality required by all river users and the protected estuarine areas. These releases should be managed effectively, in order to limit the wastage and damage caused by unnecessarily large volumes.

To test the effects of a particular release volume or duration, the **Scenario Manager** for DUFLOW can be used to set the month in which the release is made, the duration of the release and the peak volume (the hydrograph shape is discussed above). The results of the subsequent model run may then be displayed in the information system, enabling the water manager to assess the water levels and velocities in sensitive river reaches. This process may have to be iterated a number of times, with different release distributions, to achieve the most appropriate release pattern.

9.3.2 Point Source Spill Management

Once the water manager has been alerted to a spill from a point source, such as a sewage treatment plant, or industrial site, the **Scenario Manager** can be used to enter the spill type, concentration, location and duration. The DUFLOW model is then run to determine the extent and severity of the spill and its possible effects on downstream users.

Freshening releases can then be tested on a trial-and-error basis in a similar manner to the method described above in Section 9.2.1. In this way, the most effective freshening release, with acceptable impacts on downstream users, can be determined.

9.3.3 Non-Point Source Management

DUFLOW does not cater for non-point source spills explicitly and therefore a method was devised to model the effects of diffuse contaminants, such as irrigation return flows and groundwater seepage, on water quality.

In this case, a spill concentration should be entered in the vicinity of the non-point source spill and then variable upstream and downstream quality limits should be set to ascertain compliance above and below the spill reach. The calculated contaminant loads may also be monitored. The above options are discussed in more detail in the parallel WRC study by Nitsche (2000).

9.3.4 Comparative and Predictive Modelling

A further use of the Scenario Manager would be to test the impacts of possible changes in the flow regime or effluent discharges into the river, such as:

- Altered or increased irrigation releases due to extended cultivation,
- Higher effluent discharge from sewage treatment plants due to upgrading and increased capacity,
- Increased non-point source pollution due to seepage from poor sanitation facilities in new, informal or semi-formal settlements adjacent to the river,
- Releases for flood management
- Water quality monitoring and enforcement
- Comparison of the effects of various changes to river flow and quality depending on the season in which they occur.

9.4 POSSIBLE ADDITIONAL OPERATIONAL MANAGEMENT OPTIONS

Consequent to the multiple users, managers and scientists involved in managing a river successfully, there will naturally be a demand for any number of scenario analysis options. However, no one information system will ever satisfy every user's individual requirements, but will hopefully be generic enough to be applied, and provide meaningful decision support for as many situations as possible. The information system described in this project is by no means comprehensive or complete. Numerous additional scenario options have been discussed and were considered to be worthy of inclusion into the model. Two of these options are discussed below, but their implementation was considered beyond the scope of this research.

9.4.1 Linking River and Reservoir Scenario Analysis

The first option would be to develop a method of using the output of reservoir scenario analysis as the input to the river scenario analysis. In this way, the effects of the internal reservoir processes, such as stratification, on the water quality and temperature of reservoir releases can be assessed. These releases can then be routed through the river model to determine the impacts of remedial and routine releases.

9.4.2 DISA Salinity Model Reverse Routing

DISA was originally developed to predict the impact of irrigation development on riverflow and salinity using readily available data from river systems with significant irrigation (DWAF, 1990). The model is described in terms of five general use sub-models, the abstraction, inflow, farm dam, canal and river routing nodes.

As a further development, the DISA model was refined for the Berg River (Ninham Shand, 2000), to refine the management of releases by improving the scheduling of abstractions and matching these abstractions to releases. The model now takes into account the time required for water to flow from the release point to abstraction points (i.e. the hydraulic characteristics of the river channel), the current natural flow in the river, and flow inputs (tributaries and point return flows) and abstractions (irrigators) en route.

The model is quasi-hydrodynamic, with the capacity to cope with the simulation of salinity as the only water quality constituent. It operates on a half-hourly time step for a weekly cycle during the irrigation season and is capable of providing flow and salinity decision support. The required inputs are:

- Requested abstraction volumes
- Current river flow
- Current tributary inflows and return flows (quality and quantity).

The model outputs are:

- The magnitude and timing of releases from the upstream source (dam or transfer)
- The abstraction times at each abstraction point
- Graphical representations of release hydrographs and salinity variation at points of interest.

