COMPARATIVE MODELLING OF PHOSPHOROUS PRODUCTION IN RURAL CATCHMENTS

by

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DECLARATION

I, the undersigned, hereby declare that this thesis is my own original work, and has not previously been submitted at any university for a degree.

Signed

Date

ABSTRACT

The objective of this research has been to compare nonpoint sources assessment techniques for simulating phosphorous production in rural catchments which have a variety of land use types. Four nonpoint source assessment techniques capable of simulating phosphorous production, operating at different spatial and temporal resolutions, were selected after an intensive literature review. The model selection criteria included the capability to simulate phosphorous production, the need for the study to cover a range of spatial and temporal resolutions, model data requirements, model affordability and availability in South Africa. The models selected using these criteria are the Phosphorous Export Model (PEM) (Weddepohl & Meyer,1992), Impoundment and River Management and Planning Assessment Tool for Water Quality Simulation Model (IMPAQ) (DWAF,1995), the Hydrological Simulation Program Fortran (HSPF) (Bricknell,1993) and the Agricultural Catchments Research Unit Model (ACRU) (Smithers and Caldecott, 1994).

Four of the study catchments were selected within the Berg River basin in the Western Cape and the remaining four were selected within the Amatole catchments in the Eastern Cape. The four sub-catchments in the Berg River basin are the Twenty-Four Rivers, Leeu River, Kompanjies River and Doring River catchments and the four in the Amatole catchments are the Upper Buffalo, Cwencwe, Yellowwoods and Gqunube River catchments. The range of land use/cover types comprises:

Western Cape catchments : wheat, grapes, natural vegetation and forestry
Eastern Cape catchments : natural vegetation and forestry

The PEM and IMPAQ models were applied reasonably successfully to all the catchments to simulate phosphorous production, with the observed flow as the input. The HSPF model could not successfully be applied to the catchments to simulate both the catchment hydrology and phosphorous production. Hence, the investigation into HSPF was abandoned, and in its place, the ACRU daily phosphorous yield model was incorporated at a fairly late stage in the research. ACRU was applied to only the Western Cape catchments.

The estimated parameters for different land use types were compared to investigate the potential for parameter transfer in space and time. Both the PEM and IMPAQ models showed promise that land use parameters could be transferred in time for catchments located in the Western Cape catchments, but did not show promise for catchments located in the Eastern Cape. The IMPAQ model showed promise that land use parameters could be transferred in space for catchments located in the Eastern Cape, but did not perform as well in the Western Cape catchments. The PEM model showed promise that land use parameters could be transferred in space for catchments located in the Western Cape, but did not perform as well in the Eastern Cape. Since the ACRU phosphorous yield model was included at a late stage of the research, the potential for land use parameter transfer in space and time could not investigated. The model results were verified at the relevant flow and water quality gauging stations.

The ACRU phosphorous model verification results showed promise for catchments located in humid parts of the Berg River basin, but did not perform as well in the catchment located in the semi-arid part.

RECOMMENDATIONS FOR FURTHER RESEARCH :

1. Intensive research should be undertaken to develop a database of land use parameters/ export coefficients related to phosphorous production (and other non-conservative constituents) in South African catchments. Availability of these parameters would make phosphorous modelling much easier.

☆ HSPF should be configured and calibrated, more especially its water quality component, for catchments with hourly rainfall and rainfall stations located within/on the catchment boundaries, to investigate its performance under South African conditions. Given the complexity of the HSPF algorithms and the time required to familiarise oneself with the model, it is recommended that such an investigation be undertaken which is not inclusive of any other models.

☆ The spatial resolution of PEM is extremely coarse, and should be improved to allow the user to partition the total flow in the catchment according to contributions from the variety of land use types and to estimate soluble and particulate phosphorous parameters for each land use type.

☆ A study should be undertaken to investigate the potential for the ACRU phosphorous yield model parameter transfer in time and space.

☆ Sampling frequency of water quality data in South Africa should be improved, because it is difficult to assess the performance of the calibrated water quality models, more especially phosphorous export models, due to a lack of continuous data sets.

☆ Rainfall data collection in gauged catchments, more especially Western Cape catchments (e.g. Twenty-Four Rivers, Leeu, Kompanjies and the Doring River catchments), should be improved. There should be at least one rainfall gauging station located within the catchment boundaries. This would contribute towards achieving reasonable hydrological calibration or verification. Since runoff is the driving factor for water quality components, improved hydrological calibration/verification would result in reasonable water quality calibration/verification.

REFERENCES FOR ABSTRACT:

☆ BRICKNELL, B.R, IMHOFF, J.C, KITTLE, J.L, DONIGAN, A.S, JOHANSON. (1993). *Hydrological Simulation Fortran Program* : Users Manual, Release 10, EPA, Report 600/R-93/174, Athens, GA.

☆ DWAF (1995). *Amatole Water Resources System Analysis*, Vol.2, Main report, DWAF Report No. Pr 000/00/0295.

☆ SMITHERS, J.C. and CALDECOTT, R.E. (1994). *Hydrograph routing. In:Schulze R.E. Hydrology and Agrohydrology : A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, Report TT69/95. ppAT13-1 to AT13-16.

☆ WEDDEPOHL, J.P and MEYER, D.H. (1992). *Utilisation of models to simulate phosphorous loads in Southern African catchments*, WRC report.

OPSOMMING

Die doel van die navorsing was om die simulering van fosfaat produksie in landelike gebiede, wat 'n verskeidenheid grondgebruike het, met behulp van nie-punt bron evaluerings tegnieke te evulaeer. Vier nie-punt bron evaluerings tegnieke, met die vermoë om fosfaat produksie op verskillende ruimtelike en tyds resolusies te simuleer, is gekies na 'n intensiewe ondersoek van beskikbare literatuur. Die kriteria vir die keuse van die model het ingesluit die vermoë om fosfaat produksie te simuleer, die behoefte vir die studie om 'n reeks van ruimtelike en tyds resolusies te simuleer, model data vereistes, model bekostigbaarheid en beskikbaarheid in Suid Afrika. Die gekose modelle, gebaseer op bogemelde kriteria, was die PEM, IMPAQ, HSPF en ACRU modelle.

Vier van die opvanggebiede gebruik in die studie, was in die Bergrivier bekken in die Wes-Kaap en vier was in die Amatole opvanggebiede in die Oos-Kaap. Die vier opvanggebiede in die Bergrivier bekken is die Vier-en-Twentigriviere, Leeurivier, Kompanjiesrivier en die Doringrivier en die vier opvanggebiede in die Amatole opvanggebiede is die Bo-Buffels, Cwencwe, Yellowwoods, en die Gunubierivier opvanggebiede. Grondgebruik beslaan die volgende:

Wes-Kaap opvanggebiede : koring, druiwe, natuurlike weiding en plantasies.
Oos-Kaap : natuurlike plantegroei en plantasies

Die PEM en IMPAQ modelle is met redelike sukses in al die opvanggebiede gebruik vir die simulasie van fosfaat produksie, met die waargenome vloei as invoer. Die HSPF model kan nie met enige sukses gebruik word om beide die opvanggebied hidrologie en fosfaat produksie, te simuleer nie. Die HSPF model is dus uitgeskakel en in 'n redelike laat stadium van die studie met die ACRU daaglikse fosfaat leweringsmodel vervang. Die ACRU model is net op die Wes-Kaap opvanggebiede toegepas.

Die beraamde parameters vir die verskillende grondgebruik tipes is vergelyk om die potensiaal vir parameter oordrag in ruimte en tyd te ondersoek. Beide die PEM en IMPAQ modelle het belowend vertoon ten opsigte van die oordrag van grondgebruik parameters in tyd vir opvanggebiede in die Wes-Kaap, maar het geensins belowend vertoon vir die Oos-Kaap opvanggebiede nie. Die IMPAQ model het belowend vertoon ten opsigte van die ruimtelike oordrag van grondgebruik parameters vir die Oos-Kaap opvanggebiede, maar het nie so goed vertoon in die Wes-Kaap opvanggebiede nie. Die PEM model het belowend vertoon ten opsigte van die ruimtelike oordrag dat grondgebruikte parameters in die Wes-Kaap opvanggebiede is, maar het nie so goed in die Oos-Kaap opvanggebiede vertoon nie. Aangesien die ACRU fosfaat leweringsmodel op 'n laat stadium van die navorsing ingesluit is, kan die potensiaal vir die oordrag van grondgebruik parameters in ruimte en tyd nie ondersoek word nie. Die model resultate is by die toepaslike vloei en waterkwaliteit meetstasies geverifiëer

Die resultate van die ACRU fosfaat model verifikasie het belowend vertoon vir opvangebiede in die humiede gedeeltes van die Bergrivier bekken, maar het nie so goed vertoon in die semi-droeë deel van die opvangebied nie.

AANBEVELINGS VIR VERDERE NAVORSING :

☆ Intensiewe navorsing moet onderneem word ten einde in 'n databasis van grondgebruik parameters/oordrag koëffisiente met betrekking tot fosfaat produksie (en ander nie-konserwatiewe bestandelle) in Suid Afrikaanse opvanggebiede op te bou. Beskikbaarheid van hierdie parameters sal fosfaat modellering vergemaklik.

☆ Die HSPF model moet opgestel en gekalibreer word, meer spesifiek ten opsigte van die waterkwaliteit komponent, vir opvanggebiede met uurlikse reënval en reënvalstasies binne of op die opvanggebied grense, om die model se vertoning onder Suid Afrikaanse omstandighede te ondersoek. Gegewe die kompleksiteit van die HSPF algoritmes en tyd benodig om met model vertroud te raak, word dit aanbeveel dat so 'n ondersoek onderneem word met uitsluiting van die ander modelle.

☆ Die ruimtelike resolusie van die PEM model is uitermatig grof, en behoort verbeter te word ten einde die gebruiker toe te laat om die totale vloei in die opvanggebied in ooreenstemming met die bydraes van die onderskeie grondgebruik tipes te verdeel en om oplosbare en partikulere fosfaat parameters vir elke grondgebruik tipe te beraam.

☆ 'n Studie om die potensiaal vir die ruimtelike en tydsoordrag van die ACRU fosfaat leweringsmodel parameters te ondersoek, moet onderneem word.

☆ Die frekwensie van waterkwaliteit monitering in Suid Afrika moet verbeter word, aangesien dit moelik is om, weens 'n gebrek aan deurlopend waargenome data, die vertoning van gekalibreerde waterkwaliteit modelle te ondersoek, meer spesifiek nog fosfaat uitvoer modelle.

☆ Reënval inligting versameling in gemete opvanggebied, meer spesifiek die Wes-Kaap opvanggebiede (bv.Vier-en-Twintigriviere, Leeu, Kompanjies en Doringrivier opvanggebiede), behoort verbeter te word. Daar behoort ten minste een reënval stasie binne die opvanggebied grense te wees. Dit sal bydra tot die bereiking van redelike hidrologiese kalibrasie of verifikasie. Aangesien afloop die dryfveer van die waterkwaliteit komponente is, sal verbeterde hidrologiese kalibrasie/verifikasie lei tot redelike waterkwaliteit kalibrasie/verifikasie.

VERWYSINGS VIR OPSOMMING :

☆ BRICKNELL, B.R, IMHOFF, J.C, KITTLE, J.L, DONIGAN, A.S, JOHANSON. (1993). *Hydrological Simulation Fortran Program* : Users Manual, Release 10, EPA, Report 600/R-93/174, Athens, GA.

☆ DWAF (1995). *Amatole Water Resources System Analysis*, Vol.2, Main report, DWAF Report No. Pr 000/00/0295.

☆ SMITHERS, J.C. and CALDECOTT, R.E. (1994). *Hydrograph routing. In:Schulze R.E. Hydrology and Agrohydrology : A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System*. Water Research Commission, Pretoria, Report TT69/95. ppAT13-1 to AT13-16.

☆ WEDDEPOHL, J.P and MEYER, D.H. (1992). *Utilisation of models to simulate phosphorous loads in Southern African catchments*, WRC report.

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BACKGROUND TO THIS STUDY

This study arose in response to the challenge to match management information needs with appropriate techniques which are capable of predicting phosphorous yield from rural catchments dominated by nonpoint sources. In detail, some of the considerations related to this challenge include:-

☆ identification of relevant water quality modelling techniques which are capable of predicting phosphorous yield from nonpoint source dominated catchments at specified spatial and temporal resolutions appropriate to management information needs as discussed in Section 2.6.

☆ modelling philosophies under which the water quality modelling techniques were developed.

The Water Research Commission(WRC) commissioned a project in 1996 aimed at developing a guide for nonpoint source assessment in South Africa. The aims of this project were to :

☆ describe the "state of the art" with respect to nonpoint source assessment in South Africa.

☆ outline the most important nonpoint source problems in South Africa.

☆ undertake nonpoint source assessment studies in a few test catchments, and

☆ produce a Nonpoint Source Assessment guide to identify appropriate nonpoint source assessment techniques to assist water quality managers when managing these sources.

The objectives of this research were derived from the WRC project discussed above.

CHAPTER 1

INTRODUCTION

It has been well established that the water quality in South African catchments is in danger of deteriorating, unless systematic management strategies are developed and applied. The primary water quality constituents that need to be targeted in this way are Total Dissolved Salts (TDS), Phosphorous (P), Nitrogen (N), Micro-biological constituents and sediments. This thesis focuses on Phosphorous.

At relatively high concentrations, phosphorous from nonpoint source dominated catchments, can interfere with the coagulation processes in the treatment of industrial and municipal water supplies (Weddepohl &Meyer,1992). High phosphorous concentrations also stimulate the excessive and undesirable growth of aquatic plant life, called eutrophication. Management programmes are therefore essential to minimize high phosphorous concentrations. Water quality managers require efficient decision support tools that can assist in the decision making process regarding cost effective programmes for minimizing phosphorous concentrations.

Water quality models play a vital role as decision support tools to water quality managers, because the models allow the phosphorous output response from varying catchment conditions and parameters to be examined thereby providing reasonable insight into the impact that different future scenarios will have on the phosphorous loadings being exported from the catchments of concern. There are quite a number of water quality models in the literature that are capable of predicting phosphorous production in rural catchments. It was therefore considered useful to undertake a study that would compare different water quality models which might be used as decision support tools in Southern Africa.

A literature review revealed that phosphorous production from urban catchments is receiving much research attention worldwide, but that comparative modelling studies in RSA agricultural catchments, and generally rural catchments, have not been as comprehensive.

1.1 STUDY OBJECTIVES

The objectives of this study were to :

- ☆ **select** water quality modelling techniques which are capable of predicting phosphorous production from nonpoint sources at different spatial and temporal resolutions
- ☆ **compare** selected modelling techniques in terms of phosphorous production in rural catchments located in the winter and summer rainfall regions
- ☆ **investigate** the potential for land use parameter transfer in **space** from catchments located in the winter and summer rainfall regions

☆ **investigate** the potential for land use parameter transfer in **time** from catchments located in the winter and summer rainfall regions

☆ **identify** the nonpoint sources "*assessment*"levels at which the selected modelling techniques could be applied to predict phosphorous production.

1.2 STRUCTURE OF THE THESIS

Chapter 1 Discusses the background to this study, study objective and layout of the report.

Chapter 2 Provides an overview of decision support for water quality management and outlines the role of the Department of Water Affairs and Forestry (DWAF) in the prioritisation of water quality issues in South Africa, sources of phosphorous and management levels. Different water quality assessment techniques are discussed in detail.

Chapter 3 Outlines a framework developed for the selection of study catchments and models aid for model calibration.

Chapter 4 Describes spatial and temporal resolutions, capabilities, model structure and potential shortcomings of the selected models.

Chapter 5 Presents the geographical location, topography, climate, flow gauging stations, meteorological stations and land use types of the study catchments.

Chapter 6 Outlines the type and sources of both local and national data with the corresponding relevant models. The laboratory results of weekly grab samples collected from the Doring River, as part of this study, are discussed. The problems related to the data are also outlined.

Chapter 7 Explains in detail model calibration procedure and results.

Chapter 8 Provides a comparison of the calibrated land use parameters from the models.

Chapter 9 Outlines model verification results.

Chapter 10 Outlines recommendations and conclusions derived from this study.

CHAPTER 2

DECISION SUPPORT FOR WATER QUALITY MANAGEMENT

It is very important for all stakeholders in the water sector to understand the concept "water quality" and the role which DWAF might play in promoting the development, testing and implementation of decision support tools which might be of help to water quality managers in South Africa. This chapter gives a broad overview of :

- ☆ the definition of water quality
- ☆ the role of DWAF in water quality management
- ☆ the priority of water quality issues
- ☆ phosphorous as a source of pollution
- ☆ the previous local studies related to phosphorous
- ☆ the management information need levels and type of decision support tools relevant to each management level
- ☆ the way in which water quality models could provide decision support to water quality managers
- ☆ modelling philosophies and water quality models derived from the literature.

2.1 WHAT IS WATER QUALITY?

The term "quality" has meaning only when related to some specific "*use*" of water. The concept of water quality comprises both physical and chemical characteristics of water. Physical characteristics of water are colour, taste, odour and temperature. Chemical characteristics are acidity, hardness and concentrations of various water quality constituents such as nitrates, sulphates, phosphates, dissolved oxygen and man-made pollutants, including pesticides, herbicides and heavy metals (Ward and Robinson, 1989).

Water quality criteria are defined in different ways by specific countries (DWAF, 1993). According to DWAF (1993), definitions which were relevant to the development of the South African water quality guidelines are:

- ☆ US EPA (1986) : a designated concentration of a constituent that, when not exceeded, will protect an organism, an organism community or a prescribed *water use* or quality with an adequate degree of safety.

- ☆ Canada (1987): scientific data evaluated to derive recommended limits for *water uses.*

- ☆ Australia (1992) : scientific and technical information used to provide an objective means for judging the quality needed to maintain a particular environmental value.
- ☆ South Africa (1993) : a designated concentration of a constituent used as a norm to evaluate the status of the water quality with respect to the constituent.

These definitions are also accepted to be relevant for this study.

2.2 THE ROLE OF THE SOUTH AFRICAN DEPARTMENT OF WATER AFFAIRS AND FORESTRY (DWAF) IN WATER QUALITY MANAGEMENT

The overall water quality management goal of DWAF is the maintenance of the *fitness for use* of South Africa's water resources on a sustained basis (DWAF, 1993). However, the extent and multiplicity of the management functions which are necessary to reach this goal require that stakeholders at all levels, including government agencies, industries, local authorities and individuals, assume collective responsibility in safeguarding the country's water resources. It is one of the roles of DWAF and other water research organisations, like Water Research Commission (WRC), to promote (by making funds available to research institutions and/or consultants) the development, testing and implementation of decision support tools which might be of help to managers at all levels of water quality management. Some of the decision support tools developed and tested through the DWAF and WRC funding are discussed in **Section 2.5 and Chapter 4**.

2.3 PRIORITY OF WATER QUALITY ISSUES IN THE RSA

According to DWAF (1995), the water quality variables of greatest concern are:

- ☆ salinity (i.e. TDS and EC)
- ☆ eutrophication (i.e. Phosphorous and Nitrogen)
- ☆ faecal pathogen indicators (*E.Coli*)
- ☆ sediments (suspended solids and turbidity)
- ☆ industrial toxins and heavy metals

The decline in the water quality of many sources of water in the RSA is primarily as a result of salination and to a lesser extent of eutrophication and pollution by trace metals and micro-pollutants. There have been a number of studies sponsored by the WRC and DWAF to investigate the impact of salinity, eutrophication, trace metals and pathogens on the water resources of RSA.

Although of a lesser consequence than salination, eutrophication is a significant problem in the RSA. Accordingly, eutrophication control programmes are required to improve the water quality of rivers and dams so that appropriate responses to the increasing demand of a growing population can be sustained. Eutrophication and problems caused by eutrophication are discussed in **Section 2.4**.

2.4 EUTROPHICATION

According to Thomann (1987, p387), the condition of a water body can be defined or described in terms of its trophic state.

There are three commonly known trophic states for lakes, viz:

- ✫ *oligotrophic* clear, low productivity lakes
- ✫ *mesotrophic* intermediate productivity
- ✫ *eutrophic* high productivity.

The condition of a water body which is of interest in this study is the eutrophic status. According to Thomann (1987, p386), some of the consequences of eutrophication regarding water use are:

- ✫ aesthetic and recreational (use of water surfaces for such sports as boating, angling and skiing) interferences.

- ✫ extensive growth of rooted aquatic macrophytes which interfere with navigation, aeration, and channel carrying capacity.

- ✫ large diurnal variations in dissolved oxygen (DO) which can result in low levels of DO at night, which in turn, can result in the death of desirable fish species.

- ✫ large diatoms (i.e. phytoplankton that requires silica) and filamentous algae can clog water treatment plant filters resulting in reduced time intervals between backwashings.

The fate and sources of phosphorous in catchments, which is one of the constituent elements that contribute towards eutrophication of water bodies, need to be studied in detail. As stated previously, this study focuses on non-point source pollution with phosphorous as the water quality constituent of interest.

In the past, a number of studies in the RSA were undertaken to investigate the sources, washoff and transport of phosphorous in South African catchments and rivers. Some of the studies are outlined **Section 2.5.**

2.5 PREVIOUS LOCAL STUDIES

Most of these studies were undertaken to develop decision support tools for water quality managers in South Africa.

- ✫ Phosphorous Transport in the Berg River (Bath, 1989)

The main objective of this study, funded by DWAF, was to *develop a decision support tool that could describe the export of phosphorous into the Berg River and the transportation through the Berg River drainage basin*. Some of the conclusions from the study were:

- ◇ ***The hydrodynamic phosphorous transportation model, developed in the study, provided a reasonably reliable description of the phosphorous generation and transportation in the aqueous phase of the Berg River catchment within the Paarl municipal area.***

- ***The model provided reliable temporal information on the phosphorous input to any impoundment in the Berg River in the Misverstand Weir.***

- ***The developed model was site specific and should not be applied to other catchments with different hydrological, topographical and catchment characteristics.***

☆ Development of the PEM model(Weddepohl & Meyer,1992)

The key overall objective of this study, funded by WRC, was to *develop a decision support tool for predicting phosphorous export from catchments experiencing changing phosphate loadings from point and nonpoint sources*. The decision support tool, PEM (discussed in detail in **Chapter 4**), was developed and applied successfully to the catchments listed in **Table 4.3.** The primary findings of the study are discussed in **Chapter 4**, **Section 4.2.1.**

☆ Kuils River Metropolitan Open Space System (Chittenden Nicks Partnership and Ninham Shand Pty (Ltd), 1999).

The objective of this study, funded by the Cape Metropolitan Council together with the City of Tygerberg, as well as Oostenberg and Helderberg Municipalities, was to *demarcate the Metropolitan Open Space System (MOSS) and to describe broad land use designations and management policies*. The study comprised the flood management aspect, water quality aspect, planning aspect and public participation aspect. The key objectives of the water quality aspect were to determine in-river water quality and to identify sources of pollution based on the available data, review fitness for use and comment on various management options to improve water quality of the river system. Some of the findings with respect to the water quality aspect of the study were:

- ***Nonpoint source pollution is generated by surface runoff particularly in urban areas, and enters the Kuils River system via overland flow and in formal urban areas via the storm water system.***

- ***High phosphorous concentrations have been recorded in Kleinvlei canal, indicative of urban runoff and the possibility of sewer leaks.***

- ***Phosphorous concentrations in the Moddergat Spruit were relatively low ranging from 0.045 to 0.073 mg/l, indicating that problems associated with eutrophication were unlikely to occur.***

☆ Amatole Water Resources System Analysis (DWAF, 1995).