In configuring the model, a modular approach was followed, allowing for a flexible means of configuring the system as a series of linked nodes. Six different types of nodes were allowed for:

- **Release nodes** are used to define release patterns at the source. In addition, this type of node can be used to define the desired outflow hydrograph at the downstream end of the system.
- **Abstraction nodes** are used to model major abstractions such as municipal, industrial and irrigation board pumping schemes. Provision is made for maximum abstraction capacities and minimum riverflow requirements for abstraction to take place.
- **Routing nodes** make use of the defined river channel geometry to route releases down the river on a sub-daily time step. Provision is made for "diffuse" abstractions along the routing reach, representing individual irrigation abstraction points operating on an ad hoc basis. The timing and magnitude of these abstractions represent the only major unknown quantity in the model, and will be determined by calibration against flows recorded at Observation Nodes in the main river channel (see below).
- **Observation nodes** provide a feed-back mechanism which is used to synchronise the simulated flows in the river with flows observed at one or more points along the river. If an observed flow on a given day is lower than the flow simulated by the model at the observation node, the diffuse abstractions upstream of the observation node are increased uniformly until simulated flows match what is being observed.
- **Inflow Nodes** simulate point inflows from tributaries and major effluent discharge points.
- **Reservoir Nodes** model impoundments as mixed tanks, using a daily mass balance.

The model operates on a "real-time" basis during the irrigation season, and can be updated on a daily basis if required. Release planning is carried out with a 14 day time frame, moving ahead one day at a time:

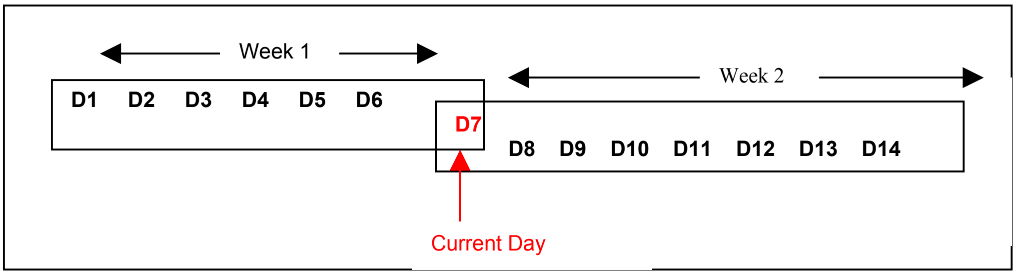


Figure 9.3: DISA Scheduling

- Days 1 to 6 represent the preceding 6 days,
- Day 7 represents the real-time current day, and
- Days 8 to 14 represent the coming week for which releases are planned.

On any given day, release planning can be carried out as follows:

- **Data Input:** Input of tributary inflows, current major abstraction rates, current release rates, and flows observed at the observation points for the current day (Day 7). At present, this is a manual process, but should eventually be replaced by an automated telemetry hook-up.
- **Synchronizing the System:** This step is completely automated and involves the estimation of diffuse abstractions in order to match observed flows. The synchronization spans the period (within days 1 to 6) since the previous synchronization. On completion, simulated model flows in the main river channel match observed flows for the preceding six days, and for the current day.
- **Release Adjustment Planning:** Release adjustment planning is carried out for the coming week (days 8 to 14) by specifying a desired outflow hydrograph at the downstream end of the system. If any release volumes have been requested by the large abstractors (pumping schemes / municipalities), these requirements are specified at the relevant abstraction nodes. At this stage, the model performs reverse routing, commencing at the downstream end of the system with the desired outflow hydrograph, and produces a required release hydrograph at the upstream end of the system.
- **Defining the Final Release Hydrograph:** The required release hydrograph produced by release adjustment planning is highly variable but can now be used as a “backdrop” to design a practical stepped release pattern. This simplified release can now be routed downstream, and the resultant outflow hydrograph at the downstream end of the system should be checked for unnecessary spillage. If required, minor adjustments to the design release can be made.

9.5 DISCUSSION

Clearly, there are many operational tools that would merit inclusion in an information system such as the WQIS. These options need to be well researched, and integrated only if they provide meaningful results to a range of river managers and water resource analysts.

CHAPTER TEN
CONCLUSIONS AND RECOMMENDATIONS

10.1 OVERVIEW

The aim of the research reported in this document was to develop an effective water quality decision support information system. To fulfil the aims of this project, complex communication and design challenges had to be dealt with effectively to produce an information system that satisfies the requirements of the intended users. Two crucial concepts that were featured were "interactive" and "integrated".

As part of the interactive communication process between the developer and users a questionnaire was distributed to potential users and those with valuable knowledge in the relevant fields. A prototype was then developed based on decisions made regarding software, methods of integration and technical feedback from the questionnaires. The prototype was then demonstrated at a series of interviews and demonstrations where further feedback was recorded and further software adjustments were made.

For this project, a number of the basic system components had already been outlined in the project proposal. The components and level of their integration required to appropriately meet user needs was agreed upon as part of the interactive development process.