The key objective of the study, funded by DWAF, was to develop a decision support tool which would be used to evaluate water quality impacts on critical land uses and future catchment developments, including planned water resource developments.

The decision support tool, IMPAQ (discussed in detail in **Chapter 4**), was developed and applied successfully to the Amatole catchments (see **Table 4.1**). Primary findings are discussed in **Chapter 4, Section 4.1.1**.

☆ Hydrology and Water Quality of the Mgeni Catchments (Kienzle *et al.*, 1997).

The objective of this study, funded by WRC, was to *develop a distributed hydrological modelling system to assist with water quantity and quality management in the Mgeni catchment.* The decision support tool, the ACRU phosphorous model (discussed in detail in **Chapter 4**), was developed and applied successfully to the Mgeni catchments (see **Table 4.7**). The primary findings are discussed in **Chapter 4, Section 4.4.1**.

2.6 SOURCES OF PHOSPHOROUS

Sources or causes of phosphorous in rivers and reservoirs can be classified as either point or non-point sources.

2.6.1 Point Sources

Definition: Point sources are defined as sources of pollutants that enter the transport routes at discrete, identifiable locations and that can usually be measured (Novotny, 1994). Examples of the common point source contributors to the phosphorous load on the water environment are as follows:

☆ domestic sewage related effluents from settlements, factories, residences and institutions
☆ industrial wastewater
☆ piped drainage water from active mines
☆ effluents from solid waste disposal sites
☆ concentrated washoff or runoff from concentrated animal feeding operations
☆ return flow from irrigated agriculture when it is collected by artificial drainage
☆ aquaculture.

2.6.2 Nonpoint Sources

Definition: Nonpoint sources are defined as the distributed or dispersed discharges of phosphorous from surface runoff, infiltration or atmospheric sources (DWAF, 1993). According to Novotny (1994), some of the examples of common nonpoint sources which contribute to the phosphorous loads are:

☆ runoff from unsewered settlement areas (e.g. informal, rural and semi-formal high-density settlements).
☆ runoff from both agricultural and afforested areas.
☆ return flows from irrigated agriculture.

- ☆ urban runoff from activities that generate contaminants (e.g. lawns, streets, golf clubs, and other sports fields).

It was hoped that this study would help to quantify major nonpoint source contributors in selected rural catchments.

2.7 MANAGEMENT INFORMATION NEED LEVELS

According to Pegram and Görgens (1997), there is a range of management goals and information needs that must be supported by appropriate levels of nonpoint source assessment. These may be grouped into the following four general levels of assessment:

- ☆ scoping level
- ☆ evaluation level
- ☆ prioritisation level, and
- ☆ selection level.

Scoping level

A question which the manager may ask at this fairly limited level of assessment is : *what are the issues for nonpoint source assessment*?A scoping level exercise should involve the characterisation of the of the nonpoint source assessment task, in terms of the *management goals*, *water quality concerns* and *source area character* (see **Appendix A**)

The *scoping* assessment should indicate the critical *water quality concerns*, whether nonpoint sources contribute significantly, and which sub-catchments require further nonpoint source assessment. In those cases where the assessment task is clearly defined and the practitioner has an understanding of the issues, scoping may be bypassed, moving directly to the level of assessment that is appropriate to their assessment purpose. At this level of assessment, the manager requires a highly economic decision support tool which might provide a broad overview about the existence of a nonpoint source pollution problem in the catchment of interest.

Evaluation level

The management question related to this assessment level is : *which nonpoint sources are causing the water quality concerns*? The understanding gained from this level of assessment should support the prioritisation and selection levels (referred to) and should focus further analysis on those sources and activities with the greatest water quality impact. The assessment may be appropriate at coarse or fine spatial and temporal resolutions, depending upon the nature of the critical *water quality concerns*, the nonpoint source character and the management information needs, as defined during the scoping assessment. At this level of assessment, the manager is interested in the decision support tools which might help to identify the different sources of nonpoint source pollution within the catchment of interest.

Prioritisation level

The management question asked at this level is : *which nonpoint sources and processes should be managed*? Prioritisation should be based on the techniques and information obtained during evaluation. At this level, the manager would be interested in the decision support tools which are well known and capable of providing reliable information about the degree of contribution from each source of pollution and related processes. The results from the decision support tool should act as a guide to water quality managers for prioritising sources and related processes, which need to be managed to minimize the nonpoint source pollution.

Selection level

The appropriate management question at this level is : *how should the nonpoint sources be managed*? Selection assessment may be the responsibility of an individual polluter involved in a permit application for a controlled activity, or may be required by the water quality authorities as part of a broader catchment management process.

Reaching this level is the ultimate aim of all nonpoint source assessments which support water quality management, and is thus likely to be required to some degree for most management processes. At this level, the manager requires a decision support tool which can provide information about the techniques that can be implemented to manage the nonpoint source pollution in an efficient manner.

2.8 HOW CAN WATER QUALITY MODELS PROVIDE DECISION SUPPORT?

The output of results from water quality models could be used as decision support tools by water quality managers. The output could act as a guide to the manager in making short, medium and long term decisions regarding water quality management in specific catchment. Examples of different types of outputs are:

- ☆ tabular output
- ☆ graphical output.

2.8.1 How can Tabular Output Help the Water Quality Manager?

Tabular output could provide information about the quantity of phosphorous loads from different land use types within the study catchment. These loads could be tabulated for wet and dry seasons as well as summer and winter conditions. Tabular output could show statistical comparisons between recorded and simulated phosphorous loads. This output might be of help to the manager who is interested in the quantity of phosphorous loads contributed by a specific land use types in the catchment. With this information at hand, the water quality manager could make a reasonable decision about how the production of phosphorous loads should be minimised and managed efficiently.

2.8.2 How can Graphical Output Help the Water Quality Manager?

Graphical output could provide the manager with the information about the variation of the quantity of phosphorous loads production from a specific land use type with respect to time for a specific period. It could also show statistical comparisons between the measured and simulated loads. Unlike tabular outputs, graphical outputs are easy to use when the manager would like to understand the trend of the phosphorous loads for different seasons within a specified period.

Both graphical and tabular outputs are used in this study **(refer to Chapters 7 and 9).**

2.9 DIFFERENT MODELLING PHILOSOPHIES

Research in the seventies and early eighties by universities, agencies and researchers, has resulted in the development of a large number of decision support tools (models) which could be used for nonpoint source modelling and for assessment of remedial measures (Novotny,1994). The nonpoint source pollution models can be broadly divided into the following basic overlapping groups:

- ☆ deterministic models versus probabilistic (stochastic & statistical) models
- ☆ continuous versus event-based models
- ☆ lumped versus distributed parameter models
- ☆ empirical versus physically based models, and
- ☆ calibrated models.

Deterministic models

For a given set of inputs such models provide only one set of outputs (Novotny, 1994). These models often take into account some or many of the physical processes in the catchment (Ward and Robinson, 1989, Weddepohl & Meyer, 1992), but they may also be purely empirical (e.g. PEM).These are the so-called "*black box*" models (Kienzle et.al., 1997).

Stochastic models

These are models which explicitly incorporate uncertainty into the representations of relationships and data, with each input data set leading to a number of possible outcomes with different probabilities of occurrence (Novotny, 1994). These are the so-called "*black box*" models (Kienzle et.al., 1997).

Lumped parameter models

If only one "representative" set of parameters is specified for a whole catchment, the model concerned is a lumped parameter model (Görgens,1983, Weddepohl & Meyer, 1992).

Distributed parameter models

The expression of the spatial variability common to all catchments in the form of different sets of parameters for different segments of a catchment is known as a distributed parameter approach. The model concerned is known as a distributed parameter model (Görgens,1983, Weddepohl & Meyer, 1992).

Event-based models

These models reflect the impact of a single hydrometeorological event (e.g. a major rainfall or snowfall event or an incident such as a major contaminant spill), given initial conditions (Novotny, 1994). The principal disadvantage of event modelling is that it requires specification of the design storm, antecedent moisture and pollutant storage conditions, thereby assuming equivalence between the recurrence interval of the design storm and the recurrence interval of runoff or pollutant output load /concentration.

Continuous simulation models

They are models which provide a time series of impacts over a period including a large number of events (Novotny, 1994). The most comprehensive estimates of nonpoint source loads are obtained from continuous simulation models (e.g. HSPF, STORM, SWMM and CREAMS) (Mills,1985).

Empirical models

These are models which are based on statistically fitted relationships describing observed behaviour or outcomes, without representing the underlying physical processes.

Physically-based models

These are models which explicitly incorporate relationships representing the primary physical processes governing the nonpoint sources impacts. These are the so-called "*white box*" models (Kienzle et.al., 1997).

Calibrated models

These are models which require first stage "tuning" to field /observed data, preferably a set of field data not used in the original configuration of the model (Thomann,1987, p386, Jonker and Görgens, 1995). The "tuning" of the model should include a consistent and rational set of theoretically defensible parameters and inputs. The major drawbacks of these models are that they are data demanding (for calibration procedure) and that parameters are identified for a particular catchment, making parameter transfers to ungauged catchments problematic and speculative (Kienzle et.al., 1997).

Table 2.1 lists some of the models described in the literature:- a literature review of potentially suitable and available models and of modelling approaches was done as part of this study. The objective of the literature review was to assemble a set of water quality models which are capable of simulating phosphorous production at different spatial and temporal resolutions, and to select relevant models according to the model selection criteria outlined in **Section 3.1.1.**

In **Table 2.1.** The author lists the name of the model, runoff generation method, model time step, spatial resolution of the model, the method for simulating phosphorous production, the method for simulating sediment production within the catchment and lastly, the availability of the model. The costs and ongoing financial support for some of the models, especially models from the United States Department of Agriculture (USDA), Cornell University and University of Georgia, could not be found and therefore were not shown in **Table 2.1**.

The headings in different columns of **Table 2.1** helped to identify water quality models which could be selected to aid in achieving the objectives of this study.

Table 2.1 Primary Features of Phosphorous Yield Models Described in the Literature

Model	Primary Features and Availability of Phosphorous Yield Models Assembled from the Literature					
	Runoff generation	Model time step	Spatial resolution	Phosphorous	Sediment	Availability
[9]HSPF (Beasly, 1981)	Moisture budgeting-empirical functions	from one minute to daily, continuous	Relatively homogeneous land use units	Optional : Sorption Kinetics or exponential storage decay functions	Rain drop erosion	Available free of charge from the [4]CCWR. Efficient ongoing user support is also offered by the [4]CCWR
[11]PEM (Weddepohl & Meyer, 1992)	Moisture budgeting-Pitman model	Monthly, continuous	Homogeneou s land use units	Exponential storage decay functions	[15]USLE (Wischmeier & Smith, 1978)	Available free of charge from the [16]WRC or [7]CSIR. Ongoing user support is not available
[10]IMPAQ Catchment Washoff Module (DWAF, 1995)	[12]SCS curve numbers	Monthly, continuous	Homogeneou s land use units	Loading functions (DWAF, 1995)	[15]USLE (Wischmeier & Smith, 1978)	Available from Ninham Shand Ltd (Pty), Cape Town. Ongoing user support available
[5]CNS (Haith, 1981)	Moisture budgeting-empirical functions	Monthly, continuous	Lumped cropland	Sorption kinetics kinetics (see **Chapter 4**)	[17]MUSLE (Williams,1975)	Cornell University
[13]SWRRB (Arnold, 1989)	Moisture budgeting -[12]SCS curve numbers	Daily, continuous	Distributed parameter model	use [6]CREAMS routine	Modified [17]MUSLE (Williams,1975)	[14]USDA-ARS, Georgia
[8]GWLF (Haith, 1987)	Moisture budgeting - [12]SCS curve numbers	Monthly, continuous	Distributed model	Loading functions	[15]USLE	Cornell University
[2]AGNPS (Young *et al.*, 1986)	Moisture budgeting- Unit Hydrograph	Single event, continuous	Uniform square cells	Sorption kinetics (see **Chapter 4**)	[17]MUSLE	[14]USDA-ARS, Minnesota
[6]CREAMS (Knisel, 1980)	Moisture budgeting- [12]SCS curve numbers or Green-Ampt equation	Single event, continuous	Distributed parameter model	Associated with runoff and sediment	[17]MUSLE (Williams, 1975)	[14]USDA-ARS, Georgia
[1]ACRU (Smithers & Caldecott, 1994)	Moisture budgeting : multi-layer soil water budgeting	Daily, Continuous	Point, lumped or distributed parameter model	Associated with runoff and sediment	[17]MUSLE (Williams, 1975)	Available free of charge from the University of Natal. Ongoing user support available
[3]ANSWERS (Beasly, 1981)	Moisture budgeting : backward solution of continuity equation	Single event	Uniform square elements of one to four hectares	Associated with runoff & sediment	[17]MUSLE (Williams, 1975)	University of Georgia

Acronyms used in **Table 2.1** are defined as follows :-

[1]ACRU :- Agricultural Catchments Research Unit

[2]AGNPS :- Agricultural Nonpoint Source

[3]ANSWERS :- Areal, Nonpoint Source, Watershed Environmental Response Simulation

[4]CCWR :- Computing Center for Water Research

[5]CNS :- Cornell Nutrient Simulation

[6]CREAMS :- Chemicals, Runoff, and Erosion from Agricultural Management Systems

[7]CSIR :- Council for Scientific and Industrial Research

[8]GWLF :- Generalized Watershed Loading Functions

[9]HSPF :- Hydrological Simulation Program Fortran

[10]IMPAQ :- Impoundment and river Management and Planning Assessment Tool for Water Quality Simulation Model

[11]PEM :- Phosphorous Export Model

[12]SCS :- Soil Conservation Service

[13]SWRRB :- Storage, Treatment, and Outflow Runoff Model

[14]USDA-ARS :- United States Department of Agriculture- Agricultural Research Service

[15]USLE :- Universal Soil Loss Equation

[16]WRC :- Water Research Commission

[17]MUSLE :- Modified Universal Soil Loss Equation

The following paragraphs outline a brief summary on how each of the water quality models in **Table 2.1** simulate moisture budgeting, sediment and phosphorous production. Spatial and temporal resolutions of the models are also discussed.

Moisture budgeting:

The water quality models listed in the table above use different techniques to simulate moisture budgeting. The HSPF, CNS and Pitman models use empirical functions to simulate moisture budgeting and the AGNPS model use the Unit Hydrograph technique. A number of models from **Table 2.1**. use SCS curve numbers to generate runoff (e.g. CREAMS; SWRRB; GWLF and IMPAQ models). The PEM uses the Pitman Hydrological Model to generate runoff. ACRU model simulates runoff generation through multi-layer water budgeting.

Sediment production

The ACRU, CNS, AGNPS, CREAMS, SWRRB and ANSWERS models use the MUSLE to estimate sediment production from the catchment. The PEM, GWLF and IMPAQ models use USLE to estimate sediment production from the catchment.

The USLE provides for an estimate of the long term average annual soil loss resulting from sheet and rill erosion (Smithers and Caldecott, 1994). It thus excludes the soil loss resulting from concentrated flow and gully formation and if used for sediment yield estimations requires the inclusion of a separate term to represent the delivery ratio, which accounts for the portion of eroded soil which leaves the catchment (Smithers and Caldecott, 1994). The USLE requires an index of annual rainfall erosivity, soil erodibility factor, slope length and gradient factor, land cover and management factors, and support practice factor, as the input parameters. These parameters are explained in detail in **Chapter 4.** The HSPF model is the only one which uses rain drop driven erosion to estimate the production of sediments in the catchment.

Phosphorous production

The water quality models listed in **Table 2.1.** simulate phosphorous production in different ways. Out of all the models listed above, HSPF is the only model which gives the user the option of selecting the technique for simulating phosphorous production from the catchment. The user has the option of using either sorption kinetics (i.e. adsorption and desorption of phosphorous using the *first-order kinetics*) or exponential storage decay functions. The ACRU phosphorous yield model simulates phosphorous production from land use types through equilibrium between the adsorbed and dissolved phases which are controlled using an *adsorption isotherm equation* (see **Chapter 4, Section 4.4.5.4** for more details), and the desorption kinetics during a rainfall event is controlled by the *desorption isotherm equation* (see **Chapter 4, Section 4.4.5.4** for more details). Both ACRU and HSPF models are capable of simulating "dry deposition (i.e. the deposition of phosphorous through adherence to dust particles)" and "wet deposition (i.e. the deposition of phosphorous from the atmosphere in rainfall)" processes.
The CNS and AGNPS models use sorption kinetics to simulate phosphorous production. The PEM model uses exponential storage decay functions. Both the IMPAQ and GWLF models use loading coefficients (i.e. coefficients which reflect average concentrations of phosphorous in baseflow, surface runoff and sediment from a specific land use type) to estimate phosphorous production from the catchment.

Spatial and temporal resolutions

Four of the models (i.e PEM, IMPAQ, CNS and GWLF) listed above operate on a monthly time step and three (i.e HSPF, GIBSI and SWRRB models) operate on a daily time step. HSPF operates on a 24 hours or shorter time step. ACRU operates on a daily time step. All the models, with the exception of CNS, are capable of using the distributed parameter approach. PEM can operate as a distributed parameter model, but does not allow the breakdown of flow for each land use units.

According to Tsihrintzis (1996), some other nonpoint source pollution models which are widely used, are:GLEAMS (Ground Water Loading Effects of Agricultural Management Systems), ARM (Agricultural Runoff Model), PRZM (Pesticide Root Zone Model), SWMM (Storm Water Management Model) and NPS (Non Point Source). A brief review of an outline of these models indicated that their data requirements could not be met in this study.The models selected for this study are the ACRU, HSPF, IMPAQ and PEM models. The model selection criteria used are discussed in **Chapter 3**.

CHAPTER 3
METHODOLOGY

A clearly defined methodology that the researcher is going to follow in addressing the problem in order to achieve research objectives, helps the researcher to focus on the problem at hand. This chapter outlines the tasks which make up the methodology for the research. These tasks are : model selection criteria, study catchment selection criteria, database development, selection of objective functions and model calibration.

3.1 TASKS

3.1.1 Model Selection Criteria

The water quality models PEM, HSPF, IMPAQ and ACRU, were selected from **Table 2.1.**

As discussed in **Chapter 2**, a range of water quality models were investigated, using literature sources. As explained, some of the models are single event models, while others are continuous simulation models. Given the wide range of water quality models potentially available, it was decided to introduce a selection criteria to aid the selection of the relevant water quality models. The selection criteria are derived from the research objectives.

As the water quality variable relevant to this study is phosphorous, the *first* criterion was obviously that the selected models should be capable of simulating catchment phosphorous export. Many water quality models can simulate a range of water quality variables like TDS, EC, N, SS, $P0_4$ and TP (e.g the IMPAQ model).

The *second* criterion was that the selected models should cover a range of spatial and temporal resolutions. The spatial resolution refers to the degree to which the catchment characteristics and land uses are "lumped", or considered separately. In order to investigate the impact of spatial resolution on model output, one must first model the catchment according to distributed catchment characteristics and a variety of land use types, with each land use type having its own model coefficients on parameter settings. The alternative is to "lump"the land use type or physical characteristic parameters. The selected water quality model should provide insight into the importance of spatial resolution in terms of simulated phosphorous output.

The temporal resolution refers to the model time step. Appropriate minute-by-minute, hourly or daily water quality data sets are generally rare. Therefore, coarser temporal resolutions are often used in water quality studies. Due to a general lack of continuous water quality data at the finer time steps, it was decided that spatial resolution be quantified using daily and monthly time step models. The selected water quality models should be of either daily or monthly time steps.

The *third* criterion was that the selected model (s) should be readily available and affordable for use in Southern Africa. There are water quality models which can meet the *first* and *second* criteria, but are not available for use or easily affordable.

The *fourth* criterion was that the data requirements of the selected models should comply with the availability of data in the RSA, because some of the models may meet the first, second and third criteria, but require extensive data which may not be easily obtained.

The abovementioned criteria were applied to the set of water quality models listed in **Table 2.1** and the following four models were selected

- ☆ IMPAQ
- ☆ PEM
- ☆ HSPF, and
- ☆ ACRU.

It can be seen that the selected models belong to the deterministic, continuous event, calibrated, lumped and distributed categories. These models will be discussed in detail in **Chapter 4**.

3.1.2 Study Catchment Selection Criteria

The RSA has a large number of catchments which are gauged. About 2000 flow gauging stations are located at different points across the country (DWAF, 1990). These flow gauging stations are generally well maintained by the DWAF. Water quality monitoring in the form of grab samples or continuous EC monitoring has been undertaken at many of these stations.

In order to select appropriate study catchments for this study, selection criteria were derived from the study objectives.

The *first* criterion was that the selected catchments should allow assessment of the importance of spatial resolution in modelling. The selected catchments therefore should cover a variety of land use types as a group, but preferably each should have one dominant land use type. This would potentially allow comparison of model coefficients/parameters across dominant land use types.

The *second* criterion was that the temporal resolution requirements also had to be met, which implies that the selected catchments should have phosphorous and streamflow data. The regular collection of grab samples from some of the flow gauging stations occurs at a sampling interval that usually is weekly. The sampling interval is usually weekly, but could be longer. These collected samples are then sent to the laboratory for analysis. It is too costly and impractical for DWAF to collect daily grab samples for analysis as a rule.

The selected catchments were, therefore, required at least to have regular weekly phosphorous data.

The *third* criterion focused on streamflow data. Catchment runoff is the transporting medium for water quality constituents. The representativeness of the water quality modelling results depends on the reliability of the observed catchment runoff. It is of vital importance for the selected catchments to be served by flow gauging stations with sound daily and monthly flow data sets.

The *fourth* criterion was that catchments had to be selected from regions with different climatic and geological conditions to assess the role of climatic and geological variation in model performance. To assess this, one has to configure the model for two regions with different climatic and geological conditions. According to the abovementioned criteria, four suitable catchments in the Eastern (a typical summer rainfall region) Cape and four in the Western Cape (a typical winter rainfall region) were selected. These catchments are discussed in **Chapter 5**.

3.1.3 Database Development

Different methods were used to collect data locally and nationally. The national data was made available through the electronic mail and local data was received from the Department of Agriculture in Elsenburg. A small data set of weekly grab samples were also collected specifically for this project. Some of the meteorological data were extracted from the CCWR database.

More information on the data collected and their sources is provided in **Chapter 6** and **Tables 6.1 & 6.2.**

3.1.4 Model Calibration

The procedure by which model parameter values are determined for a specific catchment is known as the calibration of the model. Sometimes, certain model parameters can be derived by field observation of catchment processes; however, it is common practice to determine most parameter values by a trial-and-error procedure based on the correspondence between observed and simulated streamflows and/or water quality variables (Görgens,1983, Weddepohl & Meyer, 1992).

Estimation of parameters, or calibration, can be carried out in three ways:

☆ model parameters can be deduced from measurable catchment characteristics. This approach is known as an *a priori* approach (Chapman,1975) and can be regarded as being reasonably objective. This approach presupposes that the model is sufficiently deterministic, or at least physically realistic, to such an extent that field and/or laboratory measurements of catchment characteristics and processes become meaningful prerequisites for successful operation of the model (Görgens,1983).

- the model parameters can be deduced by curve-fitting or goodness-of-fit procedures, in other words finding parameters that will ensure close correspondence between specific characteristics of one or more simulated hydrological time series and their equivalent observed time series. Exactly how closely the simulated and observed time series correspond is measured by one or more statistical procedures. Any specific fitting criterion employed in the parameter estimation process is described as the objective function (Görgens,1983). It goes without saying that the nature of the "objective function" will dictate the outcome of the calibration process (Diskin and Simon, 1977). A purely curve fitting approach to parameter estimation is usually accompanied by uncertainty as to whether or not the deduced parameters are "artifacts of the fitting process" (Chapman,1975), and to what extent they can be related to the "true" values which they claim to represent. This approach can range from being completely objective, achieved by using automatic optimization routines (Ibbit and O'Donnell, 1971), to being pragmatically subjective in performing trial-and-error fitting by manual perturbation of model parameters and relying strongly on visual observations of the correspondences between the simulated and observed time series (Pitman,1976).

- model parameters can be deduced by a mixed approach employing both *a priori* and curve-fitting methods. Exactly what mix of the two methods may be employed in a specific situation, may depend on which, and how many, of the model components are physically based to an extent that warrants *a priori* parameter estimates, and also on whether the objectives of the model application and available resources justify the effort and cost that *a priori* estimates may entail (Görgens,1983). Important to note is that the *a priori* component of the mixed calibration approach often does not comprise more than merely basing initial estimates of so-called physically realistic parameters on catchment data. These initial estimates are further "hardened" by subsequent curve-fitting calibration methods (Görgens,1983). The practising hydrologist is, however, often left with little choice but to accept the inevitability of a certain amount of "curve-fitting" when using hydrological models in an applied or operational situation (Görgens,1983).

According to Görgens (1983), some of the shortcomings of the goodness-of-fit/curve-fitting methods can be redressed in two ways, viz :

- by ensuring that before calibrating the model, *a priori* estimation of at least some parameters takes place, even if they are merely initial parameter values in the fitting process to ensure that the calibration starts in a realistic parameter environment.

- by using, additional to streamflow records, measured hydrological time series such as soil moisture or groundwater storage in model calibration.

The principles discussed above can also be applied in the calibration of water quality models. However, calibration of water quality models would be more difficult. Due to the irregular grab-sample nature of water quality data, what is regarded as "observed" values, often include a certain degree of "infilling" or "patching" to provide reasonably likely estimates of the values on un-sampled days or months.

The accuracy of the "observed" values is therefore, dictated by the accuracy of the patching/infilling technique.

3.1.4.1 Description of Objective Functions

Diskin and Simon (1977) and Görgens (1983) provide a comprehensive analysis of objective functions which can be used in the calibration of the category of models selected for this study.These are as follows:

☆ error in mean annual runoff/load (▵MAR) :

$$\triangle MAR = 100*(MAR_{Ys} - MAR_{Xo})/ MAR_{Xo} \qquad 3.1a$$

Where :

MAR_{Ys} ⇉is the simulated mean annual runoff/load ,
MAR_{Xo} ⇉is the observed mean annual runoff/load.

☆ error in annual or monthly standard deviation (▵SD) :

$$\triangle SD = 100*(SD_{Ys} - SD_{Xo})/ SD_{Xo} \qquad 3.1b$$

Where :

SD_{Ys} ⇉is the standard deviation of the simulated flow/load/concentration (annual or monthly).
SD_{Xo} ⇉is the standard deviation of the observed flow/load/concentration (annual or monthly).

☆ coefficient of determination (CD) :

CD = (correlation coefficient)^2 , where

$$\text{correlation coefficient} = (\sum^{N} Y_S + X_O)/ \surd\{\sum^{N}(Y_S)^2 - (\sum^{N}(Y_S))^2)*(\sum^{N}(X_O)^2 - (\sum^{N} X_O)^2)\}$$

This is a common measure of one-to-one fit, but offers no information on systematic errors.

☆ monthly or daily coefficient of efficiency (MCE/DCE) based on the mean flow/concentration/load for each calender month :

$$MCE/DCE = 1 - \sum^{N}(Ys\text{-}Xo)^2 / \sum^{N} (Xo\text{-}X_{OM})^2 \qquad 3.1c$$

Where :

Ys ⇉ is the simulated flow/load/concentration for each calender month or day,
Xo ⇉is the observed flow/load/concentration for each calender month or day,
X_{OM} ⇉ is the mean of the mean observed flow/load/concentration for each calender month or day.

This function is a dimensionless measure of one-to-one fit sensitive to systematic error and first proposed by Nash and Sutcliffe (1970)

☆ the difference between coefficient of determination (CD) and coefficient of efficiency (CE) :

The function is a measure of systematic error.

☆ the sum of the squared residuals (SSRES), which is defined by the mathematical relationship
below :

$$SSRES = \sum (Y_S\text{-}X_O)^2, \qquad 3.1d$$

where :X_O ⇉ are the values of the concentration/load/flow for a specified time interval, and
Y_S ⇉ are the values of the concentration/load/flow simulated for the same time interval.

Early in time series modelling history this was said to be the most commonly used objective function for hydrological simulation models (Diskin and Simon,1977). This function gives a one dimensional measure of one-to-one fit.

☆ Sum of residuals (logarithms) (SSRESL) :

SSRESL = SSRES calculated on logarithms

The function is a measure of one-to-one fit of low to medium flows/concentrations/loads.

☆ relative absolute error (RAE) :

$$RAE = \sum^{N} |Y_S - X_O| / X_O \qquad 3.1e$$

This function is a measure of a one-to-one fit.

☆ the sum of squared ratios of simulated and observed flows/concentrations/loads (SSRAT) :

$$SSRAT = \sum^{N} (Y_S / X_O)^2 \qquad 3.1f$$

☆ the sum of squared ratios (logarithms) (SSRATL) of simulated and observed flows/concentrations/loads :

SSRATL = SSRAT calculated on logarithms.

☆ error in index of seasonal variation (I_S) of flow/concentration/load :

$$I_S = 100*(I_{Ys} - I_{Xo}) / _{Ixo} \qquad 3.1g$$

Where I_{Ys} ⇉ is the index of seasonal variation of simulated flow/concentration/load
I_{Xo} ⇉ is the index of seasonal variation of observed flow/concentration/load

☆ proportional error of estimate (PEE) :

$$PEE = [\sum^{N}(Ys\text{-}Xo)^2 / \sum^{N} (Xo)^2]^{0.5} \qquad 3.1h$$

The function is a dimensionless measure of a one-to-one fit biased towards low to medium flows/loads/concentrations.

☆ Coefficient of persistence (CP) : a measure of systematic error (persistence in residual errors)

$$CP = \sum^{N} A^2_N / SSRES \qquad 3.1i$$

This function was first proposed by Wallis and Todini (1975) and used in the WHO (1975) catchment model comparison project.

☆ relative mean persistence (RMP) :

$$RMP = (\sum^{N} A^2_N / B)^{0.5} / X^2_{OM} \qquad 3.1j$$

where : A_N ⇉ is the area of positive or negative residual run
B ⇉ is the number of positive or negative residual runs

This function is a measure of systematic error (persistence in residual errors) and was developed by Görgens (1983) as an improvement on the CP.

- visual inspection : this includes, *inter alia*, inspection of variation patterns of phosphorous loadings during high and low flow conditions throughout different seasons of the simulation period, phosphorous behaviour during the falling and rising limbs of the flood hydrograph.

3.1.4.2 Selection of Objective Functions

As shown above, a number of potentially applicable objective functions have been reported in the literature. After inspection of the objective functions, and cognisant of the relatively limited water quality data sets available to this study, it was decided that using all the objective functions simultaneously might be too time consuming and costly. It was therefore decided to select six robust objective functions for use in this study. These are:

- error in monthly and annual mean,
- error in standard deviation,
- error in seasonal distribution,
- daily and monthly coefficients of determination,
- daily and monthly coefficients of efficiency, and
- visual inspection.

CHAPTER 4

WATER QUALITY MODELS SELECTED FOR THIS STUDY

It is self-evident that it is not prudent to purchase and use unknown models from software vendors without learning about the model creators and their reputations, or acquiring models that have not been extensively tested and used by others. Selection of appropriate models was therefore a vital part of the research process, in this study. As indicated in **Chapter 3**, the selected models are IMPAQ, PEM, HSPF and ACRU. This chapter contains a brief introduction of the selected water quality models, South African catchments in which the models were applied, model resolution, data adequacy in selected catchments, model capabilities, model structure, potential shortcomings of the models in terms of study objectives and parameters that are adjusted during model calibration.

4.1 IMPAQ (DWAF, 1995)

4.1.1 Introduction

The IMPAQ model, originally developed by Ninham Shand (Pty) Ltd, is an integrated system of modules which are capable of determining key conservative and non-conservative constituent monthly loads at selected points in the catchment in response to changing point and nonpoint source loads. It has five modules viz:

- ☆ Catchment Washoff Module (CWM)
- ☆ Point Source Module (PSM)
- ☆ River Transport Module (RTM)
- ☆ Reservoir Module (RM), and
- ☆ Urban Washoff Module (UWM).

The module of IMPAQ that is used in this study is the CWM. Although the RTM, PSM and RM modules had been used in a number of studies for DWAF since 1991, the full IMPAQ system was for the first time used in the Amatole catchments, to investigate long-term water quality of the system (DWAF, 1995). **Table 4.1** shows the basins in which the model was applied, province, objective for application, flow gauging stations and dominant land use types.

Table 4.1 Amatole Catchments in which IMPAQ was Applied

Basin	Province	Objective for Application	Gauge number(s)	Dominant land use (s)
Buffalo and Yellowwoods Rivers	Eastern Cape	Evaluate the performance of the model to simulate total dissolved salts, phosphorous and suspended solids	R2H001, R2H002 R2H005, R2H006 R2H007, R2H008 R2H009, R2H010 R2H011, R2H012 R2H015, R2H019 R2R001, R2R002 R2R003	forest and natural vegetation
Nahoon River	Eastern Cape		R3H003 & R3R001	natural vegetation
Qgunube River	Eastern Cape		R3H001	natural vegetation
Upper Kubusi River	Eastern Cape		S6H001, S6H002 S6H004, S6H005 S6R001, S6R002	natural vegetation and forest

The model was configured and tested on the Buffalo, Yellowwoods and Kubusi Rivers. The primary findings were:

- ***The model provided a reasonable simulation of TDS (Total Dissolved Salts), $P0_4$ (soluble phosphorous) and E.coli in the river system. The simulated and measured TDS loads showed similar, or nearly identical, time varying patterns in that the simulated peaks and troughs were superimposed.***

- ***The simulated and measured $P0_4$ loads showed similar patterns in that the simulated and measured peaks and troughs were roughly superimposed (DWAF, 1995). However, unlike the TDS simulation, there were peaks in the measured $P0_4$ data set which could not be reproduced by the model. The failure to reproduce the measured $P0_4$ peaks was attributed to analytical methods and sample collection, difficulties in quantifying the input loading of $P0_4$ to the river from point and nonpoint sources and the variation in the $P0_4$ concentration of the river as a result of localised mixing conditions, biological, chemical and physical processes which take place in a river.***

- ***It was thus concluded that TDS simulation using IMPAQ is comparatively straight forward but the simulation of non-conservative constituents (e.g. $P0_4$) are more difficult to mirror the changes in the measured data sets (DWAF, 1995).***

4.1.2 Resolution

This model operates on a monthly time step and requires the catchment to be discretized according to land use units.

4.1.3 Data Adequacy in Selected Catchments

The input data requirements for CWM are:

- ☆ monthly observed flow data or the Water Resources Yield Model (WRYM*) simulated flow series ($M.m^3$)
- ☆ monthly rainfall data (mm)(per sub-area or averaged over the whole catchment)
- ☆ USLE parameters
- ☆ monthly soluble phosphorous ($P0_4$) or total phosphorous (TP) concentration (mg/l) data recorded at the catchment outlet.

Available data in the selected catchments met the data requirements of the model (see **Chapter 5**).

* The WRYM was developed as part of the Vaal River System Analysis (DWAF, 1987)

4.1.4 Model Capabilities

- ☆ Simulation of monthly nonpoint source pollution of *E.coli*, total and dissolved phosphorous, sediment and suspended solids.
- ☆ Provide sub-catchment export loading time series as input to the river transport and reservoir models.
- ☆ Prediction of the impact of future land use development scenarios on sub-catchment export.
- ☆ Prediction of the impact of catchment management alternatives associated with future scenarios on sub-catchment export.

4.1.5 Model Structure

4.1.5.1 Introduction

As discussed above, the component of IMPAQ that is relevant for this study is CWM. The aim of developing CWM as part of IMPAQ, was to assist, at a coarse scale, in the evaluation of water quality impacts (particularly associated with the bulk water supply and projected growth in water demands) caused by current land use patterns, as well as future catchment development and/or management. The model was developed based on South African conditions.

The structure chart for the CWM model is shown in **Figure 4.1**

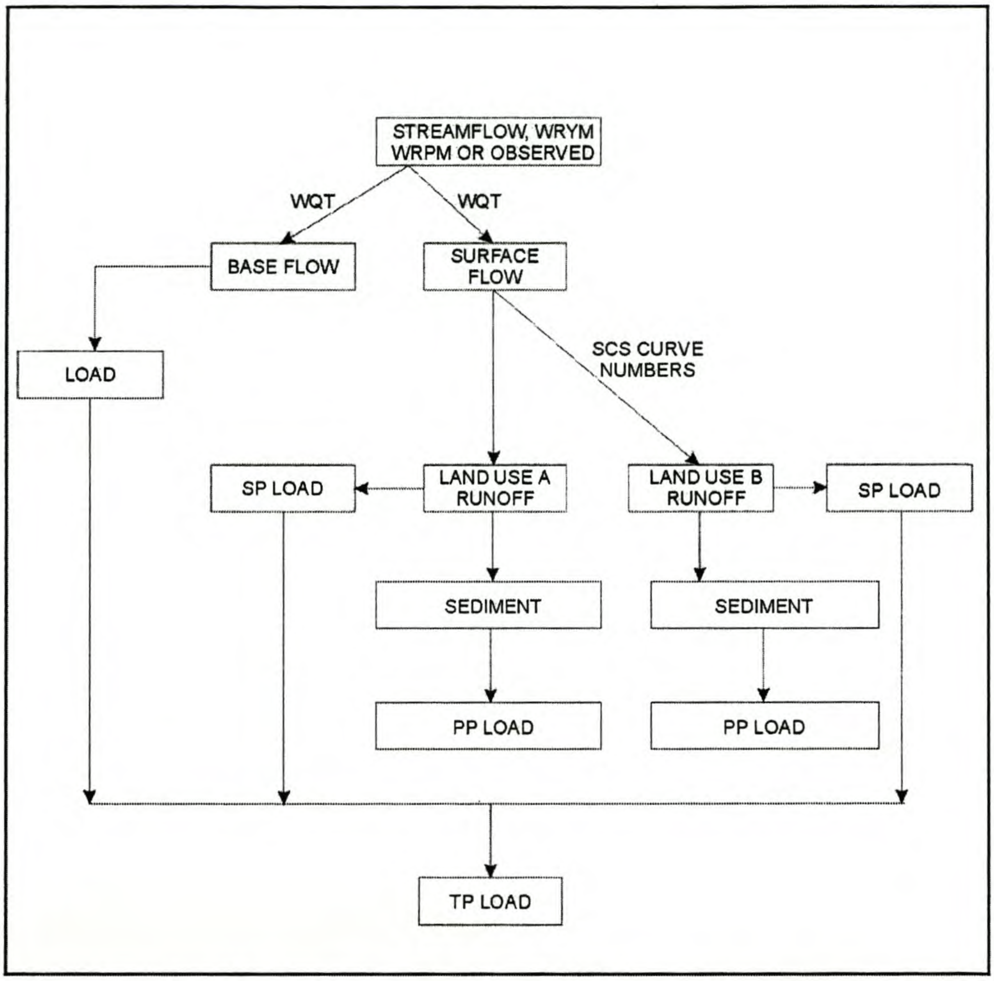


Figure 4.1 Structure Chart for the CWM Model

4.1.5.2 Hydrology

i. Disaggregation Between Surface Runoff and Baseflow

The Water Quality Model (WQT) is a hydro-salinity model developed to provide monthly hydro-salinity values for use in the Water Resources Planning Model (WRPM) (DWAF, 1997). WQT provides the methodology for disaggregating monthly streamflow time series into surface and baseflow that is used in IMPAQ. Application of this physically coherent approach requires the calibration of parameters based on observed salinity loads and streamflow (DWAF, 1995). The streamflow used for the calibration is based on the natural flow as used in WRYM and WRPM, before abstractions are subtracted or point sources added.

The dual nature of the calibration (flow and salinity) provides a relatively accurate disaggregation, because baseflow salinity concentrations are generally higher than surface runoff concentrations. Thus, the calibration is based on additional information, relative to a "flow-only" calibration.

ii. Disaggregation of the Surface Runoff Retween Land Uses

The land use based nonpoint source washoff modelling requires an estimate of the surface runoff associated with different land uses within each sub-catchment, because these may have significantly different contamination potential (e.g informal settlements generally produce higher phosphorous loads than grassland) (DWAF, 1995). Therefore, a simple generalised approach based on the simulation of surface runoff from daily rainfall using the widely applied SCS curve number equation (SCS,1986), adapted for continuous simulation (Haith,1985), was used. The rainfall-runoff relationship was based on the following equation:

$$\text{Monthly Surface Runoff} = \alpha\ (\text{Rainfall}-\beta)^{\gamma} \qquad 4.1a$$

where:

α ⇉ is a dimensionless slope factor,
β ⇉ is a detention factor(mm),
γ ⇉ is a power factor, which, for general use, can be approximated by a constant equal to 1.67.

The α and β factors were selected according to their perceived fit against the generated data for different curve numbers. The land use rainfall-runoff relationships (f_i[Rain]), together with the associated land use area (A_i) in a sub-catchment, are used to derive the proportion of the total surface runoff volume in month (m) generated from each land use in a sub-catchment , given the total rainfall. *These proportions are used to disaggregate the WQT generated total surface runoff between different land uses* (i). Surface runoff for each land use is generated from the equation:

$$\text{Surface runoff}_{im} = (\text{Total Surface Runoff}_m * f_i[\text{Rain}_m] * A_i) \;/ (\Sigma_i \{f_i[\text{Rain}_m] * A_i\}) \qquad 4.1b$$

iii. Sediment Yield

The USLE was used to estimate sediment yield. It was originally developed for long-term annual estimates of sediment yield from a field site, but for the Catchment Washoff Module monthly estimates of sediment yield from a sub-catchment are required. The approach proposed by Mills *et al.* (1985), based on work by Haith (1985), was adopted to disaggregate the long term sediment yield to provide annual and monthly estimates of sediment yield. This approach is based on an extension of the USLE in three different ways.

Firstly, the rainfall erosivity factor is related to monthly rainfall. Secondly, the portion of the long term average sediment yield which is delivered from a sub-catchment (delivery ratio) is related to the drainage characteristics (drainage density) of the sub-catchment. Thirdly the annual sediment yield from each land use within a sub-catchment is actually delivered to the streams and rivers according to the relative surface runoff carrying capacity in each of the months of the "sediment year".

Richardson (1983) developed a relationship between daily rainfall (mm) and erosivity ($N.h^{-1}.a^{-1}$), based on observed rainfall throughout the central and eastern United States. He found that the power relationship of 1.81, with summer and winter scale factors (a), provided an adequate fit to the data:

$$\text{Daily Rainfall Erosivity} = a\ (\text{Daily Rainfall})^{1.81} \qquad 4.1c$$

This relationship was used to determine the monthly erosivity-rainfall relationship. Thus, the annual sediment yield from land use (i) with area A_i (km^2) in each sub-catchment was given by:

$$\text{Annual Sediment Yield}_i = DR*100*A_i*K*LS*C*P_i\ \Sigma_{m=1..12}\{\text{Rainfall Erosivity}_m\} \qquad 4.1d$$

where:

DR ⇉ is the delivery ratio,
100 ⇉ is the conversion factor from ha to km^2,
LS ⇉is the slope-length,
K ⇉ is the soil erodibility parameter,
C ⇉ is the land cover,
P ⇉ is the management practice factor,
A_i ⇉ is the land use area,
R ⇉ is the rainfall erosivity parameter.

The sediment yield from land use (i) in month (m) is calculated by distributing the annual sediment yield from the land use, as follows:

$$\text{Sediment yield}_{im} = \text{Annual Sediment Yield}_i*(\text{Total Surface Runoff}_m)^{1.2} / \Sigma_{m=1..12}\{\text{Total Surface Runff}_m)\} \qquad 4.1e$$

The proportion of the available sediment delivered in any one month is related to the carrying capacity of the surface runoff during that month by the power function. Mills *et al.*(1985) proposed that this power function be 1.2 (DWAF, 1995).

The baseflow carries relatively small sediment load, but it should be estimated to take account of low flow adsorbed nutrient dynamics. This was estimated using a constant average baseflow sediment concentration (CX_{base}) for each sub-catchment multiplied by the estimate of the baseflow volume ($10^6 m^3$) in each month. This is added to the sum of the sediment yield from each land use in that month to provide the total monthly sediment export load (ton/month) from the sub-catchment.

$$\text{Sediment Export Load}_m = CX_{base*}\text{Baseflow}_m + \Sigma_i\{\text{Sediment Yield}_{im}) \qquad 4.1f$$

iv Phosphorous Yield

The well established loading function approach (Haith and Shoemaker, 1987; McElroy *et al.*, 1976; Mills *et al.*, 1985) was used to determine monthly nonpoint source phosphorous loads from the land uses in each sub-catchment. This may be done directly in the case of surface washoff.

For baseflow, it was assumed that the contribution of each land use to baseflow and baseflow sediment was proportional to the area of that land use relative to the total area (TA) of the sub-catchment. Both soluble and particulate phosphorous loads (kg/a) are made up of a baseflow and surface washoff component in a sub-catchment as shown in the equations below:

$$\text{Particulate Phosphorous}_m\ (PP_m) = (en)\ \Sigma_i\ \{(A_i{*}\gamma_i{*}CX_{base}{*}\text{Baseflow}) / TA + (\gamma_i{*}\text{Sediment Yield}_{im})\} \qquad 4.1g$$

$$\text{Soluble Phosphorous}_m\ (SP_m) = 10^3.\Sigma_i\{(A_i{*}\alpha{*}\text{Baseflow}_m)/TA + (\beta_i{*}\text{Surface Runoff}_{im}) \qquad 4.1h$$

where :

en ⇉ the enrichment ratio(this ratio represents the enrichment of particulate phosphorous concentrations due to the washoff of a higher portion of finer materials with relatively higher adsorption potential), which was estimated from a range of observed cases to have an average value of 2.0 (Haith and Shoemaker,1987),

α, β, γ ⇉ loading coefficients reflecting average concentrations of phosphorous in baseflow, surface runoff and sediment from land use i, respectively. These coefficients were derived and synthesised from information presented in Haith and Shoemaker (1987), McElroy *et al.* (1976) and Mills *et al.* (1985), together with South African data summarised in Pegram *et al.*(1997).