The functionality and analysis offered by the WQIS is fairly comprehensive, but by no means covers all the requirements of every river water resource manager or user. However, the development environment and design of the system are sufficiently flexible to allow the inclusion of other simulation models and analysis options to ensure that the WQIS fulfils its role as a decision support and information tool for a broad spectrum of users.

Future research and system developments needs were highlighted in some of the interviews and the Steering Committee meeting for this project. Some of these are discussed in the following section.

10.2 FUTURE RESEARCH AND DEVELOPMENT

One of the main concerns expressed about the WQIS was, how to prevent this information system becoming just "another" system that is used for one project or application and then shelved. Therefore, in the research and development of the WQIS, numerous steps (listed below) were taken to avoid this occurrence.

- The system was developed interactively with the users to create a feeling of ownership and buy-in.
- Modelling capabilities were offered that produced meaningful results for a range of managers in the water management environment.
- The system design is simple and intuitive and offers comprehensive on-line help to cater for all levels of computer literacy.
- The system may be transferred to other river systems provided certain data naming and format conventions are followed.
- The information system is sufficiently generic to allow the inclusion of additional simulation and analysis tools.
- The WQIS may be used as an educational facility for catchment orientation, GIS exposure and map creation.

These precautions may, however, not be sufficient to ensure the continued use and applicability of the information system. The format of the input and output of this system needs to be compatible with that of the main water regulatory organisation, DWAF. In this way the input information of the system may be updated easily and the results may be distributed and used in other studies. DWAF is currently developing a data storage system based on the WDM principles (Lumb *et al*. 1988), for the purpose of standardising the format of their water resources data and any future information systems should be required to conform to this standard. However, the WDM development is not complete and therefore no standards are available as yet. For this reason, the WQIS was developed with its own database, but created sufficiently flexible to ensure that future conversions to WDM format proceed smoothly.

Concern was also expressed that the water quality constituents modelled in the WQIS were not adequate to describe the quality of the Berg River water used for irrigation and the subsequent irrigation return flows and leaching. However, due to the paucity of measured data, the modelling of more specific water quality indexes (such as the Sodium Adsorption Ratio rather than TDS) would require an extensive and lengthy gauging and data collection exercise. In the interests of improved modelling and decision support, any improvement in measured water quality and flow data is always encouraged and should be considered at the outset of any modelling or simulation project.

10.3 CONCLUDING REMARKS

One of the achievements of this research has been the creation of an Integrated Water Quality Information System for use in water resource operational and planning decision support. In addition, however, the interaction with water managers has developed a clearer understanding of the day to day operational needs of these managers and which tools would best fulfil their requirements. Greater insight has been gained concerning the type of analysis and simulation tools which are suitable for integration into an information system and the benefits of using existing models rather developing new tools from scratch.

If the considerable interest and discussion stimulated by the development of this system is an indication of the need for effective decision support, then the WQIS could form the building block of an efficient, workable tool to be used in a wide range of future water resource applications.

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RESEARCH ON BERG RIVER WATER MANAGEMENT

VOLUME 3

(Summarised)

WATER AND SOIL QUALITY INFORMATION FOR INTEGRATED WATER RESOURCE MANAGEMENT: BERG RIVER CATCHMENT

By

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TABLE OF CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

WATER AND SOIL QUALITY INFORMATION FOR INTEGRATED WATER RESOURCE MANAGEMENT: BERG RIVER CATCHMENT

1. INTRODUCTION

The Riviersonderend-Berg River (RSE-BR) system supplies about 80 percent of the water available to Greater Cape Town. A variety of expansion schemes are proposed to meet the growing needs of its water users. Both the expansion to existing irrigation schemes and the development of new schemes are likely, resulting in the extraction of 20% more water from the RSE-BR system.

These developments may exacerbate moderately high salinity levels in the middle-lower Berg River. Firstly, as a result of the removal of more fresh water from the river, its salinity can be expected to rise. Secondly, increased irrigation of the naturally saline soils of the river basin can be expected to mobilize residual salts, and the resulting saline drainage water may contribute to higher salinity in the RSE-BR. However, the importance of the latter process to the future quality of water in the system is unclear.

This study aims to help us understand the influence of irrigated agriculture on salinization of river water in the RSE-BR system. A better understanding of this aspect of water quality will allow improved management of the system and more accurate prediction of the outcome of expanded irrigation in the system's catchment area.

2. OBJECTIVES

The goal of this component of the project was to develop a sufficient understanding of irrigated soils in the RSE-BR system catchments to be able to:

1) Predict the quality and volume of irrigation drainage from various soil types, and
2) Assess the suitability of soils for irrigation, with regard to their potential to pose a salinity hazard to the RSE-BR system.