4.1.6 Potential Shortcomings of the Model in Terms of Study Objectives

- ☆ Most of the input parameters required by the model may have to be obtained from the literature.
- ☆ The model may not perform well in catchments dominated by groundwater.
- ☆ The USLE parameters cannot be varied on a monthly basis.
- ☆ The USLE was originally designed for small agricultural plots, it is not known how applicable it is to large catchments.

4.1.7 Parameters that are Adjusted During Calibration

The following model parameters are adjusted during calibration.

Table 4.2 Parameters Adjusted During the Calibration of CWM

Parameter Name	Description
Salpha$_i$ (α_i)	Loading coefficient reflecting average concentration of phosphorous in baseflow from land use i
Sbeta$_i$ (β_i)	Loading coefficient reflecting average concentration of phosphorous in surface flow from land use i
ppgamma$_i$ (γ_i)	Loading coefficient reflecting average concentration of phosphorous in sediment from land use i

These model parameters are adjusted for each land use type in the catchment.

4.2 **PEM** (Weddepohl and Meyer,1992).

4.2.1 Introduction

PEM is a simple deterministic model which was developed to simulate the accumulation and washoff of phosphorous loads from nonpoint source dominated catchments. The main objective developing PEM, was to predict phosphorous export from catchments experiencing changing phosphate loadings from point and nonpoint sources (Weddepohl & Meyer, 1992). As a test case the model was applied to the following catchments to predict phosphorous export :

Table 4.3 The South African Catchments in which PEM was Applied

Basin	Province	Objective for Application	Flow gauging station number	Dominant land use in the catchment
The Crocodile River basin	Gauteng	Evaluate the performance of the model to simulate catchment phosphorous export	A2H013	Agriculture
The Upper Berg River basin	Western Cape		G1H020	Agriculture
The Upper Buffalo River basin	Eastern Cape		R2H006	Forestry
The Umgeni River basin	Kwazulu-Natal		U2H012 U2H013	Forestry
The Upper Vaal River basin	Free State		C1H006 C1H007	Agriculture
The Lower Vaal River basin	Free State		C4H004	Agriculture
The Olifants River basin	Mpumalanga		B1H005	Agriculture

The primary findings of the model application were:

- ***Model applications showed a better simulation of phosphorous loads at low flows than high flows. This was expected as the phosphorous load was directly related to the quantity of flow and was highly variable at times of high flow when the system was not in equilibrium.***

- ***It was discovered that high flows might present a major problem concerning the water quality of the catchment outflow and subsequent inflow to a reservoir, not only in terms of the additional phosphorous load exported from the catchment, but also due to resuspension of bottom sediments and adsorbed phosphorous in the transporting waterway.***

- ***In some catchments, poor results were attributed to the inaccuracies of the stratification of the observed flows which were used for estimating phosphorous loads in the program Flux (Flux is explained in Chapter 6).***

4.2.2 Resolution

The model operates on a monthly time step. The USLE land use divisions are used to discretize the catchment into land use units. The model can simulate a maximum of 20 land use units per catchment.

4.2.3 Data Adequacy in Selected Catchments

The input data requirements are:

- ☆ observed or Pitman generated flow data ($M.m^3$),
- ☆ observed $P0_4$ or TP load (tons/month),
- ☆ USLE parameters.

Available data in the selected catchments met the data requirements of the model.

4.2.4 Model Capabilities

- ☆ Simulation of total and dissolved phosphorous accumulation and washoff from the catchment.
- ☆ Simulation of runoff using Pitman Model.

4.2.5 Model Structure

4.2.5.1 Introduction

PEM was developed to simulate phosphorous (P) accumulation and washoff from predominantly non-point source dominated catchments. This model was developed based on South African conditions as shown in **Table 4.3**. PEM accepts as input recorded or simulated monthly runoff volumes and appropriate catchment and process parameters. It was originally envisaged as a sub-routine of the Pitman monthly runoff simulation model which would act as a source of simulated monthly runoff. In its present form, however, as that of a stand-alone model, the monthly runoff input can be generated by any of a number of suitable available models (Weddepohl and Meyer,1992).

The monthly runoff volumes input to PEM are separated into surface runoff and groundwater flow components. P is assumed to accumulate on the catchment surfaces at a rate that depends on a number of replenishment factors as well as a user-defined growth index. The P load washed off the catchment surface depends, therefore, on the monthly runoff volume as well as on sediment loss. The structure for the model is shown in **Figure 4.2**

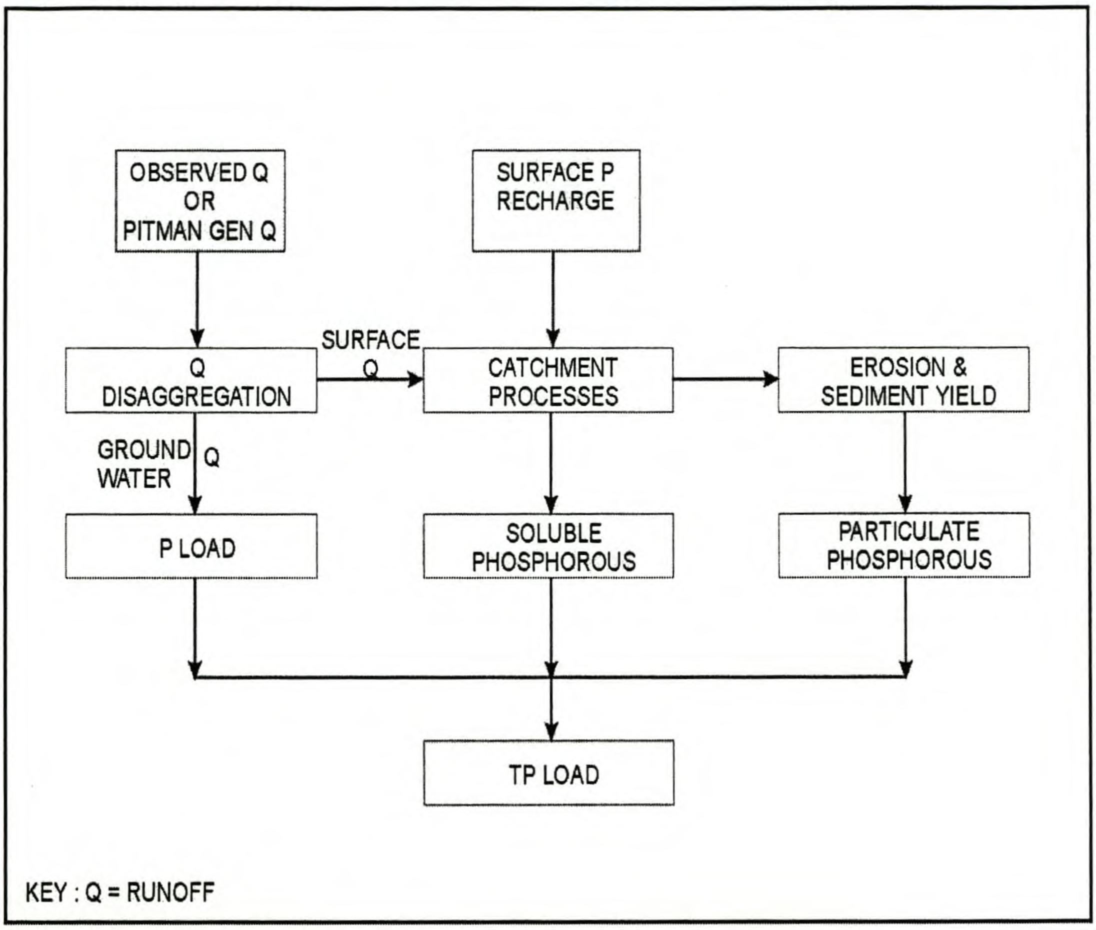


Figure 4.2 Structure Chart for the PEM Model

4.2.5.2 Estimation of the Surface and Groundwater Components of Runoff

If the Pitman model is used, then a file of monthly groundwater and surface flow components can be obtained from the Pitman model for input to PEM, but if another model is used to generate runoff volumes, or observed volumes are used, then the monthly runoff must be separated into the groundwater and surface flow components. A sub-routine to accomplish this task is included in PEM. The assumption is made that streamflow below GGMAX (i.e. the maximum possible groundwater flow, in million m^3/month, during the current month) is derived from groundwater flow (Herold,1980). Thus:

$$Qs_i = Q_i - GGMAX \text{ (for } Q_i > GGMAX) \qquad 4.2a$$

or

$$Qs_i = 0 \text{ (for } Q_i \leq GGMAX) \qquad 4.2b$$

Therefore : $QG_i = Q_i - Qs_i$

where : QS_i is the surface runoff during month i in million m^3 /month,
QG_i is the groundwater contribution during month i in million m^3/month,
Q_i is the total streamflow during month i in million m^3/month.

The value of GGMAX is adjusted according to the surface runoff during the preceding month and is assumed to decay with time (Herold,1980).

$$GGMAX_i = (DECAY*GGMAX_{i-1}) + (PG/100*QS_{i-1}) \qquad 4.2c$$

where : DECAY is the groundwater decay factor (0 < DECAY < 1) PG is the groundwater factor (%) and subscripts i and i-1 refer to the current and preceding months, respectively.

4.2.5.3 Sediment Yield

The catchment sediment yield is calculated using the USLE (Wischmeier and Smith, 1978). The yield is calculated from :

$$Sed = Erosion*Reg*Dratio \qquad 4.2b$$

where: *Erosion* ⇉ USLE gross catchment erosion (tons),
Reg ⇉ regional annual EI_{30} distribution fraction for the current month,
Dratio ⇉ sediment delivery ratio.

$$Erosion = (R*K*LS*C*P)_i.Uarea_i.100.0 \qquad 4.2c$$

R ⇉ USLE rainfall (EI_{30}) and runoff factor,
K ⇉ USLE soil erodibility factor,
LS ⇉ USLE topographic factor,
C ⇉ USLE cover and management factor,
P ⇉ USLE support practice factor,
Uarea ⇉ area of land-use section (i)(km^2),
i ⇉ one of 20 land-use or otherwise delineated areas,
100 ⇉ conversion factor for ha to km^2.

The factor *Erosion* in equation 4.2d above is the USLE estimate of long term average annual soil loss from a catchment. As PEM operates on a monthly time step, the average of annual soil loss must be disaggregated into monthly values. Two methods were combined in order to satisfy this requirement.

The first method utilises the monthly distribution of EI_{30} (Smithen,1981) values for four Southern African regions. **Figure 4.3** shows for each month and region, the percentage of the annual EI_{30} contributed during that specific month.

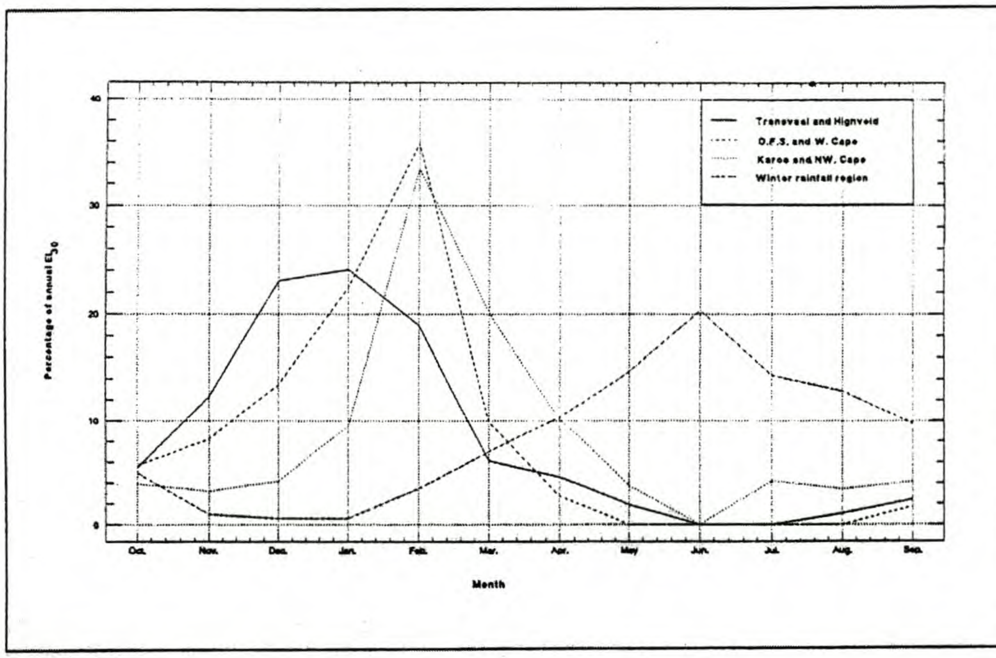


Figure 4.3 The Percentage of the Annual EI_{30} Contributed During that Specific Month

The factor, *Reg*, in equation 4.2h above is thus set to the percentage fraction for the relevant region for the current month in the calculations.

The second method ensures that the annual soil loss erosion from the area in question, is adjusted so that the ratio of soil loss to mean annual soil loss for each particular year is the same as the ratio of streamflow to mean annual runoff for that year. This method is only applicable if suitable observed or simulated runoff records exists.

4.2.5.4 Surface Phosphorous Balance

The rate of surface phosphorous accumulation can be expected to increase annually due to the expected increases in human activities and subsequent deterioration of the environment. Provision is made for the P accumulation rate to be adjusted annually by means of a growth index, POP.

This index is user-defined and can be set proportional to the growth rate of the population or industrialised area, or some other index of the catchment, or neighbouring development that is likely to affect P accumulation on catchment surfaces (Herold,1980). The rate at which surface P accumulates is assumed to be proportional to the growth index, POP.

During year (i) the surface P recharge rate is given by :

$$R_i = AREA*R_0*(POP_i/POP_0) \qquad 4.2d$$

where: AREA is the catchment area (km^2),
R_0 is the P recharge rate at the start of the simulation in tons/km^2.month.
POP_i is the growth index for the year i,
POP_o is the growth index for the starting year.

Soluble phosphorous is assumed to be depleted at a rate proportional to the surface runoff intensity.

The equation used is :

$$SL_i = L_{i-1} \{ 1 - e^{(-SPAR*QSi*\Delta t)} \} \qquad 4.2e$$

where: SL_i is the soluble P load washoff from catchment surface during time Δt [tons/km^2].
L_{i-1} is the P load on the catchment surface at the start of time step Δt [tons/km^2]
SPAR is the soluble P washoff parameter (m^{-3} $*10^{-6}$), and
Δt is the time step (one month in this case),
QS_i is the surface runoff during month i in million m^3 /month.

Particulate phosphorous is assumed to be depleted at a rate proportional to the sediment yield of the catchment:

$$PL_i = L_{i-1} \{1 - e^{(-PPAR*Sed*\Delta t)}\} \qquad 4.2f$$

where: PL_i is the particulate P load washed off the catchment surface, during time Δt (tons/km^2), PPAR is the particulate washoff parameter in ($m^{-3}*10^{-6}$), Sed is the catchment sediment yield for the current month (tons/month).

4.2.5.5 Streamflow P Concentration

The P concentration of the streamflow at the catchment outlet (C_p) is computed as the total P loss divided by the total streamflow:

$$C_p = (SL_i + PL_i) / (QS_i + QGi) \qquad 4.2g$$

4.2.6 Potential Shortcomings of the Model in Terms of Objectives

- ☆ The model is restricted to agricultural/rural catchments dominated by diffuse pollution of phosphorous.
- ☆ Monthly USLE parameters cannot be varied throughout the year.
- ☆ The temporal scale of the model is fixed.
- ☆ The model can simulate a maximum of 20 land use units per catchment.
- ☆ The use of USLE in large catchments, because USLE was originally designed for small agricultural plots.
- ☆ Detailed knowledge of the catchment, or more data, is required to estimate the initial phosphorous storage parameter as well as the recharge rate parameter in the catchment.

- ☆ The model assumes that surface runoff is the same for all land use types.
- ☆ It assumes that the soluble phosphorous washoff parameter is the same for all land use types.

4.2.7 Parameters that are Adjusted During Calibration

Table 4.4 summarises the model parameters which are adjusted during calibration. These parameters are adjusted for soluble or particulate phosphorous washoff in the whole catchment and not for each land use type in the catchment.

Table 4.4 Parameters Adjusted During the Calibration of PEM

Parameter Name	Description
Spar	soluble phosphorous washoff parameter
Ppar	particulate phosphorous washoff parameter

4.3 HSPF (Beasly, 1981)

4.3.1 Introduction

HSPF is used to simulate for extended periods of time the hydrological and associated water quality processes on pervious and impervious land surfaces and in streams and well-mixed impoundments. Unlike PEM, IMPAQ and ACRU, HSPF was not developed based on South African conditions, but on those in the United States of America.

HSPF uses continuous rainfall and other meteorological records to compute streamflow hydrographs and pollutographs. HSPF simulates interception, soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, groundwater recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, faecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton. The program can simulate one or many pervious or impervious unit areas discharging to one or many river reaches or to reservoirs. Frequency-duration analysis can be done for any time series. Any time step from 1 minute to 1 day that divides equally into 1 day can be used. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, flow diversions, etc.

The programs, available separately, support data preprocessing and postprocessing for statistical and graphical analysis of data are saved to a so-called Watershed Data Management (WDM) file (Bicknell, 1997).

The model was used in the following areas in the Republic of South Africa : Phalaborwa area (Northern Province) by Trevor Coleman of Sutherland and Associates, Newcastle and Vryheid areas (Northern Natal) by Mike Howard, Pinetown area by Rob Johanson and Dean Simpson. It has been configured for Mgeni and Mkomaas River catchments by the Computing Center for Water Research (CCWR) and is currently being configured for Mhlatuze and the Wonderfontein catchments (De Vos, personal communication,1999). ***HSPF was also applied in the Sabie River catchment without successs, due to the scarcity of the data (i.e. solar radiation, dew-point temperature and number of sunshine hours) (Jewitt and Görgens, 2000).***

4.3.2 Resolution

The spatial discretization required by the model is based on a relatively homogeneous land use type. Spatial variation of rainfall and physiographic catchment parameters is provided for by dividing the catchment into areas of similar hydrological response. The model can operate at intervals between a minute and 24 hours (Bicknell, 1997).

4.3.3 Data Adequacy in Selected Catchments

Model data requirements are:

- ☆ meteorological data (i.e rainfall, evaporation and temperature data)
- ☆ soil data
- ☆ solar radiation data
- ☆ wind data,
- ☆ land use data,
- ☆ channel geometry.

4.3.4 Model Capabilities

- ☆ Simulation of water budget for pervious and impervious land segments, accumulation, washoff and transport of sediments, water quality constituents (e.g. nitrogen, total and dissolved phosphorous, pesticides and tracer elements), accumulation and melting of snow and ice, soil, air and water temperatures, heat exchange and behaviour of constituents involved in biochemical transformations.

- ☆ Estimation of the moisture and fractions of solutes being transported in the soil layers.

- ☆ Routing of channel flow according to different routing functions.

4.3.5 Model Structure

4.3.5.1 Introduction

As discussed above, HSPF comprises computer codes with 550 sub-routines. The key water quantity and quality modules in HSPF are the Pervious Land Segment Module (PERLND) and the Impervious Land Segment Module (IMPLND). The PERLND simulates hydrological and water quality processes which occur in a pervious land segment and the IMPLND simulates the hydrological and water quality processes which occur in an impervious land segment. This study is based on agricultural catchments which are dominated by pervious areas. Therefore, the relevant module is PERLND. This module comprises 12 sections which simulate different hydrological and water quality processes. The primary sub-modules in PERLND are SNOW (for simulating snow accumulation and melt), PWATER (for simulating water budget), SEDMNT (for simulating sediment produced by land surface erosion), PQUAL and the agri-chemical modules (for simulating water quality constituents by various methods). Other sections perform the auxiliary functions of correcting air temperature (i.e. section ATEMP) for use in snowmelt and soil temperature calculations, producing soil temperatures (i.e. section PSTEMP) for estimating the outflow temperatures and influencing reaction rates in the agri-chemical sections, and determining outflow temperatures which influence the solubility of oxygen and carbon dioxide. The structure chart for the PERLND module is shown in **Figure 4.4.**

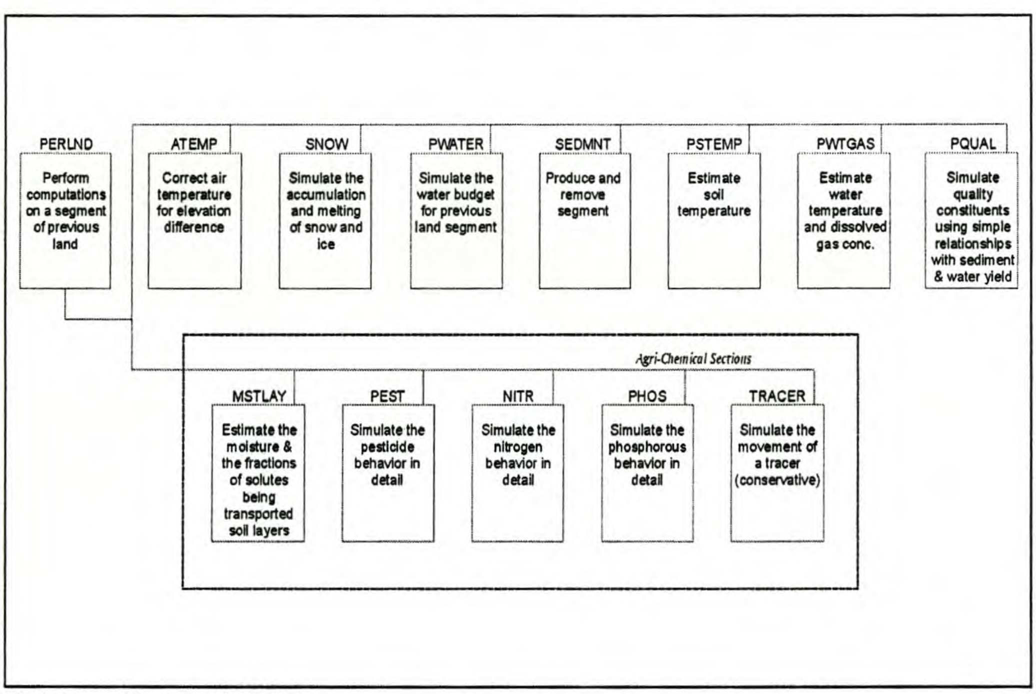


Figure 4.4 Structure Chart for the PERLND Module

4.3.5.2 Hydrology

The sub-module for modelling catchment hydrology in PERLND is PWATER. This module calculates the components of the water budget and primarily predicts runoff from pervious areas. The number of time series required by PWATER depends on whether snow accumulation and melt is being considered. When such conditions are not considered, only potential evapotranspiration and rainfall are required. However, when snow conditions are considered, air temperature, rainfall, snow cover, water yield and ice content of the snow pack are also required. Also the evaporation data are adjusted when snow is considered.
The snow conditions are not considered for this study. The hydrological processes simulated in PWATER are rainfall interception by interception storages (CEPS) (e.g. vegetation), inflow to the surface detention storage (SURS), outflow from the surface detention storage (SURO), infiltration (INFILT) through the surface, lateral external inflows to interflow and active groundwater storages (i.e. IFWS and AGWS, respectively), outflow from the interflow (IFWO) and active groundwater (AGWO) storages.

i. Simulation of Overland or Surface Flow(sub-routine PROUTE)

Overland flow is treated as a turbulent process. It is simulated using the Manning equation and an empirical expression which relates outflow depth to detention storage. The rate of overland flow discharge is determined by the equations:

For SURSM < SURSE

$$SURO = \Delta 60 * SRC * (SURSM * (1.0 + 0.6(SURSM/SURSE)^3)^{1.67} \qquad 4.3a$$

For SURSM $\geq$ SURSE

$$SURO = \Delta 60 * SRC * (SURSM * 1.6)^{1.67} \qquad 4.3b$$

where: SURO $\rightrightarrows$ is the surface outflow (mm/interval),
$\Delta 60$ $\rightrightarrows$ number of hours per interval (hr/interval),
SRC $\rightrightarrows$ is the routing variable defined by:

$$SRC = 1020.0 * (SQRT(SLSUR)/(NSUR * LSUR) \qquad 4.3c$$

Where: SLSUR $\rightrightarrows$ is the slope of the overland flow plane (m/m),
NSUR $\rightrightarrows$ is the Manning's n for the overland flow plane,
LSUR $\rightrightarrows$ is the length of the overland flow plane (m),
SURSM $\rightrightarrows$ is the mean surface detention storage over the time interval (mm),
SURSE $\rightrightarrows$ is the equilibrium surface detention storage (mm) for current supply rate.

Equilibrium surface detention storage is calculated by:

$$SURSE = DEC*SSUPR^{0.6} \qquad 4.3d$$

Where: DEC ⇉ is the routing variable defined by:
$DEC = 0.00982*(NSUR*LSUR/SQRT(SLSUR))^{0.6}$,
SSUPR ⇉ is the rate of moisture supply to the overland flow surface,
The routing variables SRC and DEC are calculated daily.

ii. Simulation of Interflow (sub-routine INTFLW)

Interflow can have an important influence on storm hydrographs particularly when vertical percolation is retarded by a shallow, less permeable soil layer. Additions to the interflow component are retained in storage or routed as outflow from the land segment. The calculation of interflow outflow (i.e. IFWO) assumes a linear relationship to storage. It is calculated by:

$$IFWO = (IFWK1*INFLO)+(IFWK2*IFWS) \qquad 4.3e$$

where : IFWO ⇉ is the inteflow outflow (mm/inetrval),
INFLO ⇉ is the inflow into interflow storage (mm/interval),
IFWS ⇉ is the interflow storage at the start of the interval,
IFWK1 and IFWK2 are variables determined by:
IFWK1 = 1.0 - (IFWK2/KIFW),
$IFWK2 = 1.0 - e^{-KIFW}$,
$KIFW = -ALOG(IRC)*\Delta 60/24.0$, 4.3f

where: IRC ⇉ is the interflow recession parameter (per day),
Δ60 ⇉ number of hours per interval,
24.0 ⇉ number of hours per day,
ALOG ⇉ natural logarithm function.

IRC is the value of the present rate of interflow outflow to the value 24 hours earlier, if there was no inflow.

iii. Simulation of Upper Zone Behaviour(sub-routine UZONE)

The sub-routine UZONE is used to calculate water percolating from the upper zone storage. Percolation only occurs when UZRAT minus LZRAT is greater than 0.01. When this happens, percolation from the upper zone storage is calculated by the empirical expression :

$$PERC = 0.1*INFILT*INFFAC*UZSN*(UZRAT-LZRAT)^3 \qquad 4.3g$$

where: PERC ⇉ percolation from the upper zone (mm/interval),
INFILT ⇉ infiltration parameter (mm/interval),
INFFAC ⇉ a factor to account for frozen ground, if any,
UZSN ⇉ a parameter for upper zone nominal storage (mm),
UZRAT ⇉ is the ratio of upper zone storage to UZSN,
LZRAT ⇉ is the ratio of lower zone storage to lower zone nominal storage (LZSN).

iv. Simulation of Lower Zone Behaviour (sub-routine LZONE)

This sub-routine determines the quantity of infiltrated and percolated water which enters the lower zone. The fraction of the direct infiltration plus percolation that enters the lower zone is based on LZRAT. The inflowing fraction is determined by:

$$LZFRAC = 1.0 - LZRAT*(1.0/(1.0+INDX))^{INDX} \qquad 4.3h$$

when LZRAT is greater than 1.0, and by

$$LZFRAC = (1.0/(1.0+INDX))^{INDX}$$

when LZRAT is greater than 1.0 INDX is defined by:

$$INDX = 1.5*ABS(LZRAT - 1.0) + 1.0 \qquad 4.3i$$

where: LZFRAC ⇉ is fraction of infiltration plus percolation entering LZS,
LZRAT = LZS/LZSN,
ABS ⇉ is the function for determining the absolute value.

The fraction of the moisture supply remaining after the surface, upper zone and lower zone components are subtracted is added to the groundwater storages.

v. Simulation of Groundwater Fluxes (sub-routine GWATER)

The groundwater sub-routine determine the amount of the inflow to groundwater that is lost to deep or inactive groundwater and to determine the amount of active groundwater outflow. The outflow from active groundwater is based on the assumption that the discharge of an aquifer is proportional to the product of the cross-sectional area and the energy gradient of the flow. Further, a representative cross-sectional area of flow is assumed to be related to the groundwater storage level at the start of the interval. The groundwater outflow is calculated by:

$$AGWO = KGW*(1.0 + KVARY*GWVS)*AGWS \qquad 4.3j$$

where : AGW0 ⇉ active groundwater outflow (mm/interval),
KGW ⇉ is the groundwater outflow recession parameter (/interval),
KVARY ⇉ is the parameter which can make the active groundwater storage to outflow relation nonlinear (/mm),
GWVS ⇉ is the index to groundwater slope (mm),
AGWS ⇉ is the active groundwater storage at the start of the interval (mm).

$$KGW = 1.0 - (AGWRC)^{(\Delta 60/24.0)} \qquad 4.3k$$

AGWRC is the daily recession constant of groundwater flow if KVARY or GWVS is zero.

4.3.5.3 Simulation of the Production and Removal of Sediments (section SEDMNT in PERLND)

Sediment from the pervious land surface is one of the pollutants of waters from urban, agricultural and forested lands. Removal of sediment by water is simulated as washoff of detached sediment in storage (WSSD) and scour of matrix soil (SCRSD). The washoff process involves two parts, viz the detachment/attachment of sediment from/to the soil matrix and the transport of this sediment. Detachment (DET) occurs by rainfall and attachment occurs only on days without rainfall. Module section SEDMNT has two options for simulating detached sediment and scour of soil. The first option uses sub-routine SOSED1 and the second option uses sub-routine SOSED2. These options will be discussed in detail below.

i. Detachment of the Soil Matrix by Rainfall (sub-routine DETACH)

The purpose of this sub-routine is to simulate the splash detachment of the soil matrix caused by the impact of rain. Kinetic energy from rain falling on the soil detaches particles which are then available to be transported by overland flow.

The equation that simulates this process is :

$$DET = \Delta 60 * (1.0 - CR) * SMPF * KRER * (RAIN/\Delta 60)^{JRER} \quad 4.31$$

where: DET ⇉ sediment detached from the soil matrix by rainfall (tons/km^2.interval)
$\Delta 60$ ⇉ is the number of hours per interval,
CR ⇉ is a fraction of the land covered by snow and other cover,
SMPF ⇉ is a supporting management practice factor,
KRER ⇉ is a detachment coefficient dependent on soil properties,
JRER ⇉ is a detachment exponent dependent on soil properties,
RAIN ⇉ rainfall (mm/interval).
CR is a parameter which for pervious areas will typically be the fraction of the area covered by vegetation and mulch. The parameter CR can be input on a monthly basis.

ii. Washoff of Detached Sediment by Overland Flow (sub-routine SOSED1)

When simulating the washoff of detached sediment, the transport capacity of the overland flow is estimated and compared to the amount of detached sediment available. The transport capacity of the overland flow is calculated by the equation:

$$STCAP = \Delta 60 * KSER * ((SURS+SURO)/\Delta 60)^{JSER} \quad 4.3m$$

where: STCAP ⇉ capacity of the overland flow for removing detached sediment ($tons/km^{2}$. interval),
$\Delta 60$ ⇉ is the number of hours per interval,
KSER ⇉ coefficient for transport of detached sediment,
SURS ⇉ surface water storage (mm),
SURO ⇉ surface outflow of water (mm/interval),
JSER ⇉ exponent for transport of detached sediment.

When STCAP is greater than the amount of detached sediment in storage, washoff is calculated by:

$$WSSD = DETS*SURO/(SURS+SURO) \qquad 4.3n$$

If the storage is sufficient to fulfil the transport capacity, then the following relationship is used :

$$WSSD = STCAP*SURO/(SURS+SURO) \qquad 4.3o$$

where: WSSD ⇉ washoff of detached sediment ($tons/km^2$.interval),
DETS ⇉ detached sediment storage ($tons/km^2$).

Transport and detachment of soil particles from the soil matrix is estimated with the following equation:

$$SCRSD = SURO/(SURS + SURO)*\Delta 60*KGER*((SURS+SURO)/\Delta 60)^{JGER} \qquad 4.3p$$

where: SCRSD ⇉ scour of matrix soil ($tons/km^2$.interval),
KGER ⇉ coefficient for scour of the matrix soil,
JGER ⇉ exponent for scour of the matrix soil.

The sum of SCRSD and WSSD represents the total sediment outflow from the land segment.

iii. Washoff of Detached Sediment by Overland Flow (sub-routine SOSED2)

This method differs from SOSED1 in that it uses the homogeneous term SURO/$\Delta 60$, while SOSED1 uses a dimensionally nonhomogeneous term (SURS + SURO) /$\Delta 60$ in the above equations. The capacity of the overland flow to transport detached sediment is determined by:

$$STCAP = \Delta 60*KSER*(SURO/\Delta 60)^{JSER} \qquad 4.3q$$

When STCAP is more than the amount of the detached sediment in storage, the flow washes off all of the detached sediment storage (DETS). However, when STCAP is less than the amount of the detached sediment in storage, the situation is transport limiting, so WSSD is equal to STCAP.

Direct detachment and transport of the soil matrix by scouring is simulated with the following equation:

$$SCRSD = \Delta60*KGER*(SURO/\Delta60)^{JGER}. \qquad 4.3r$$

iv. Simulating Re-attachment of Detached Sediment (DETS) on the Surface (sub-Routine ATTACH)

Attachment to the soil matrix is simulated by reducing DETS. DETS is reduced by multiplying it by (1.0 - AFFIX), where AFFIX is a parameter.

4.3.5.4 Simulation of Water Quality Constituents using Simple Relationships with Sediment and Water Yield (section PQUAL of module PERLND)

The PQUAL module section simulates water quality constituents or pollutants in the outflows from a pervious land segment using simple relationships with water and /or sediment yield. *Any constituent can be simulated by this module section.*

The user supplies the name, units and parameter values appropriate to each of the constituents that is needed in the simulation. However, more detailed methods are available for simulating sediment, phosphorous, nitrogen, dissolved carbon dioxide, dissolved oxygen, heat, soluble tracers, and pesticide removal from pervious land segment are available, in other module sections.

i. Removal of Phosphorous by Association with Sediment (sub-routine QUALSD)

The QUALSD routine simulates the removal of a quality constituent from a pervious land surface by association with the sediment removal determined in module section SEDMNT. This approach assumes that the particular quality constituent removed from the land surface is in proportion to the sediment removal. The relation is specified with the user-input "potency factors". Potency factors indicate the constituent strength relative to the sediment removed from the surface.

Removal of the sediment associated constituent by detached sediment washoff is simulated by:

$$WASHQS = WSSD*POTFW \qquad 4.3s$$

where: WASHQS ⇉ flux of quality constituent associated with detached sediment washoff (quantity/km^2 per interval),
WSSD ⇉ washoff of detached sediment (tons/km^2.interval),
POTW ⇉ washoff potency factor (quantity/ton).

Removal of the constituent by scouring of the soil matrix is simulated by:

SCRQS = SCRSD*POTFS 4.3t

where: SCRQS ⇉ flux of quality constituent associated with scouring of the matrix soil (quantity/km^2 per interval),
SCRSD ⇉ scour of matrix soil (tons/km^2.interval),
POTFS ⇉ scour potency factor (quantity/ton),
WASHQS and SCRQS are combined to give the total sediment associated flux of the constituent from the land segment, SOQS.

ii. Accumulation and Removal of Phosphorous by a Constant Unit Rate and by Overland Flow (sub-routine QUALOF)

The QUALOF simulates the accumulation of a quality constituent on the pervious land surface and its removal by a constant unit rate and by overland flow. When there is surface outflow and some quality constituent is in storage, washoff is simulated using the commonly used relationship :

$$SOQO = SQO*(1.0 - e^{-SURO*WSFAC}) \quad 4.3w$$

where: SOQO ⇉ washoff of the quality constituent from the land surface (quantity/km^2 . interval),

SQO ⇉ storage of available quality constituent on the surface (quantity/km^2),
SURO ⇉ surface outflow of water (mm/interval),
WSFAC ⇉ susceptibility of the quality constituent to washoff (/mm).

The storage is updated once a day to account for accumulation and removal which occurs independent of runoff by the equation:

SQO = ACQOP + SQOS*(1.0 - REMQOP) 4.3x

where: ACQOP ⇉ accumulation rate of the constituent (quantity/km^2.day),
SQOS = SQO at the start of the interval,
REMQOP ⇉ unit removal rate of the stored constituent (per day),
REMQOP = ACQOP/SQOLIM,
WSFAC = 2.30/WSQOP,

where: SQOLIM is the asymptotic limit for SQO as time approaches infinity (quantity/km^2), if no washoff occurs,
WSQOP is the rate of surface runoff that results in 90% washoff in one hour (mm/hour).

iii. Simulation of Phosphorous by Association with Interflow Outflow (sub-routine QUALIF)

The user specifies a concentration for each constituent which is linked to interflow outflow. Optionally, one can specify 12 monthly values, to account for seasonal variation and the system will interpolate a new value each day.

iv. Simulation of Phosphorous by Association with Active Groundwater Outflow (sub-routine QUALGW)

The user specifies a concentration for each constituent which is linked to active groundwater outflow. Optionally, one can specify 12 monthly values, to account for seasonal variation and the system will interpolate a new value each day.

4.3.5.5 Simulation of Phosphorous Behaviour in Detail (section PHOS in module PERLND)

The module section PHOS simulates transport, plant uptake, adsorption/desorption, immobilization and mineralization of the various forms of phosphorous. Atmospheric deposition input can be specified in two possible ways, depending on the form of data available. If the deposition is in the form of flux (mass per unit area per time), then it is considered "dry deposition". If it is in the form of a concentration in rainfall, then it is considered "wet deposition", and the program automatically combines it with the input rainfall time series to compute the resulting flux.

If atmospheric deposition data are input to the model, the soil storage is updated for each of the two species of phosphorous for both affected soil layers using the formula:

$$P = P + ADFX + PREC*ADCN \qquad 4.3y$$

where: P ⇉ storage of phosphorous species in the soil layer (mass/area),
ADFX ⇉ dry or total atmospheric deposition flux (mass/area per interval),
PREC ⇉ precipitation depth,
ADCN ⇉ concentration for wet atmospheric deposition (mass/volume).

i. Simulation of Adsorption and Desorption of Phosphorous using First-order Kinetics (subroutine FIRORD)

Phosphate is adsorbed and desorbed by either first-order kinetics or by the Freundlich method. The calculation of desorption and adsorption reaction fluxes by first-order kinetics for soil layer temperature less than 35^{0}C takes the form:

$$DES = CMAD*KDS*THKDS^{(TMP-35.0)-} \qquad 4.3aa$$
$$ADS = CMSU*KAD*THKAD^{(TMP-35.0)} \qquad 4.3bb$$

where: DES ⇉ current desorption flux of chemical (mass/area per interval),
CMAD ⇉ storage of adsorbed chemical (mass/area),
KDS ⇉ first-order desorption rate parameter (per interval),
THKDS ⇉ temperature correction parameter for desorption,
TMP ⇉ soil layer temperature (^{0}C),
ADS ⇉ current adsorption flux of chemical (mass/area per interval),
CMSU ⇉ storage of chemical in solution (mass/area),
KAD ⇉ first-order adsorption rate parameter (per interval),
THKAD ⇉ temperature correction parameter for adsorption,
THKDS and THKAD are typically about 1.06. All of the variables except the temperature may vary with the layer of the soil being simulated.

ii. Simulation of Adsorption and Desorption of Phosphorous using the Single Value Freundlich Method (subroutine SV)

The Freundlich isotherm methods, unlike first-order kinetics, assume instantaneous equilibrium. That is, no matter how much chemical is added to a particular phase, equilibrium is assumed to be established between the solution and adsorbed phase of the chemical. These methods also assume that for any given amount of chemical in the soil, the equilibrium distribution of the chemical between the soil solution and on the soil particle can be found from an isotherm. The Freundlich equation for determining the partitioning of the chemical into the adsorbed and solution phases is:

X = KF1*C** (1/N1) + XFIX 4.3cc

where: X ⇉ a chemical adsorbed on soil (ppm of soil),
KF1 ⇉ a single value Freundlich K coefficient,
C ⇉ an equilibrium chemical concentration in solution (ppm of solution),
N1 ⇉ a single value Freundlich exponent,
XFIX ⇉ a chemical which is permanently fixed (ppm of soil).

iii. Simulation of Mineralization, Immobilization, and Plant Uptake of Phosphorous (subroutine PHORXN)

Phosphorous uptake is simulated in each of the four layers of the soil (i.e. surface, upper, lower, and active groundwater). Immobilization, mineralization and plant uptake are simulated using the temperature dependent first-order kinetics discussed previously.

4.3.6 Potential Shortcomings of the Model in Terms of the Study Objectives

☆ Model data requirements are extensive (e.g. daily time series of sediment data is required for sediment calibration, observed daily phosphorous data is required for the calibration of phosphorous, solar radiation, wind run and dew-point temperature are required at the time step similar to that of the simulation)(Bicknell, 1996).

If daily rainfall is provided as the input to the model, the rainfall is distributed into equal quantities of hourly rainfall for 24 hours. This might not be true because in practice, it is rare to record the same quantity of rainfall every hour. The user must supply a large number of parameters for the various processes, although default values are provided for many of these.

☆ HSPF running costs are significant (Bicknell, 1996). A comprehensive knowledge of the HSPF's hydrological and water quality processes is required before attempting any calibration of the model parameters, because most of the parameters are interlinked. A large budget is therefore required for training before the model can be used.

☆ The tool to help calibrating rainfall-runoff parameters of HSPF (i.e. "expert system") is available, but it only operates in Imperial units. This makes it difficult for the modeller in South Africa whose data is in Metric units. There is no tool, like an "expert system", to aid in the calibration of water quality parameters.

☆ HSPF 's required calibration makes it difficult to evaluate changing land use patterns, because the model is calibrated for the existing land use and users would be uncertain how to modify parameters for other scenarios (Jewitt and Görgens, 2000).

☆ The fact that HSPF has not been extensively used in South Africa to model land use patterns means that little local knowledge about, and few recommendations regarding land use parameter values are available.

4.3.7 Parameters Adjusted During Model Calibration

Table 4.5 Parameters Adjusted when Calibrating the Hydrological Component of the Model (i.e. PWATER)

Parameter Name	Description
UZSN	Parameter for upper zone nominal storage
INFILT	Infiltration rate parameter
LZETP	Lower zone evapotranspiration parameter
LZSN	Lower zone nominal storage
INTFLW	Interflow parameter which influence storm hydrographs
IRC	Interflow recession constant parameter
AGWRC	Daily recession constant of groundwater flow

Table 4.6 Parameters Adjusted when Calibrating the Water Quality Component of the Model

Parameter Name	Description
ACQOP	Phosphorous accumulation rate on the land surface
SQOLIM	Maximum phosphorous storage on the land surface
WSQOP	Phosphorous washoff rate parameter
POTFW	Washoff potency factor
POTFS	Scour potency factor

The parameters in **Tables 4.5 & 4.6** are described in detail in **Chapter 7**.

4.4 ACRU (Smithers and Caldecott, 1994)

4.4.1 Introduction

ACRU is an agrohydrological modelling system that can be characterised as follows:

☆ *Physical conceptual (*i.e. it is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes are represented explicitly).

☆ *Multi-purpose (*i.e. it integrates the various water budgeting and runoff producing components of the terrestrial hydrological system with risk analysis, and can be applied in design hydrology, crop yield modelling, reservoir yield simulation and irrigation demand/supply, planning optimum water resource utilisation etc.

☆ *Multi-level* (e.g. hydrograph routing, reservoir storage, maximum as well as total evaporation, values of soil water retention constants, interception losses and reference potential evaporation, all may be estimated by various methods according to the level of input data at hand or the relative accuracy of simulation required).

ACRU operates on daily time steps and performs *multi-layer soil water budgeting* (Smithers and Caldecott, 1994). The model originated in a distributed catchment evapotranspiration based study carried out in the Natal Drakensberg in the early 1970s (Smithers and Caldecott, 1994). It was, therefore, developed based on South African conditions. ACRU is not intended to be a parameter fitting or optimising model. The model input variables are usually estimated from physical characteristics of the catchment. The model comprises the following modules:

☆ hydrology
☆ reservoir yield analysis

- ☆ sediment yield
- ☆ irrigation demand and supply
- ☆ land use impact
- ☆ climate change
- ☆ crop and timber yields
- ☆ phosphate yield.

The modules of ACRU which were used in this study are hydrology, sediment yield, irrigation, land use impacts and phosphate yield. The phosphate component of the model has only recently been developed and is applied in this study as part of its exploratory development process. The standard ACRU model has been applied to many South African catchments, but the phosphate component of the model has been applied in only a few South African catchments. **Table 4.7** shows the basin in which the phosphate component of the model was applied, province, objective for application, flow gauging stations and dominant land use types.

Table 4.7 South African Catchments in which the Phosphate Component of ACRU has been Applied

Basin	Province	Objective for Application	Gauge number(s)	Dominant land use (s)
Mgeni River	Kwazulu-Natal	develop water quantity and quality management tool for Mgeni catchment		Forestry, dryland and irrigated agriculture, urban, peri-urban and rural , natural vegetation

The standard ACRU model has been used extensively and successfully in South Africa to simulate crop yield, primary production, irrigation water demands and supply, assessments of impacts of land use changes on water resources, assessments of potential impacts of global climate change on crop production and hydrological responses, and assessments of water resources (Smithers and Caldecott, 1994). The primary findings of the ACRU phosphorous yield model application were:

- ☆ ***Mean annual phosphorous yield values from Mgeni catchments range from 0.5 to 850 kg/km^2.***

- ☆ ***The distribution of high and low annual phosphorous yield values over the Mgeni catchments were dissimilar to the distribution of long-term annual sediment yields.***

- ☆ ***Significant nonpoint source phosphorous loads emanated from the Albert Falls Management Catchment, with its many feedlots, whereas the sub-catchment had a relatively low sediment yield.***

- ☆ ***High phosphorous loads were due to the large amounts of source phosphorous (Kienzle et al., 1997)***

4.4.2 Resolution

The model operates on daily time steps. ACRU is capable of operating as a point, lumped and/or distributed catchment model. In distributed mode, the individual sub-catchments should ideally not exceed 50 km^2, except where a high level of homogeneity exists or where the rainfall gauging network is very sparse. The sub-catchments have to be relatively homogeneous in terms of climate, soils and land cover.