The study consisted of two tasks:

Task 1: Plot-scale fieldwork. The objective of the plot-scale fieldwork was to assess the respective salt mobilisation rates and irrigation return-flow processes in two sets of irrigated plots on Malmesbury shale-derived soils, over three irrigation seasons. One set of plots represented a newly-established irrigation scheme and the other land which had long history of irrigated agriculture. Each set was to consist of at least two different irrigation treatments, typical of local practice. Irrigation application rates were to be measured and resultant return-flows gauged and sampled in artificial drain outflows. These drains would be installed at the interface of the soil and the weathered shale layer above the bedrock. Nutrient levels (phosphate and nitrate concentrations) in the drain outflow would also be measured. Soil water content was to be monitored using a neutron probe. Samples of soil water, for salinity measurement, would be collected using soil water extractors. Groundwater observation holes were to be drilled and, if possible, existing boreholes converted to allow monitoring of groundwater level and salinity changes. Estimates of potential evapotranspiration would be made by measuring a set of meteorological variables using an existing automatic recording weather station, strategically placed relative to the two sets of plots. At the end of each season, the data were to be analysed statistically and interpreted to provide input to the other tasks in related projects.

Task 2: Develop generic methods for salinity hazard assessment. The project was to make use of the GIS infrastructure of the DA's Winter Rainfall Region Office at Elsenburg, as well as soil maps, data and the expert knowledge held by this office to develop generic methods for salinity hazard assessment using soils maps, GIS techniques, salinity data from monitored tributaries and the findings of the plot-scale studies described above. The methods developed for salinity hazard assessment were to be demonstrated by identifying zones along the Berg River and its primary tributaries where irrigation may result in a significant increase in downstream salinity.

3. METHODS

Task 1: Plot-scale fieldwork

The study of irrigation return flow was carried out at two sites, Broodkraal and Rooihoogte, currently hosting vineyards under micro-irrigation. Comprehensive data sets of irrigation and rainfall quantities, weather conditions, drainage water volumes and drainage and irrigation water salinity and ionic composition were collected, over a period of 18 months. Soil moisture measurements were also made on a regular basis.

Samples of soil water were collected from several points on the plots, at the beginning, middle and end of the irrigation season, using suction cup lysimeters to sample the soil solution at shallow, intermediate and deep locations in the soil profile. After making a number of simplifying assumptions, the data were used to model predicted drainage volumes and salt export from the land under irrigation.

A programme of soil sampling was designed with the aim of applying geostatistical methods to describe soil salinity variability. Samples of soil were collected from each plot at the start and end of the experiment, using a 45 m by 50.5 m grid pattern to define sampling positions. In addition, a number of samples (4 x 17) were taken within grid rectangles to allow the statistical description of inter-sample variability. The EC, ER, pH, clay percentage, stone percentage, density and field capacity of these samples was measured.

In addition, the contribution of heuweltjies (relict termite mounds) to dryland salinity and the potential consequences of irrigation schemes on lands with high heuweltjie density was investigated on areas of the farms currently used for dryland wheat cultivation. Deep (4 m) trenches were excavated into the mounds and inter-mound regions, using a mechanical shovel. The exposed soil profiles were mapped and classified, and soil samples were collected for determination of their pH, ER and exchangeable and soluble cation concentrations.

Task 2: Developing generic methods for salinity hazard assessment

The geostatistical approach revealed a lot of new information. The large spatial variability was dealt with sufficiently and this in itself limited the representativity of samples. The maximum spatial dependence ranged between 45 and 100 m. this result placed a large question mark behind using historic data that is not space and time correlated. Methods were defined with which rapid salinity assessment can be made over large areas.

A GIS-based, 1:50 000 scale map of the soils in the Berg River catchment was compiled by means of field mapping and reference to existing maps and information. Particular attention was paid to areas with potential for new irrigation development. This map was used to produce a crop suitability map and salinity hazard map of the catchment's soils to indicate the change in return-flow hazard when agricultural practice are altered.

4. SUMMARY OF RESULTS AND CONCLUSIONS

The detailed studies at Broodkraal and Rooihoogte allowed us to compile a comprehensive climate database for the farms. This has been used to calculate actual evapotranspiration for the sites (e.g. Figure 1), which is a necessary input for our irrigation return flow model.

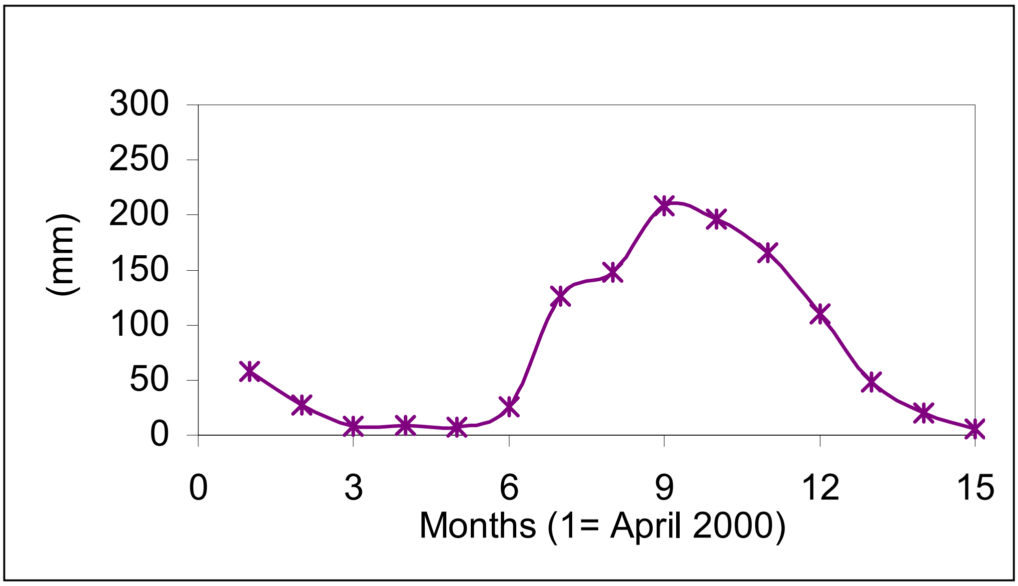

Figure 1. **Total monthly AET measured at the Broodkraal Farm using published crop factors for this region**

Soil mapping at the sites produced soil maps of suitable resolution. Monitoring of soil water and drainage water quality showed, in the case of Broodkraal, that drainage water salinity generally increased throughout the irrigation season, with a slight decrease in average salinity of soil water as one moves from higher to lower elevations. However, soil water quality showed considerable variation with time (Table 1).

Table 1 **Analytical results of soil water samples taken from Position B on the Broodkraal Farm sampled with suction cup lysimeters**

Date	Depth	EC	Ca	Mg	Na	K	Total. cations	Cl	NO3	SO4
	(cm)	(mS/m)	(mg/l)							
00.11.29	**20**	180.6	17.8	9.9	98.4	4.1	130.2	192.3		34.8
00.11.29	**40**	114.7	34.4	13.6	141.5	21.0	210.5	317.2	8.5	73.2
00.11.29	**75**	73.2	55.3	24.7	233.2	9.5	322.7			
00.12.07	**20**	153.3	45.8	21.9	195.7	4.0	267.5	328.7	57.4	145.8
00.12.07	**40**	126.8	38.4	15.4	150.0	5.2	208.9	314.8	28.8	88.4
00.12.07	**75**	82.5	19.3	11.6	94.8	4.2	129.8			
00.12.19	**20**	133.5	49.2	22.1	163.2	3.9	238.4	243.1	150.5	91.9
00.12.19	**40**	116.8	37.1	15.2	150.7	3.8	206.8	304.9	22.2	74.5
00.12.19	**75**	74.4	16.7	10.0	94.0	4.3	125.0			
01.01.11	**20**	83.7	27.4	12.8	96.5	3.3	140.0			
01.01.11	**40**	121.3	71.0	123.4	584.4	19.8	798.5	1084.1	8.1	767.5
01.01.11	**75**	90.5	16.8	11.4	110.8	0.0	139.0			
01.01.30	**20**	124.9	42.8	19.8	133.9	4.7	201.2	337.7	2.1	47.5
01.01.30	**40**	169.2	55.1	23.3	203.5	4.0	285.9	516.8	2.2	85.4
01.01.30	**75**	135.5	28.7	18.8	164.5	3.4	215.4	402.3		58.8
01.02.20	**20**	124.0	44.4	21.2	145.6	3.5	214.7	399.1		57.4
01.02.20	**40**	176.4	60.4	25.8	223.0	5.0	314.1			

The relationship between the electrical conductivity of saturated paste extracts (EC_e) and soil water (EC_{sw}) is not simple. EC_{sw} is generally higher that EC_e, but more so at greater soil depths. At Rooihoogte, EC_e of irrigated, deeply-prepared vineyard soils was lower than that of shallowly prepared soils used for dryland wheat farming (Table B).

Table 2 Depth-weighted mean values for pH, EC_e and total dissolved solids (TDS) in vineyards and wheat lands

	pH	EC_e (mSm^{-1}) Sat. extract	TDS (mg/L)	TDS (ton/ha)
Deep cultivated soils Sample taken between rows	7.26	148.8	952	11.4
Deep cultivated soils Sample taken in vine row	7.00	93.8	600	7.2
Shallow cultivated soils (wheat)	5.66	274.8	1758	21.1

The irrigated soils drain rapidly after irrigation (Figures 2 and 3).