4.4.3 Data Adequacy in Selected Catchments

The ACRU agrohydrological model comprises a suite of software tools to aid in the preparation of input information (ACRU *Menubuilder*) and output information (ACRU *Outputbuilder*). The *Menubuilder,* an interactive and user friendly program of over 250 subroutines, prompts the user with a series of questions, facilitating the parameterisation of a distributed catchment (Kienzle et.al., 1997). Some of the input data required by the model are:

- ☆ meteorological data (i.e. rainfall, temperature and evaporation data)
- ☆ soil data
- ☆ land use data.

Information is input into the *Menubuilder* in a sequential mode, dealing with individual processes one at a time. Available data in the selected catchments mostly met the data requirements of the model (see **Chapter 5**).

4.4.4 Model Capabilities

- ☆ Simulation of streamflow, crop and timber yield, primary production, irrigation water demand and supply, and design flood estimation.
- ☆ Water resources assessments.
- ☆ Assessments of hydrological impacts of wetlands.
- ☆ Assessments of impacts of land use changes on water resources.
- ☆ Assessments of potential impacts of global climate change on crop production and hydrological responses.

4.4.5 Model Structure

4.4.5.1 Introduction

As discussed previously, the modules of ACRU which are used in this study are hydrology, sediment yield, irrigation, land use impacts and phosphate yield. **Figure 4.5** shows the general concepts of ACRU.

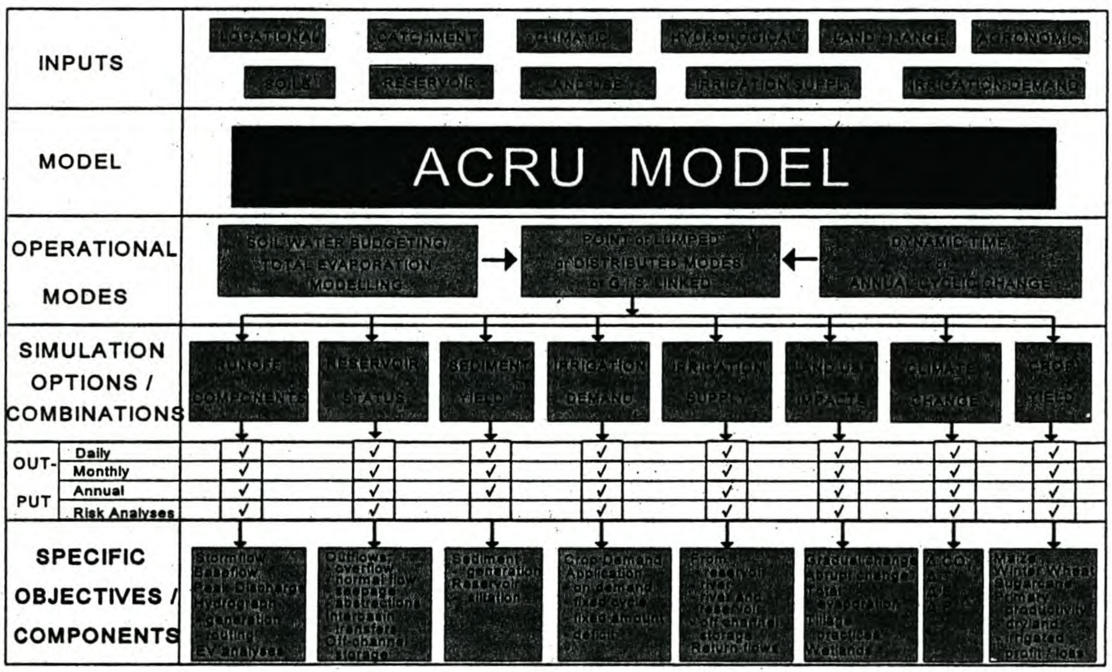


Figure 4.5 The General Concepts of ACRU

The ACRU phosphorous model was developed as part of the Mgeni study, to estimate long-term loadings of phosphorous from nonpoint (diffuse) sources to reservoirs and waterways, and to determine the effects of land use changes in the Umgeni Water Management Sub-catchments on the phosphorous yield. The phosphorous component of the model has not been used extensively. **Figure 4.6** shows the concepts of the ACRU phosphorous model.

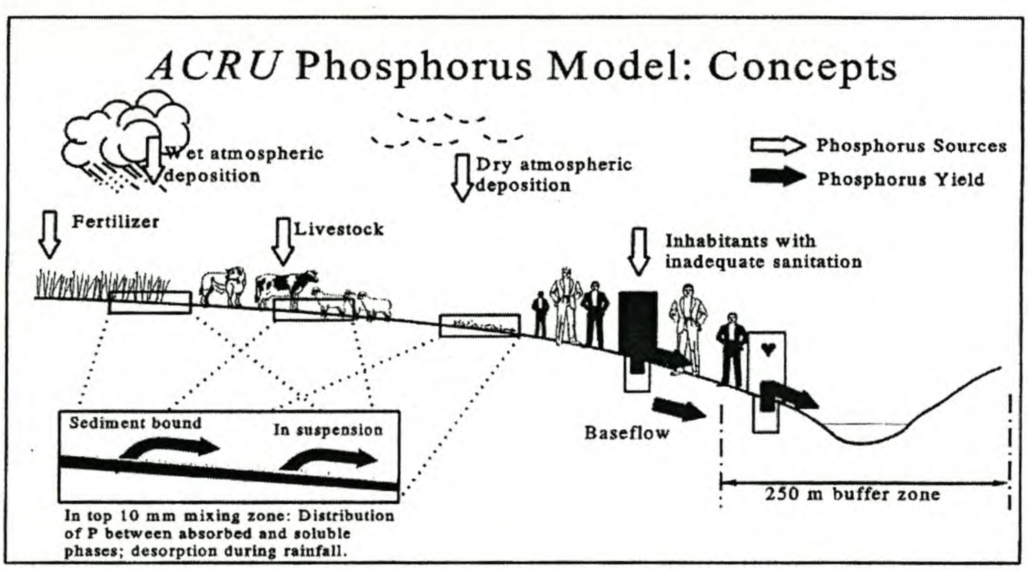


Figure 4.6 The Concepts of the ACRU Phosphorous Model

4.4.5.2 Hydrology

ACRU is centred on a daily multi-layer soil water budget, and hence the model simulates the components and processes of the hydrological cycle affecting this soil water budget. These processes of the hydrological cycle are :

- canopy interception of rainfall by vegetation
- net rainfall reaching the ground surface
- infiltration of net rainfall into the soil
- total evaporation (transpiration as well as soil water evaporation) from the various horizons of the soil profile
- the redistribution of soil water in the soil profile, both saturated and unsaturated, and
- percolation of soil water into the intermediate groundwater zone.

4.4.5.3 Sediment Yield

In ACRU, sediment yield estimation is based on the MUSLE, because it has been developed as a hydrologically driven simulator to estimate sediment yield from individual rainfall events at a catchment scale (Smithers and Caldecott, 1994). This method simulates entrainment and transporting energy of the runoff using the total stormflow and the peak discharge which are derived in ACRU on a daily basis. The source of sediment which is available for transport is defined using the soil, slope, cover and land use practice parameters derived from the RUSLE.

The USLE and RUSLE equation is given by :

$$A = R*K*LS*C*P, \qquad 4.4a$$

Where : A ⇉ long term average soil loss per unit area (tons/ha.annum),

R ⇉ an index of annual rainfall erosivity, (MJ.mm/ha.hour.annum),
K ⇉ Soil erodibility factor (tons/hour.MJ.mm),
LS ⇉ slope length and gradient factor (dimensionless),
C ⇉ cover and management factor (dimensionless), and
P ⇉ support practice factor (dimensionless).

The USLE was modified by Williams (1975), who replaced the rainfall erosivity factor with a stormflow factor. This modification, called MUSLE, allows the prediction of sediment yield directly without the need for the delivery ratio and can be applied to individual storm events. The equation for MUSLE is :

$$Y_{sd} = \alpha_{sy} (Q_v * q_p)^{\beta_{sy}} * K * LS * C * P \qquad 4.4b$$

Where : Y_{sd} ⇉ sediment yield from an individual event (tons),
Q_v ⇉ stormflow volume for the event (m^3),
q_p ⇉ peak discharge for the event (m^3/s),

α_{sy}, β_{sy} ⇉ location specific MUSLE coefficients, and factors K, LS, C, P are taken directly from the USLE.

4.4.5.4 Phosphorous Yield

The ACRU phosphorous model recognises three land uses : maize, sugarcane and mixed crop. For these three land uses total available phosphorous is added to the top 10mm of soil via fertilizer during the appropriate period of application. It is also added to the of the catchment via atmospheric deposition (Kienzle et.al., 1997). The phosphorous added to the soil from these sources is distributed between the adsorbed state and the dissolved state according to an adsorption process which is dependant on percent clay in the soil, percent soil organic matter, prevailing soil moisture status and soil pH (Kienzle et.al., 1997). The phosphorous from human sources is added to the dissolved state in the event of rainfall and runoff of sufficient magnitude causing septic tanks to discharge into streams in the catchment (Kienzle et.al., 1997).

The phosphorous loading to water courses is dependant on the balance between dissolved phosphorous carried in the runoff and the adsorbed phosphorous, carried with the sediments. The equilibrium between the adsorbed and dissolved phases is controlled using an ***adsorption isotherm equation*** defined by :

$$S = (S_{max}*b*C)/(1+b*C) \qquad 4.4c$$

Where : S ⇉ adsorbed phosphorous concentration from the source (PAD**) (mg/kg),
S_{max} ⇉ maximum adsorbed phosphorous concentration from the source (PADM**) (mg/kg),
b ⇉ adsorption isotherm constant for soils in each source (PADC**) (l/g),
C ⇉ dissolved phosphorous concentration from the source (PDIS**) (mg/l).

The ***desorption kinetics*** during a rainfall event is controlled by the equation:

$$P_{des} = K_{phos}*P_0*\ t^{\alpha}*W^{\beta} \qquad 4.4d$$

Where : P_{des} ⇉soluble phosphorous concentration of runoff (PDES**)(mg/l),
K_{phos} ⇉desorption constant for a given soil (PKL**),
P_0 ⇉ initial available soil phosphorous (PAD**)(mg/kg),
t ⇉ runoff event duration (hard coded) (20 minutes),
α ⇉desorption constant for a given soil (PALPHA**),
W ⇉ water to soil ratio (WR) (m^3/kg),
β ⇉ desorption constant for a given soil (PBETA**).

*** is the land use descriptor with su = sugarcane, mz = maize, mx = mixed crops and rs = remainder of the catchment.*

The current version of ACRU phosphorous yield model has routines for simulating phosphorous export from areas dominated by sugar cane, maize and mixed crops. Phosphorous export from all other land uses has to be simulated as the remainder of the catchment.

4.4.5.5 Potential Shortcomings of the Model in Terms of Study Objectives

The phosphorous yield model has no specific components for the simulation of phosphorous export from areas dominated by wheat and grapes, which are some of the dominant land use types in the Western Cape Province. For the purposes of this research, the maize routine was used to simulate phosphorous export from the areas dominated by wheat and the sugarcane routine for the areas dominated by grapes.

4.4.5.6 Parameters that are Adjusted During Calibration

It was the intention of the ACRU model developers that the model should ideally not require calibration, but the reality of the South African data situation does require a certain degree of parameter adjustment from "default" values to achieve a reasonable goodness-of-fit of model outputs.

4.5 COMPARISON OF THE SELECTED MODELS IN TERMS OF PHOSPHOROUS SIMULATION

Table 4.8 Comparison of Selected Models

Characteristics	PEM	IMPAQ	HSPF	ACRU
Assessment level	scoping/screening	evaluation	prioritisation & selection	prioritisation & selection
Sediment yield	sediment yield estimation is based on the USLE	sediment yield estimation is based on the USLE	sediment yield estimation is based on the detachment and washoff of sediment	sediment yield estimation is based on the MUSLE
Variables	can simulate diffuse pollution by phosphorous only	capable of modelling diffuse pollution by *E..Coli*, phosphorous and suspended solids	can simulate diffuse pollution by nitrogen, phosphorous, pesticides, metals and coliform	can simulate diffuse pollution by phosphorous and *E..coli*
Phosphorous export	phosphorous export is linked to surface runoff and sediment yield	phosphorous export is linked to surface runoff, baseflow and sediment yield.	phosphorous export is linked to overland flow, groundwater, interflow and sediment yield.	phosphorous export is linked to surface runoff and sediment yield
Calibration	should be calibrated	*a priori* or calibrated	should be calibrated	Should not be calibrated according to model developers, but this author begs to differ
Transport in the channel	has no routine for modelling phosphorous transport in the channel	has a sub-routine for phosphorous transport in the channel	has a module for phosphorous transport in the channel	has no module for phosphorous transport in the channel
Temporal resolution	monthly	monthly	minute to 24 hours	daily
Spatial resolution	land use units based on the USLE	relatively homogeneous land use units based on the land cover	relatively coarse homogeneous land use units based on the spatial variability of rainfall and physiographic characteristics of the catchment	relatively homogeneous land use units in terms of climate, soils and land cover
Phosphate	exponential storage decay functions	[1]loading coefficients	optional : exponential storage decay functions, sorption kinetics (see **Section 4.3.5.5**), or potency factors	adsorption and desorption isotherm equations (see **Section 4.4.5.4**)
Runoff	moisture budgeting : Pitman model	moisture budgeting : SCS curve numbers	moisture budgeting : empirical functions	moisture budgeting : multi-layer soil water budgeting
Data requirements	can be obtained from different sources in the RSA	can be obtained from different sources in the RSA	it is not easy to get the data required by the model	can be obtained from different sources in the RSA

[1]coefficients which reflect average concentrations of phosphorous in baseflow, surface runoff and sediment from a specific land use type.

The PEM model does not allow the user to partition the total runoff in the catchment according to the variety of land use types, even if the model is applied to the catchment as a distributed parameter model. The model does not allow the user to estimate soluble and particulate phosphorous parameters for each land use type in the catchment. There is one calibration parameter for soluble phosphorous and another for particulate phosphorous representing all the land use types in the catchment. When PEM is applied as a distributed parameter model, the catchment is discretised into relatively coarse homogeneous land use units using the USLE. The USLE parameters are estimated per land use type and sediment yield estimation is based on these parameters. PEM is a very coarse model in terms of spatial resolution, and may be used at the "*screening/scoping*" level of assessing the phosphorous loadings from the catchment. PEM may be regarded as a so-called "*black box*" model.

The CWM model of IMPAQ allows the user to partition the total runoff in the catchment using the "SCS curve numbers" according to a variety of land use types. The model allows the user to estimate soluble and particulate phosphorous parameters for each land use type. Soluble phosphorous parameters may be calibrated for each land use type in the catchment and these parameters are divided into baseflow (α) and surface flow (β) components. When CWM is applied as a distributed parameter model, the catchment is discretised into homogeneous land use units based on the land cover. The USLE parameters are estimated per land use type and sediment yield estimation is based on these parameters. Unlike PEM, CWM is less coarser in terms of spatial resolution, and may be applied at the "*evaluation*" level of assessing the phosphorous loadings from the catchment.

The HSPF model allows the user to partition the total runoff in the catchment using empirical functions according to a variety of land use types. Phosphorous parameters are estimated per land use. When HSPF is applied as a distributed parameter model, the catchment is discretised into homogeneous land use units based on the spatial variability of rainfall and physiographic characteristics of the catchment. The user is expected to input the channel geometry for each of the main sub-catchments. Sediment yield estimation is based on rain drop erosion. Unlike PEM and CWM, HSPF is finer in terms of temporal resolution. The model might be applied at a "*prioritisation or selection*" level of assessing the phosphorous loadings from the catchment, depending on the level of input information. The fine temporal resolution of HSPF might cause problem for the user in getting hourly rainfall from South African rain gauges.

In ACRU, the catchment is discretised into relatively homogeneous land use units in terms of climate, soils and land cover. Each of the units is defined as a "*cell*". Runoff is generated for each "*cell*". Phosphorous parameters are estimated for each of the land use units. Unlike in the PEM, CWM and HSPF models, sediment yield estimation is based on the MUSLE, hence there is no need for delivery ratios. ACRU, a daily model, is finer in terms of spatial and temporal resolutions than PEM and CWM (both models operate on a monthly time step), but coarser in terms of temporal resolution compared to HSPF, which is an hourly model. ACRU might be applied at a "*prioritisation or selection*" level of assessing the phosphorous loadings from the catchment, depending on the level of input information.

CHAPTER 5

STUDY CATCHMENTS

After a review of the availability of simultaneous flow and water quality data, study catchments were selected from two regions with different rainfall and geological characteristics, i.e. the Western Cape and Eastern Cape, which have winter and summer rainfall, respectively. Four study catchments were selected from each of the regions. This chapter outlines the flow, water quality and meteorological gauging stations related to the study catchments, including the topographical, geographical and climatic characteristics of the selected catchments.

5.1 STUDY CATCHMENTS IN THE WESTERN CAPE

Four sub-catchments of the Berg River were selected to represent Western Cape conditions. **Figure 5.1.** shows the Berg River basin and the sub-catchments selected for this study are shaded. The land use for each of the selected catchments is shown in **Figure 5.2.** These sub-catchments, together with their mean annual runoff (MAR), mean annual precipitation (MAP), mean annual evaporation (MAE) and dominant land uses are listed in the table below:

Table 5.1 Selected Catchments to Represent Western Cape Conditions

Catchment	Flow Gauge Number	MAP (mm) (DWAF,1993)	MAR (mm) (Midgley et. al., 1990 and DWAF, 1993)	MAE (mm) (DWAF, 1993)	Dominant land use
Doring River	G1H039	500	44	2200	wheat
Kompanjies River	G1H041	707	214	1595	wheat
Leeu River	G1H029	997	467	1605	forestry
Twenty-Four Rivers	G1H028	1285	732	1640	natural vegetation

The Leeu and Twenty-Four Rivers catchments have high MAP's compared to the Doring and Kompanjies River catchments as shown in the table above. The Doring River catchment has the lowest MAP, with highest MAE.

Figure 5.1 Shows the location of the flow gauging stations in the selected study catchments.

Table 5.2 is a summary of the flow gauging stations in the Western Cape study catchments.

Table 5.2 Flow Gauging Stations in the Western Cape Study Catchments

River	Flow Gauge Number	Place	Starting date of Automatic Recording	End Date
Doring	G1H039	Grensplaas	1978-12-14	---
Kompanjies	G1H041	De Eikeboomen	1979-08-30	---
Leeu	G1H029	De Hoek Estates	1972-10-31	---
Leeu	G1H059	De Hoek Estates	1972-10-31	--
Twenty-Four	G1H028	Drie-Das-Bosch	1972-05-06	---
Twenty-Four	G1H058	Drie-Das-Bosch	1972-05-06	---

The flow gauging station in the Doring River catchment is located in the lower reaches of the river, just a few kilometres upstream of its confluence with the Berg River. The relevant DWAF number for the flow gauge is G1H039.

The flow gauging station in the Kompanjies River catchment, is located in the lower reaches at De Eikeboomen. The relevant DWAF flow gauge is G1H041.

The flow gauging station in the Leeu River catchment is located in the middle reaches of the river at De Hoek Estates. The relevant DWAF number for the flow gauging station is G1H029. There is a diversion canal which drains into Voëlvlei dam. The DWAF number for the flow gauging station located in the canal is G1H059. The flow data from G1H029 and G1H059 were aggregated for model calibration purposes, because during dry periods most of the flow is diverted into the canal.

The flow monitoring point in the Twenty-Four Rivers catchment is located in the middle reaches of the river at Drie-Das-Bosch. The relevant DWAF number for the flow gauging station is G1H028. Upstream of this gauge, is a diversion canal which flows into Voëlvlei Dam. The DWAF number for the flow gauging station located in the canal is G1H058. The flow data from G1H028 and G1H058 were aggregated for model calibration purposes. Under normal operating conditions, flow is allowed to enter the diversion canal. A large portion of this flow , however, is allowed to spill from the canal at a silt trap located shortly upstream of the G1H058 flow monitoring point. Thus the river flow component cannot be ascertained using a mass balance (DWAF, 1993). All the flow gauging stations in **Table 5.2** are still operating. The common calibration period, according to the availability of flow and phosphorous data as shown in **Tables 5.2 and 5.3**, respectively, is 1980 to 1996.

Table 5.3 is the summary of phosphorous data availability in the study catchments. Water quality grab samples were collected at weekly intervals in each of the selected study catchments.

Table 5.3 Phosphorous Data Availability in the Western Cape Study Catchments

River	Water Quality Gauge Number	Place	Start date of Phosphorous Data Availability	End Date
Doring	G1H039	Grensplaas	1980-01-01	---
Kompanjies	G1H041	De Eikeboomen	1980-01-01	---
Leeu	G1H029	De Hoek Estates	1973-05-17	---
Twenty-Four	G1H028	Drie-Das-Bosch	1977-07-20	---

Figure 5.2 shows the location of the rainfall stations within/outside the study catchments and a summary of rainfall stations considered for the Western Cape study catchments is given in **Table 5.3**

Table 5.4 Rainfall Stations Considered for the Western Cape Study Catchments

Rainfall Station Number	Place	Latitude	Longitude	Period
0021 639	H.L.S Boland	33°52'	18°52'	1970-date
0021 816	Landau	33°36'	18°58'	1973-date
0022 004	Welbedacht	33°34'	19°01'	1978-1978
0022 005	Welbedacht	33°36'	19°01'	1978-date
0022 038	Vrugbaar	33°38'	19°02'	1904-date
0022 113	Franschhoek La Motte	33°53'	19°04'	1919-date
0022 157	Bainskloof	33°37'	19°06'	1991-date
0022 214	Bainskloof	33°34'	19°08'	1982-1989
0041 417	Malmesbury-TNK	33°27'	18°44'	1877-date
0041 598	Grasrug	33°28'	18°50'	1979-date
0041 746	Jonkershoek	33°26'	18°55'	1982-date
0041 836	Malmesbury	33°26'	18°58'	1941-1979
0041 871	Porterville	33°01'	19°00'	1980-date
0042 001	Porterville	33°01'	19°01'	1980-1989
0042 011	Saron	33°11'	19°01'	1877-1979
0042 166	Mont Pellier	33°16'	19°06'	1927-1960
0042 227	Tulbach	33°17'	19°08'	1877-date
0042 250	Tulbach Avalon	33°10'	19°09'	1984-date

Rainfall stations were selected based on their proximity to the catchment boundary, the length of the rainfall record and the number of gaps in the record.

The rainfall stations selected for each sub-catchment are discussed below:

The Doring River catchment

The following rainfall stations were considered for the Doring River catchment:

- ☆ 0021 639
- ☆ 0041 417
- ☆ 0041 598
- ☆ 0041 746

It was found that there were no rainfall stations within the catchment boundary. Stations located in the proximity of the catchment boundary were considered. Rainfall station 0041 598 was selected and used for modelling, because its record is relatively complete and it is near the catchment boundary.