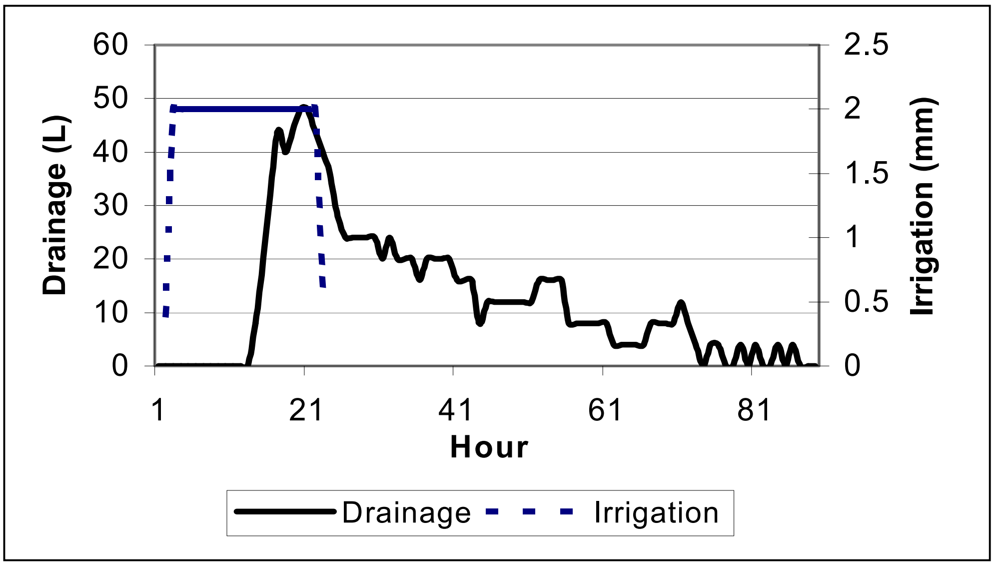

Figure 2. Drainage response to an irrigation event at Broodkraal Farm

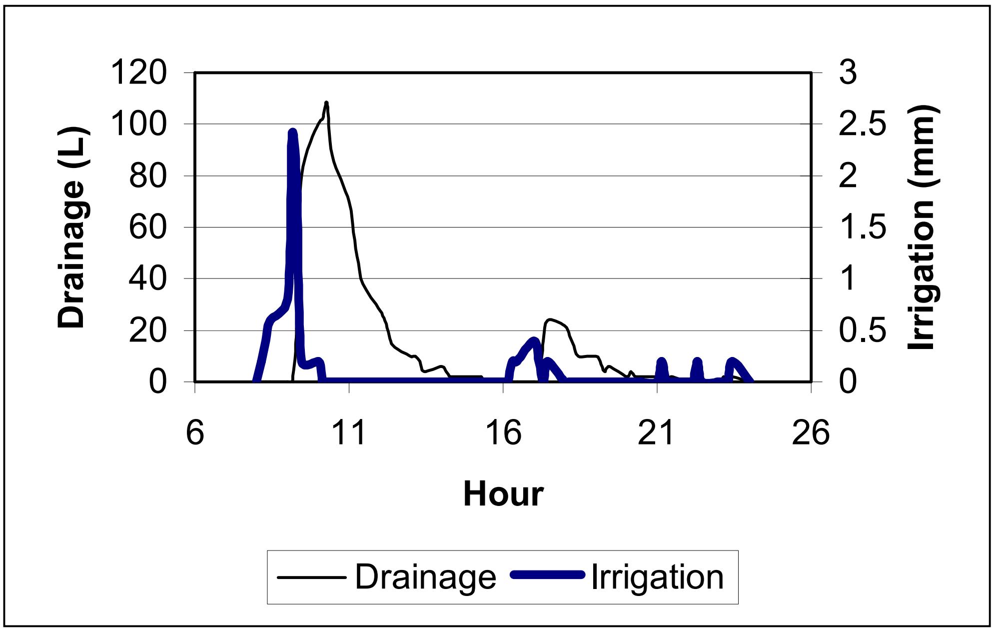

Figure 3. Drainage response to irrigation in a vineyard on the Farm Rooihoogte

A simple mass balance model was used to predict drainage volume for each soil-water sampling position at Broodkraal (Figure 4).

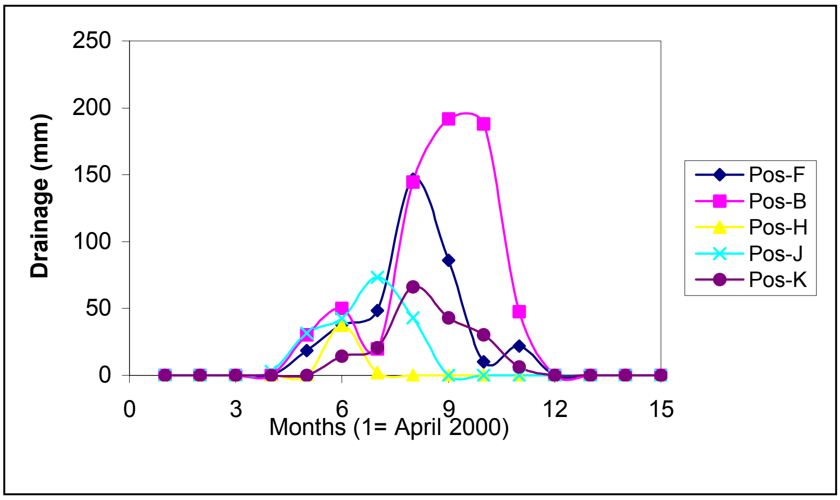

Figure 4. **Monthly total drainage in mm from five different locations on Broodkraal Farm**

Average electrical conductivity ranged between 200 mSm-1 and 550 mSm-1. Based on the modelled drainage volumes (Figure 4), and assuming a reasonable average salinity, it was possible to model net salt export from irrigated land at Broodkraal (Figure 5).

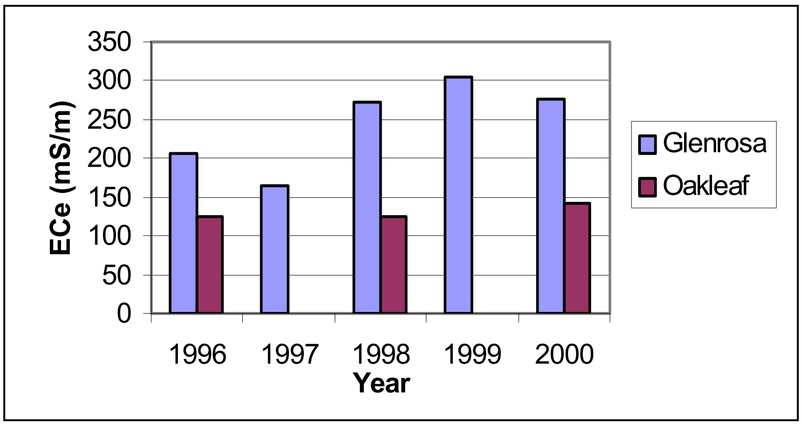

Figure 5. **Predicted monthly return flow given as total amount of salt in kg/ha based on a fixed yearly average EC_{sw} of 256 mSm-1 below the root zone at five sites on the Broodkraal Farm**

There is a clear distinction between soils of the Oakleaf and Glenrosa forms with respect to their salinity. The latter sustain higher EC_e values than the former over time in established, irrigated vineyard soils (Figure 6).

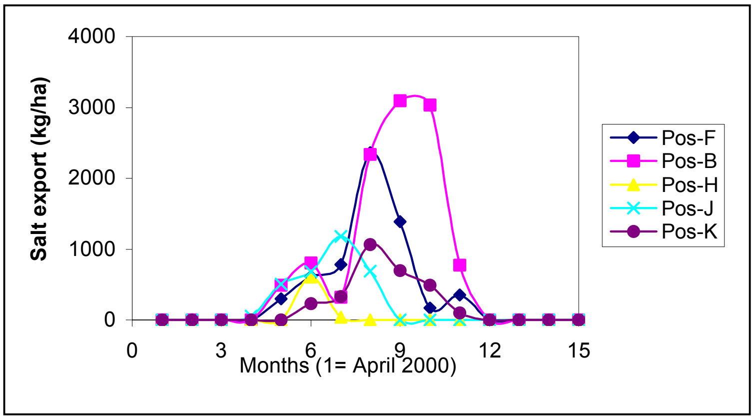

Figure 6. **The mean of 4 depth-weighted mean EC_e samples per site from irrigated vineyards. 'Year' refers to year of planting**

The study at Rooihoogte of dryland salinity and the role of heuweltjies revealed that these termite mounds have a higher base status, pH and salinity than inter-mound areas. In addition, the saprolitic subsoil associated with inter-mound areas also has a relatively high salinity. Prediction of the salinity hazard of future irrigation schemes on heuweltjie-pocked soils must take into account the variability in soil chemistry associated with these structures.