The Kompanjies River catchment

The rainfall stations below were considered for the Kompanjies River catchment:

- ☆ 0022 004
- ☆ 0022 005
- ☆ 0022 157
- ☆ 0022 214
- ☆ 0021 816
- ☆ 0022 038
- ☆ 0041 836

Rainfall stations 0022 005, 0022 157, 0022 214 and 0021 816 were used for modelling, because of their records which are relatively complete and they are near the catchment boundary.

The Leeu River catchment

The rainfall stations below were considered for the Leeu River catchment:

- ☆ 0042 001
- ☆ 0042 011
- ☆ 0042 166
- ☆ 0042 227
- ☆ 0042 250
- ☆ 0041 871

Rainfall stations 0042 001, 0042 011, 0042 166, 0042 227 and 0041 871 were used for modelling, because of their records which are relatively complete and some are located near the catchment boundary.

The Twenty-Four Rivers catchment

The rainfall stations considered for the Twenty-Four Rivers catchment are as follows:

- ☆ 0022 113
- ☆ 0041 871
- ☆ 0042 001
- ☆ 0042 166
- ☆ 0042 227

None of the stations given above is located within the catchment boundary. However, all of them were used for modelling purposes, because of their records which are relatively complete.

Table 5.5 summarises temperature stations which were considered for the Western Cape study catchments.

Table 5.5 Temperature Stations Considered for the Western Cape Study Catchments

Temperature Station Number	Place	Latitude	Longitude	Period
0021 639	H.L.S Boland	33°39'	18°52'	1970-date
0021 816	Landau	33°36'	18°58'	1973-date
0041 598	Grasrug	33°28'	18°50'	1979-date
0042 001	Porterville	33°01'	19°01'	1980-1988

The temperature stations 0041 598, 0042 001 and 0021 816 were used for the Doring River catchment, Leeu & Twenty-Four Rivers catchment and Kompanjies River catchment, respectively, because they are near the catchment boundary and their record lengths are adequate.

Evaporation stations which were considered for the Western Cape study catchments are summarised in **Table 5.6.**

Table 5.6 Evaporation Stations Considered for the Western Cape Study Catchments

Evaporation Station Number	Place	Latitude	Longitude	Period
0021 639	H.L.S Boland	33°39'	18°52'	1970-date
0021 816	Landau	33°36'	18°58'	1973-date
0041 598	Grasrug	33°28'	18°50'	1979-date
0042 001	Porterville	33°01'	19°01'	1973-1989

The evaporation stations 0041 598, 0042 001 and 0021 816 were used in the Doring River catchment, Leeu & Twenty-Four Rivers catchment and Kompanjies River catchment, respectively, because of their proximity to the catchment boundary and their record lengths.

5.1.1 The Berg River Main Stem

Figure 5.1 shows the Berg River basin, with the catchments selected for this study, shaded.

5.1.1.1 Geographical Location

The Berg River is located in the Western Cape Province of the Republic of South Africa and rises in the Jonkershoek and Franschhoek mountains from where it flows in a north-westerly direction and discharges into the sea at Laaiplek. The length of the river valley is approximately 160km from the headwaters to the sea and its width varies from 1 to 5km near its headwaters to between 30 to 40km at the coast. The length of the main river channel is approximately 270km and it drains a catchment area of about 9000km^2.

5.1.1.2 Topography

The upper basin of the Berg River, which extends from the headwaters to Drieheuwels, is bounded on the eastern side by a range of mountains (RL1500m), on the western side the basin flattens out to a hilly plain. The river basin falls exponentially from the headwaters to the sea, about 900m over 50km from the headwaters to Paarl and a further 100m over 220km between Paarl and the sea. The lower reach of the river is extremely flat so that sea water intrusion pushes up nearly 100km from the river mouth under high tide conditions.

5.1.1.3 Climate

The catchment lies within the winter rainfall zone of the Western Cape. The rainfall is high in the mountains, up to 3000 mm per annum. In the adjoining valleys it varies from 900mm to 1200mm annually, but drops to between 400 and 500mm in the hilly plain through which the river travels for most of its length. Eighty percent of the rainfall falls during the six months of winter (i.e. April to September).

The rainfall is of a frontal nature normally extending over a few days with significant periods of clear weather in between. The tributaries are perennial on the eastern side and semi-perennial on the western side.

5.1.1.4 Flow Gauging Stations

The Berg River catchment comprises quite a number of flow and water quality monitoring points. Almost all the sub-catchments in the Berg River are gauged.

5.1.1.5 Land Use

The Berg River catchment is dominated by agricultural practice and the main areas of irrigation lies between the Franschhoek and Banghoek valley. Wheat, pastoral, cattle and pig farming are practised in the areas along Paarl and Wellington away from the river channel.

5.1.2 The Doring River

5.1.2.1 Geographical Location

The Doring River is located on the western side of the Berg River near Wellington and rises in the Perdeberg mountains from where it flows in an easterly direction in to the Berg River main channel. Its catchment area is about 44km^2 and its main channel is about 13km long.

5.1.2.2 Topography

The upper basin is bounded by Perdeberg mountains and the catchment has relatively steep slopes with hills in some parts of the catchment.

5.1.2.3 Climate

The Doring River lies within the winter rainfall zone of the Western Cape with the MAP near the catchment boundary on the western side varying between 400 and 500mm. The MAE is about 2200mm (DWAF, 1993). It is a semi-perennial tributary of the Berg River, with continuous flow between April and September each year.

5.1.2.4 Land Use

The primary land use in the catchment is wheat. There are few vineyards within the catchment and grazing is practised downstream of the flow gauging station.

5.1.3 The Kompanjies River

5.1.3.1 Geographical Location

The Kompanjies River is located on the eastern side of the Berg River and rises from the Limiet mountains. The Kompanjies flows in a westerly direction into the Berg River. The confluence of the Kompanjies River with the Berg River is downstream of that with the Doring River. The catchment area is about 122km^2 and its main channel is about 18km long.

5.1.3.2 Topography

The Kompanjies River is bounded on the eastern side by the Limiet mountains and the lower reaches of the catchment are relatively flat.

5.1.3.3 Climate

The Kompanjies River lies in the winter rainfall zone, with the MAP on the eastern side of the catchment being 1699mm and the southern side between 600 and 700mm. The MAE varies between 1300 and 2300mm (DWAF, 1993). The Kompanjies River is one of the perennial tributaries of the Berg River.

5.1.3.4 Land Use

The primary land use in the catchment is wheat. Sheep and cattle farming are practised on the flood plain just upstream of the flow gauging station. A chemical factory is located in the catchment at Kranzkop. Effluent from this factory is discharged into an extensive evaporation pond system and there is no direct discharge into the river (DWAF, 1993).

5.1.4 The Leeu River

5.1.4.1 Geographical Location

The Leeu River is located on the eastern side of the Berg River and rises in the Twenty-Four River mountains. The catchment area is about 36km^2 and the flow gauging station serves as a diversion weir for the Voëlvlei dam. The length of the main river channel is about 10km.

5.1.4.2 Topography

The Leeu River is bounded by Twenty-Four River mountains with steep average slopes.

5.1.4.3 Climate

The Leeu River lies within the winter rainfall zone and the MAP on the eastern side of the catchment is about 1234mm. The MAE varies between 1600 and 2300mm (DWAF, 1993). The Leeu River is one of the perennial tributaries of the Berg River.

5.1.4.4 Land Use

The dominant land cover is natural vegetation (fynbos) and the catchment is largely pristine. There is alien vegetation along the flood plain just upstream of the flow gauging station.

5.1.5 The Twenty-Four Rivers

5.1.5.1 Geographical Location

The Twenty-Four Rivers catchment is located on the eastern side of the Berg river and northern side of the Leeu River. The two sub-catchments are separated by Twenty-Four Rivers mountains. The Twenty-Four Rivers river rises in the Twenty-Four Rivers mountains with a catchment area of about 185km^2 and includes a diversion weir for supply to Voëlvlei Dam. The length of the main river channel is about 22km.

5.1.5.2 Topography

The Twenty-Four Rivers catchment is bounded by Twenty-Four River mountains with steep average slopes.

5.1.5.3 Climate

The Twenty-Four Rivers lie within the winter rainfall zone and the MAP on the Southern side is about 1234mm and between 400 and 600mm on the eastern side. The MAE varies between 1600 and 2300mm (DWAF, 1993).

5.1.5.4 Land Use

The dominant land cover is natural vegetation with farming being practised in the upland areas.

5.2 STUDY CATCHMENTS IN THE EASTERN CAPE

Figure 5.3 shows the Amatole catchments with the sub-catchments selected for this study shaded. The land use variation in each of the selected study catchments is shown in **Figure 5.4. Table 5.7** summarises selected study catchments in the Eastern Cape.

Table 5.7 Selected Catchments to Represent Eastern Cape Conditions

Catchment	Flow Gauge Number	MAP (mm) (DWAF,1995)	MAR (mm) (DWAF,1995)	MAE (mm) (DWAF,1995)	Dominant land use
Gqunube River	R3H001	688	61	1400	natural vegetation
Yellowoods River	R2H011	662	62	1400	natural vegetation
Cwencwe River	R2H008	1011	179	1450	forestry
Upper Buffalo River	R2H001	800	95	1450	forestry

The Upper Buffalo and the Cwencwe catchments have high MAP's compared to the Gqunube and Yellowwoods catchments. The MAR's and MAP's of the Gqunube and Yellowwoods Rivers are very close, with similar mean annual evaporation.

The location of the flow gauging stations is shown in **Figure 5.3.** and **Table 5.8** summarises flow gauging stations in the study catchments.

Table 5.8 Flow Gauging Stations in the Eastern Cape Study Catchments

River	Flow Gauge Number	Place	Starting Date of Automatic Recording	End Date
Gqunube	R3H001	Outspan	1972-04-22	------
Yellowwoods	R2H011	Fort Murray	1964-09-28	1986-03-25
Cwencwe	R2H001	Pirie Main Bos Res.	1960-11-23	------
Upper Buffalo	R2H008	Edendale	1966-09-14	------

The flow gauging station in the Gqunube River catchment is located in the middle reaches of the river at Outspan. The relevant DWAF number for the flow gauging station is R3H001.

The flow monitoring point in the Yellowwoods catchment is located in the lower reaches of the river at Fort Murray Uitspan. The relevant DWAF number for the gauge station is R2H011.

The flow gauging structure in the Cwencwe River catchment is located in the lower reaches at Edendale. The relevant DWAF number for the flow gauging station is R2H008.

The weir in the Upper Buffalo River catchment is located in the lower reaches at Pirie Main Bos. The relevant DWAF number for the gauge is R2H001.

With the exception of R2H011, the above flow gauging stations are still operating. R2H011 was closed in 1986. According to the availability of phosphorous data as shown in **Table 5.9.**, the common calibration period could be 1980 to 1986.

The availability of phosphorous data in the study catchments is summarised in **Table 5.9**.

Table 5.9 Phosphorous Data Availability in the Eastern Cape Study Catchments

River	Water Quality Gauge Number	Place	Starting date of phosphorous data availability	End date
Gqunube	R3H001	Outspan	1976-11-29	------
Yellowwoods	R2H011	Fort Murray	1980-01-08	1986-08-11
Cwencwe	R2H001	Pirie Main Bos Res.	1983-01-03	-----
Upper Buffalo	R2H008	Edendale	1977-09-06	-----

The location of the rainfall stations used in this study is shown in **Figure 5.3.** and the stations details are summarised in **Table 5.10**.

Table 5.10 Rainfall Stations Considered for the Eastern Cape Study Catchments

Rainfall Station Number	Place	Latitude	Longitude	Period
0079 853	Woodlands	32°43'	27°29'	1918-1974
0080 039	Amabele	32°59'	27°49'	1908-1937
0080 457	Granta	32°38'	27°46'	1917-date
0080 569	Umzoniana	32°59'	27°49'	1918-date
0080 583	Woolhope	32°43'	27°50'	1918-1968
0079 730	Izeleni Bush	32°41'	27°25'	1909-date
0079 823	Frankfort	32°44'	27°28'	1915-1974
0080 072	Kei road	32°42'	27°32'	1876-date
0080 355	Fort-Jackson Pol	32°55'	27°42'	1881-date
0079 524	Pirie bush	32°44'	27°18'	1920-1976
0079 551	Cwencwe	32°41'	27°19'	1930-1994
0079 523	Evelyn Valley	32°43'	27°18'	1887-1985
0079 433	Evelyn Valley	32°43'	27°15'	1985-date
0079 490	Isidinge bush	32°40'	27°17'	1885-date

Rainfall stations were selected based on their proximity to the catchment boundary, the length of the rainfall records and the number of gaps in the records. The rainfall stations selected for each sub-catchment are discussed below:

The Gqunube River catchment

The following rainfall stations listed in **Table 5.10.** were considered for this catchment:

- ☆ 0079 853
- ☆ 0080 039
- ☆ 0080 457
- ☆ 0080 569
- ☆ 0080 583

There are three rainfall stations located within the catchment boundary (i.e. 0080 457, 0080 039 and 0080 583). These three stations and 0079 569 were used for modelling purposes, because of their record lengths and locations.

The Yellowwoods River catchment

The following rainfall stations listed in **Table 5.10** were considered

- ☆ 0079 730
- ☆ 0079 823
- ☆ 0079 853
- ☆ 0080 072
- ☆ 0080 355

There are three rainfall stations which are located within the catchment boundary (i.e. 0080 072, 0079 823 and 0079 853). All the stations were used for modelling purposes, because of their record lengths and locations.

The Cwencwe River catchment

The following rainfall stations were considered for this catchment

- ☆ 0079 490
- ☆ 0079 551

There is only one rainfall station (i.e. 0079 551) which is located within the catchment boundary. Both stations were used for modelling, because of their record lengths and locations.

The Upper Buffalo River catchment

The rainfall stations given below were considered for the Upper Buffalo River catchment.

- ☆ 0079 523
- ☆ 0079 524
- ☆ 0079 433
- ☆ 0079 490

There are three rainfall stations (i.e. 0079 433, 0079 524 and 0079 523) located within the catchment boundary. Rainfall stations 0079 433, 0079 523 and 0079 490 were used, because of their record lengths.

Table 5.11 summarises all temperature stations which were considered for the Amatole catchments.

Table 5.11 Temperature Stations Considered for the Eastern Cape Study Catchments

Gauge No.	Place	Latitude	Longitude	Period
0079 800	Bisho_A	32°50'	27°27'	1985-1986
0079 504	Bisho	32°54'	27°17'	1986-date
0079 712	King William's Town	32°52'	27°24'	1980-1985
0080 095	Stuterheim	32°35'	27°34'	1988-date

The temperature station 0079 712 is the only one which was used for modelling in all four sub-catchments, because of its record length compared to the other stations. The station is located 2.5km, 21km, 9.25km and 10.5km from the Yellowwoods River catchment, the Gqunube River catchment, the Cwencwe River catchment and the Upper Buffalo catchment, respectively.

Evaporation stations considered for the Eastern Cape study catchments are summarised in **Table 5.10**

Table 5.12 Evaporation Stations Considered for the Eastern Cape Study Catchments

Gauge No.	Place	Latitude	Longitude	Period
0079 800	Bisho	32°50'	27°27'	1985-1986
0079 504	Bisho	32°54'	27°17'	1986-1988
0079 811A0	Donhe	32°31'	27°34'	1980-date

The evaporation station 0079 811A0 is the only one which was used for modelling in all sub-catchments, because of its record length which is compatible with that of the temperature station 0079 712.

5.2.1 The Gqunube River

5.2.1.1 Geographical Location

The Gqunube River is located in the Eastern Cape Province of the Republic of South Africa (RSA). It is part of the Amatole River system. It rises near the Amabele Settlement and has a catchment area of 504 km^2. The length of the main river channel is about 45km.

5.2.1.2 Topography

The Gqunube catchment is mountainous with relatively steep average slopes.

5.2.1.3 Climate

The climatic conditions prevailing in the catchment are typical of the Eastern Cape Region, where December and January are the hottest months and July and August the coldest, and rainfall occurs mainly in summer. Rainfall is either from the cold fronts approaching from the south west or convectional storms. The MAP in the catchment ranges between 700 and 1000mm. The MAE in the catchment is about 1400mm.

5.2.1.4 Land Use

The Gqunube catchment is a partially pristine catchment, with natural vegetation as the primary land cover and agriculture as a secondary land use.

5.2.2 The Yellowwoods River

5.2.2.1 Geographical Location

The Yellowwoods River is located in the Eastern Cape Province of RSA. It is located upstream of Laing dam. The main towns within the catchment are Bisho and King William 's Town. It has a catchment area of about 196km^2. The length of the main river channel is about 33km.

5.2.2.2 Topography

The catchment has relatively steep average slopes at the headwaters.

5.2.2.3 Climate

The climatic conditions prevailing in the catchment are typical of the Eastern Cape Region, where December and January are the hottest months and July and August the coldest, and rainfall occurs mainly in summer. Rainfall is either from the cold fronts approaching from the south west or convectional storms. The MAP in the catchment ranges between 650 and 1000mm and the MAE in this catchment is 1400mm.

5.2.2.4 Land Use

The primary land cover is natural vegetation and secondary land use types are forestry, agriculture, formal and informal settlements.

5.2.3 The Cwencwe River

5.2.3.1 Geographical Location

It is located in the Eastern Cape province of the RSA. The river has a catchment area of about $62km^2$.

5.2.3.2 Topography

The catchment is mountainous with relatively steep average slopes.

5.2.3.3 Climate

The climatic conditions are typical of the Eastern Cape Region, where December and January are the hottest months and July and August the coldest, and rainfall occurs mainly in summer. Rainfall is either from the cold fronts approaching from the south west or convectional storms. The MAP within the catchment is between 800 and 1000mm and the MAE varies between 750 and 1450mm.

5.2.3.4 Land Use

The dominant land use is forestry. Timber, grazing and agriculture are secondary land use types in the catchment.

5.2.4 The Upper Buffalo River

5.2.4.1 Geographical Location

The Upper Buffalo River is located in the Eastern Cape Province of the RSA upstream of Maden dam. It has a catchment area of about $48km^2$. The approximate length of the main river channel is about 4km.

5.2.4.2 Topography

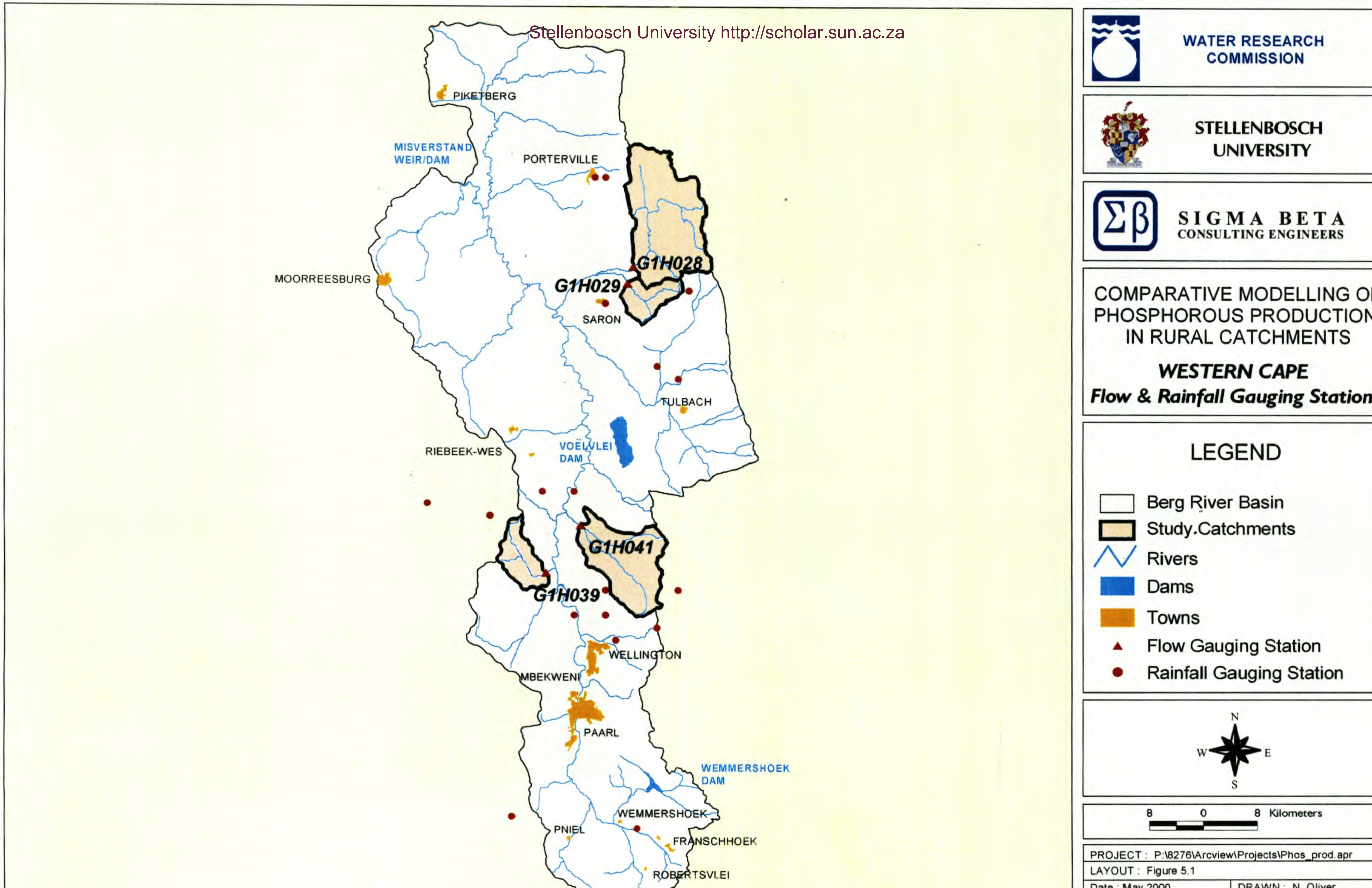
The catchment is mountainous with relatively steep average slopes.

5.2.4.3 Climate

The climatic conditions are typical of the Eastern Cape Region, where December and January are the hottest months and July and August the coldest, and rainfall occurs mainly in summer. Rainfall is mainly from the cold fronts approaching from the south west. The MAP within the catchment is between 900 and 1700mm and the MAE varies between 950 and 1500mm.

5.2.4.4 Land Use

The primary land use in the catchment is forestry and secondary land uses are grazing, timber and agriculture.