A highly significant correlation was found between the stone content of the soil and the SAR on Broodkraal. This suggest that patches of high stone content in the soil constitute preferential flow paths resulting in zones with higher leaching and therefore a lower SAR. Alternatively the stone fragments may constitute a reservoir of the weatherable bases besides Na.

Geostatistical methods proved useful in describing the spatial variation in soil salinity at Broodkraal (Figure 7).

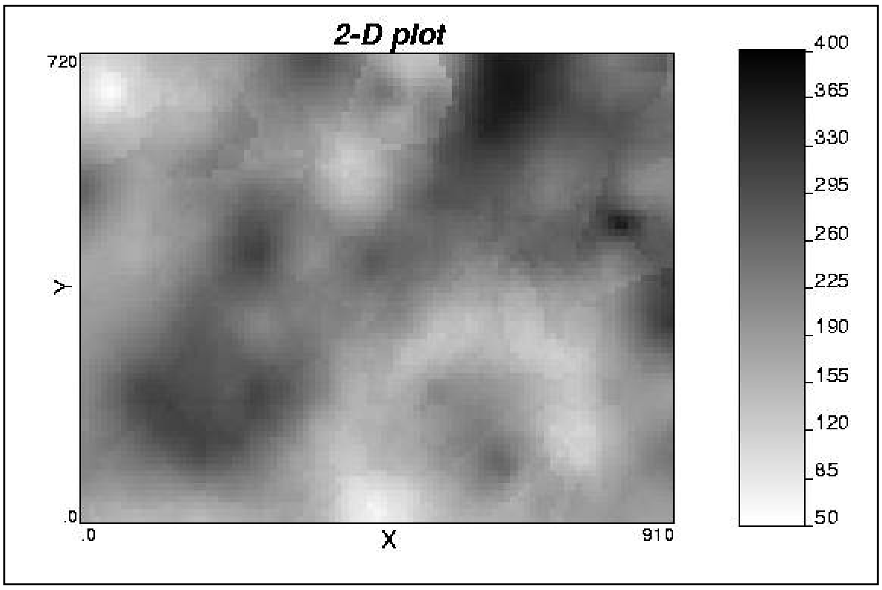

Figure 7. Map of spacial variation in EC_e of Broodkraal produced by Co-Kriging, indicated in metric distance

The lighter coloured areas in Figure 7 represent a lower salinity, which is associated with upland areas. This statistical description of the data corresponds with field observation.

Two maps were compiled for the Berg River catchment namely a soils map and a salinity hazard map. These maps and images from the Berg River Catchment are available in pdf-format on the accompanying CD-rom.

Using old data and newly acquired soil salinity data to predict soil EC change over time, proved to be of little use. The old data weren't georeferenced. This meant that a number of samples had to be taken in the vicinity of the old sampling positions. Comparing the newly acquired data with the old, variation in the soil proved to be larger between new samples than the possible change over time they were meant to constitute.

5. MEETING THE RESEARCH OBJECTIVES

Task 1: The objectives of task 1 were met. However, when this task was formulated, the assumption that the long irrigation history of the catchment would provide new research frontiers was mistaken, as was the view that irrigated agriculture is the dominant contributor of salt to the Berg River. The influence of irrigated agriculture when monitored beneath the root zone could not easily be estimated. When irrigation return flow mixes with the groundwater, the quality becomes unpredictable.

Task 2: The objectives of this task were fully met with respect to the development of generic methods for salinity hazard assessment related to irrigation agriculture. Two factors however prevented application of the methods in sections of the BRC. 1: Two key personnel at the DA's Winter Rainfall Region Office at Elsenburg, resigned during the course of the project, making interpretation work impossible. 2: Modelling of saline seep from dryland areas was impossible, as no approach to do this had been formulated. Irrigation return flow and saline seep from dryland areas enter the river as a mixture. Surface runoff of salts from wheat lands at the onset of winter rains would constitute an additional source of salts not readily amenable to quantification.

6. RECOMMENDATIONS FOR FUTURE RESEARCH

As a result of this study a number of pressing research needs have been identified. They are as follows:

There was an attempt in this study to identify the origin of the salts found in the soils of the region. A definite salinity recharge effect was picked up in soils that had remained allow for a number of years. Research needs to be done on the mechanism of this apparent recharge.

The dryland-farming areas of the catchment possibly contribute substantially more salt through cultivation than is currently the case with irrigated agriculture. This needs to be monitored.

The salinity database for the Berg River Catchment need to be expanded. This must be combined with appropriate data on land use and topographical features. A new pilot project (K5/1342) has been initiated that will address the problem of quantifying the contribution by dryland salinity to water quality in the BRC.