PIKETBERG
MISVERSTAND WEIR/DAM
PORTERVILLE
MOORREESBURG
G1H028
G1H029
SARON
TULBACH
RIEBEEK-WES
VOËLVLEI DAM
G1H041
G1H039
WELLINGTON
MBEKWENI
PAARL
WEMMERSHOEK DAM
WEMMERSHOEK
PNIEL
FRANSCHHOEK
ROBERTSVLEI
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COMPARATIVE MODELLING OF PHOSPHOROUS PRODUCTION IN RURAL CATCHMENTS
WESTERN CAPE
Flow & Rainfall Gauging Stations
LEGEND
Berg River Basin
Study.Catchments
Rivers
Dams
Towns
Flow Gauging Station
Rainfall Gauging Station
N
W
E
S
8 0 8 Kilometers
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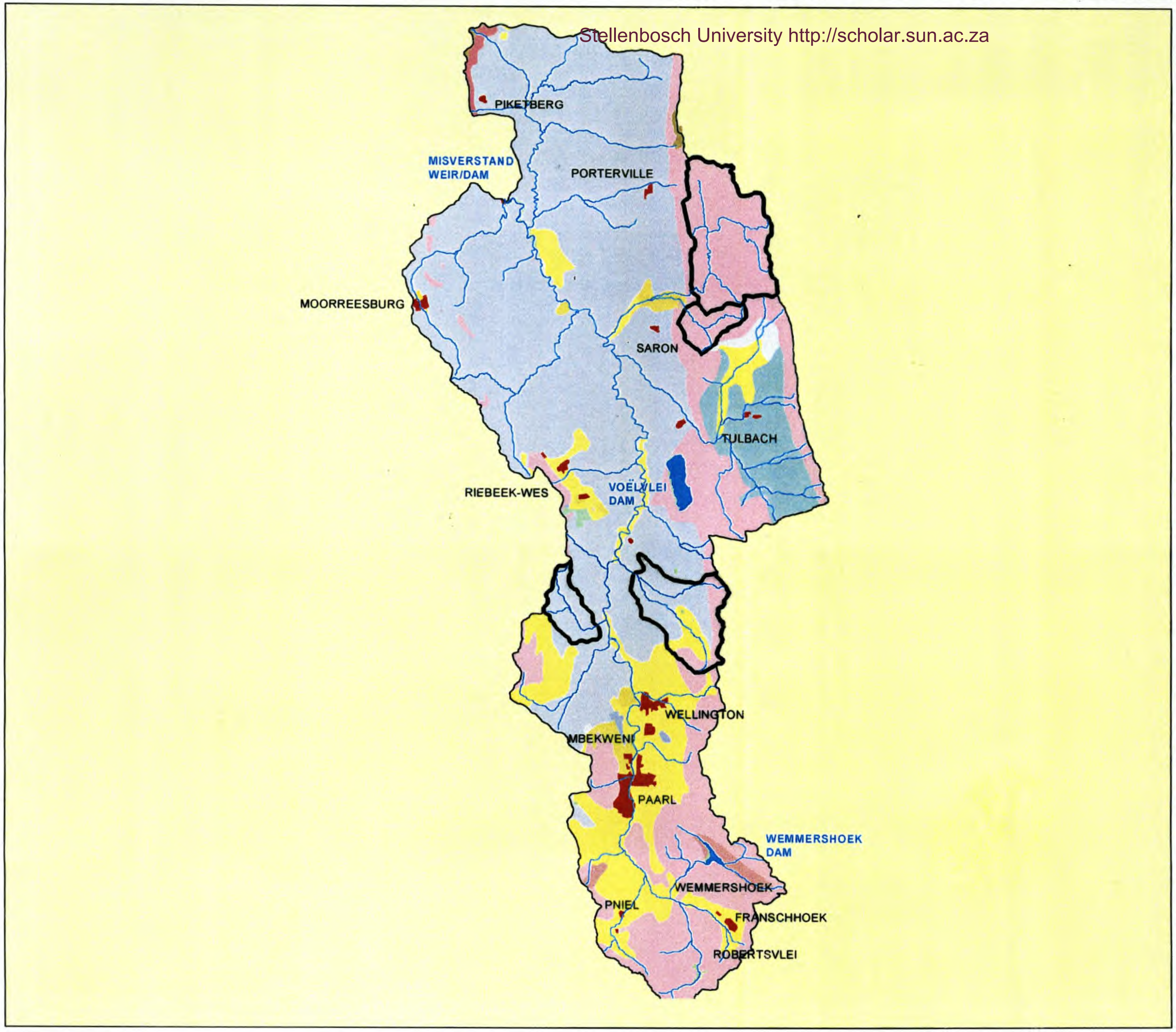
LAYOUT : Figure 5.1
Date : May 2000
DRAWN : N. Oliver

FIGURE 5.1



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SIGMA BETA
CONSULTING ENGINEERS

COMPARATIVE MODELLING OF PHOSPHOROUS PRODUCTION IN RURAL CATCHMENTS

WESTERN CAPE

Landuse

LEGEND

- Berg River Basin
- Study Catchments
- Rivers
- Dams

LANDUSE CLASSIFICATION

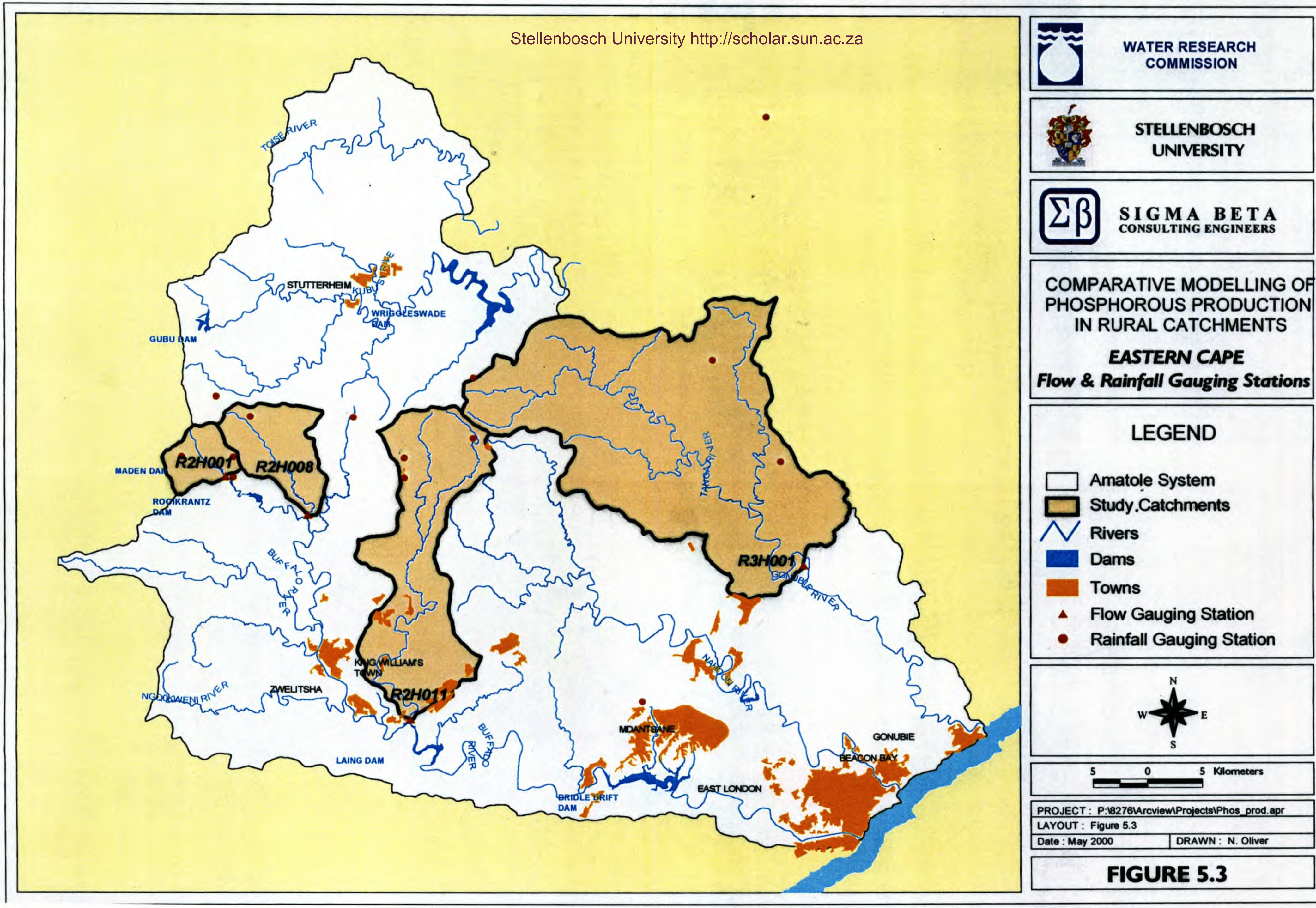
- Annual small grain
- Annual small grain/Natural grazing
- Citrus
- Dams
- Forestry
- Mining
- Natural grazing
- Other crops
- Pans
- Reserves and Mnt. veld
- Small holdings
- Wine grapes
- Wine grapes/Table grapes
- Stone fruit
- Stone fruit/Pome fruit
- Table grapes
- Unclassified
- Urban areas
- Vegetables

N W E S

8 0 8 Kilometers

PROJECT : P:\8276\Arcview\Projects\Phos_prod.apr
LAYOUT : Figure 5.2
Date : May 2000 DRAWN : N. Oliver

FIGURE 5.2



TOISE RIVER
STUTTERHEIM
KUBUSIE RIVER
WRIGGLESWADE DAM
GUBU DAM
MADEN DAM
ROOIKRANTZ DAM
R2H001
R2H008
R2H011
R3H001
BUFFALO RIVER
KING WILLIAM'S TOWN
ZWELITSHA
NGQOKWENI RIVER
LAING DAM
BUFFALO RIVER
BRIDLE DRIFT DAM
MDANTSANE
EAST LONDON
BEACON BAY
GONUBIE
GONUBIE RIVER
NAHOON RIVER
TAMGA RIVER
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EASTERN CAPE
Flow & Rainfall Gauging Stations
LEGEND
Amatole System
Study Catchments
Rivers
Dams
Towns
Flow Gauging Station
Rainfall Gauging Station
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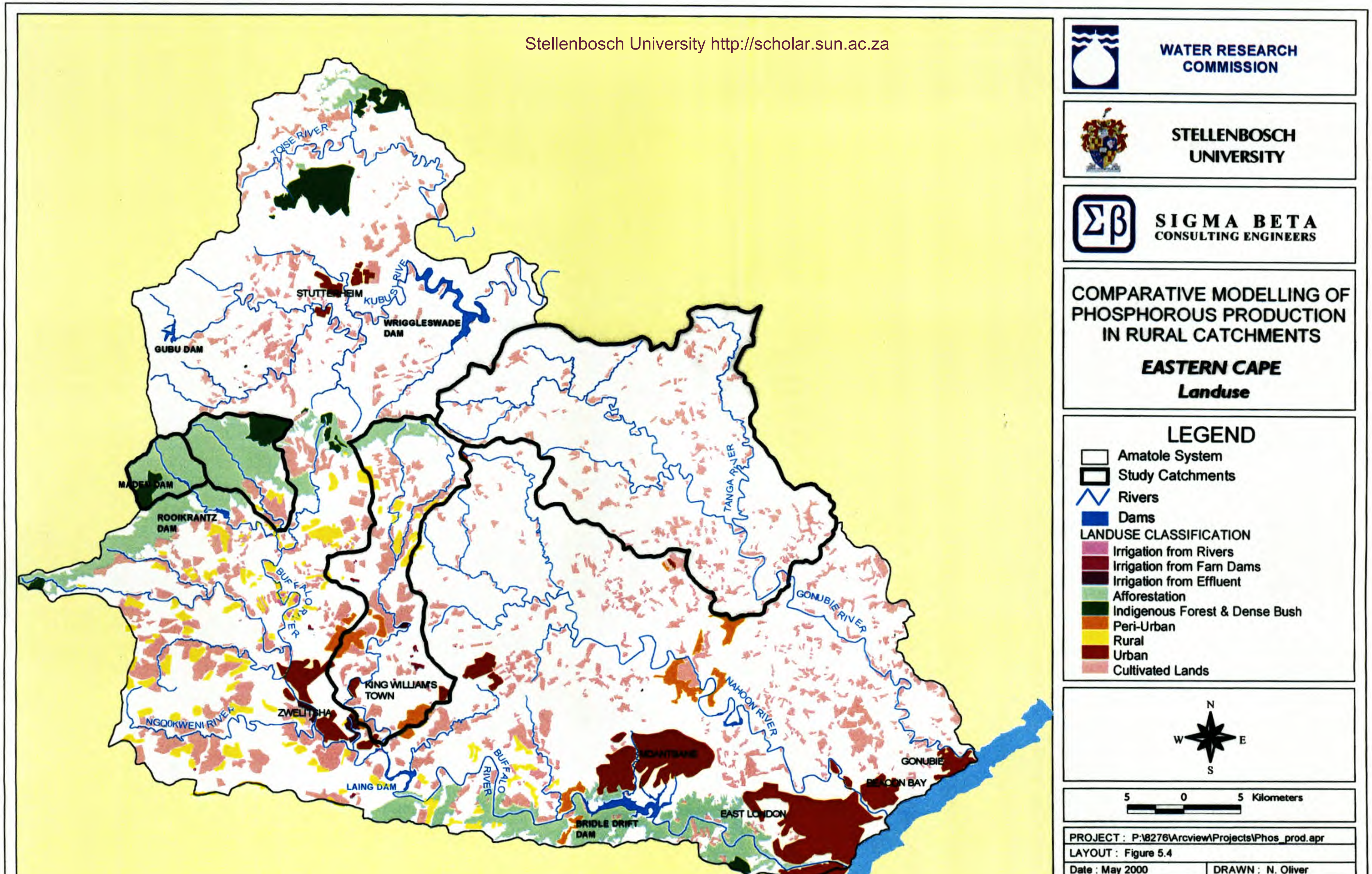
Kilometers
PROJECT : P:\8276\Arcview\Projects\Phos_prod.apr
LAYOUT : Figure 5.3
Date : May 2000
DRAWN : N. Oliver

FIGURE 5.3


TOISE RIVER
STUTTERHEIM
KUBUSI RIVER
WRIGGLESWADE DAM
GUBU DAM
MAIDEN DAM
ROOIKRANTZ DAM
BUFFALO RIVER
TANGA RIVER
GONUBIE RIVER
NAHOON RIVER
KING WILLIAM'S TOWN
ZWELITSHA
NGQOKWENI RIVER
LAING DAM
BUFFALO RIVER
MDANTSANE
BRIDLE DRIFT DAM
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EASTERN CAPE
Landuse
LEGEND
Amatole System
Study Catchments
Rivers
Dams
LANDUSE CLASSIFICATION
Irrigation from Rivers
Irrigation from Farm Dams
Irrigation from Effluent
Afforestation
Indigenous Forest & Dense Bush
Peri-Urban
Rural
Urban
Cultivated Lands
N
W
E
S
5 0 5 Kilometers
PROJECT : P:\8276\Arcview\Projects\Phos_prod.apr
LAYOUT : Figure 5.4
Date : May 2000
DRAWN : N. Oliver

FIGURE 5.4

CHAPTER 6

DATABASE DEVELOPMENT

The data sets used in this study were assembled from both local and national sources. This chapter outlines all the hydrological and meteorological data that were collected for modelling purposes. The sources of the collected data and data related issues are also discussed.

A summary of the national sources of data is given in **Table 6.1**

Table 6.1 Summary of Data Sources at the National Level

Data type	Source of data	Relevant Model	Purpose of data in the model
Daily rainfall data	SAWB & CCWR	HSPF, ACRU	input data
Monthly rainfall	SAWB	IMPAQ	input data
Monthly temperature and evaporation	SAWB & CCWR	ACRU	input data
Daily temperature and evaporation	SAWB & CCWR	HSPF	input data
Monthly runoff	DWAF	ACRU	verification
Daily runoff	DWAF	HSPF	calibration
Monthly runoff	DWAF	PEM & IMPAQ	input data
$P0_4$ and TP loads	DWAF	ACRU	verification
$P0_4$ and TP loads	DWAF	HSPF, PEM & IMPAQ	calibration

6.1 NATIONAL MONITORING NETWORKS

As stated earlier in **Chapter 3**, the national DWAF has streamflow and water quality monitoring points located on different rivers throughout the country. The SAWB also has rainfall, evaporation, temperature and solar radiation stations located at different points throughout the country. All these data form part of the national hydrological and meteorological database.

Some of the data used in this study were obtained from the national database. These data are discussed in the next sections.

6.1.1 Rainfall Data

Daily rainfall data are one of the inputs to both HSPF and ACRU. The CWM model requires monthly rainfall data as part of the input. Daily and monthly rainfall data were obtained from the SAWB and Computing Center for Water Research (CCWR).

The sources of CCWR rainfall data are SAWB, Department of Agriculture and Water Supply, South African Forestry Research Institute, Department of Environmental Affairs, SA Sugar Association Experiment Station, Provincial Parks Boards, Organised Agriculture, Municipalities, Mines and Private Individuals.

6.1.2 Runoff Data

The observed streamflow data were used as the input in both the CWM and PEM models. In ACRU, the monthly observed streamflow is used for model verification at the catchment outlet. The HSPF requires observed daily flow data for calibration purposes. These data were obtained from DWAF.

6.1.3 Evaporation and Temperature Data

The HSPF model requires both daily temperature and evaporation data as the input, whereas, ACRU requires monthly temperature and evaporation data as the input. The data were obtained from the SAWB, CCWR database and Department of Agriculture.

6.1.4 Water Quality Data

Soluble and total phosphorous concentrations data were obtained from DWAF, sampled at approximately weekly intervals. A detailed explanation of how loads are estimated is given in **Section 6.3.2**. It not all the study catchments which had observed total phosphorous data. **Due to the lack of observed total phosphorous data in some of the study catchments, it was decided to focus on soluble phosphorous data which were available for relatively longer periods in all the study catchments.**

6.1.5 Land Use Data

Land use data were obtained from topographical surveys, water quality and hydrology reports on the Berg River (DWAF,1993) and Amatole System, respectively.

6.2 COLLECTION FROM LOCAL DATABASES

The Department of Agriculture has its own rainfall, temperature, evaporation, solar radiation and wind stations located at different monitoring stations throughout the Western Cape Province. Their meteorological data form part of the local database.

Some of the data obtained from the local database are discussed below. Local data collection also included water quality sampling, as part of this project, at the Doring River flow gauging station (i.e. **G1H039**). The sampling dates and variables of interest are given in **Section 6.2.2**.

A summary of the data collected locally is as follows:

Table 6.2 Summary of Data Sources at the Local Level

Data type	Source of data	Relevant model	Purpose of the data
Daily rainfall	Department of Agriculture, Elsenburg	HSPF and ACRU	input data
Daily evaporation and temperature	Department of Agriculture, Elsenburg	HSPF	input data
$P0_4$ & TP	Sampling in this project	------------	compare with the existing data

6.2.1 Meteorological Data

Daily rainfall, evaporation and temperature data used in the Berg River catchments were obtained from the Department of Agriculture at Elsenburg.

6.2.2 Water Quality Sampling and Analysis

As part of this study it was decided to collect weekly grab samples from one of the selected catchments as an independent "control" of the grab-sample data set derived from the national monitoring. These grab samples were collected at dates different from those used by DWAF for the national programme. The key objective for collecting weekly grab samples was to check the reliability of the existing $P0_4$ data which would be used in the calibration process. However, severe budget limitations meant that only the catchment nearest to Stellenbosch could be sampled in this way. Weekly grab samples were collected just downstream of the flow gauging station G1H039 on the Doring River between the last week of July 1998 and the first week of October 1998. The analysis of these samples was done for $P0_4$, TP and EC by Abbot & Associates and the CSIR laboratories.

DWAF collected weekly grab samples as part of their data collection program. Grab sample analysis for TP is done by DWAF at some of the selected flow gauging stations, but not at this flow gauging station. **Table 6.3** summarises water quality variables measured at flow gauging station G1H039. Discussion of the laboratory results in **Table 6.3** appears in **Section 6.3.3**

Table 6.3 Summary of Water Quality Variables Measured at G1H039

Date	PO_4 (mg/l)	TP (mg/l)	EC (mS/m)	Laboratory
01-07-1998	0.060	---------	561	DWAF
08-07-1998	0.156	---------	104.2	DWAF
15-07-1998	0.094	---------	457	DWAF
22-07-1998	0.108	---------	463	DWAF
27-07-1998	0.26	0.29	635	Abbot & Associates
29-07-1998	0.083	---------	406	DWAF
05-08-1998	0.085	--------	517	DWAF
07-08-1998	<0.1	0.33	374	Abbot &Associates
07-08-1998	<0.1	0.49	370	Abbot &Associates
12-08-1998	0.147	---------	488	DWAF
14-08-1998	0.25	0.65	604	Abbot &Associates
21-08-1998	0.154	0.375	505	CSIR
28-08-1998	0.151	0.352	569	CSIR
28-08-1998	0.23	0.26	724	Abbot &Associates
02-09-1998	0.153	--------	700	DWAF
09-09-1998	0.249	--------	670	DWAF
11-09-1998	0.193	0.268	610	CSIR
16-09-1998	0.171	--------	666	DWAF
18-09-1998	0.144	0.207	664	CSIR
21-09-1998	0.141	0.188	676	CSIR
22-09-1998	0.160	0.230	704	CSIR
23-09-1998	0.128	-------	780	DWAF
28-09-1998	0.155	0.157	704	CSIR
30-09-1998	0.087	-------	735	DWAF
07-10-1998	0.112	------	908	DWAF
09-10-1998	0.080	0.086	840	CSIR
14-10-1998	0.110	--------	858	DWAF

6.2.3 Catchment Site Visits

All study catchments were visited. During each site visit, soil and land use types were observed and photographs were taken. The selected catchments were found to comply with the selection criteria in terms of land use.

The Doring River catchment was visited more than once during the study. The objective of the visits was to monitor land use variation throughout the year and to collect water samples.

6.3 DATA ISSUES

6.3.1 Rainfall Data

The data received from DWAF was checked for errors and anomalies. Stationarity of the rainfall records was checked by double mass plots. Most of the rainfall data had gaps in the record. These monthly gaps were patched using programs CLASSR and PATCHR (Pegram,1994). Daily rainfall data abstracted from the CCWR database were patched using the available software from the CCWR. The patched daily data were used as the input to the ACRU and HSPF models.

6.3.2 Phosphorous Data

As indicated earlier, the focus of this research was on soluble phosphorous due to a lack of observed total phosphorous data in some of the study catchments. It is an expensive exercise to sample Total Phosphorous (TP) or soluble phosphorous ($P0_4$) loads in a river continuously. Several methods are available for estimating TP or $P0_4$ loads from the daily discharge and TP or $P0_4$ data (Bodo and Unny, 1983; Walker,1987; Bath, 1989). The most appropriate method to use depends on the characteristics of the system being investigated, the statistical properties of the discharge and concentration records and the degree of dependence between concentration and discharge (Walker,1987; Bath,1989).

For this study an internationally recognised interactive infilling program, FLUX (Walker,1987), was used to estimate soluble phosphorous loadings.

This program requires two data sets as the input: one comprising instantaneous flow (m^3/s) and corresponding TP or $P0_4$ concentration (mg/l), and the second instantaneous flow (m^3/s) for the entire period over which samples were taken. The program then interprets phosphorous concentration data and flow data derived from the intermittent grab or event sampling to estimate mean or total loading over the complete flow record between any two dates.

The daily estimated $P0_4$ concentration was used by HSPF for calibration. These daily data were converted to flow-weighted monthly values for use by CWM. Daily loads were converted to monthly for use by the PEM model. The ACRU phosphorous model was verified at the catchment outlet using daily phosphorous loads.

6.3.3 Analysis of Laboratory Results

Samples collected for this project from the Doring River were analysed by two laboratories, as stated in **Section 6.2.2**. On the 7th August 1998, two samples were taken at the same time and at the same sampling point with two separate sampling bottles. Both samples were sent to the Abbot & Associates laboratory for analysis. According to the laboratory results these two samples had TP concentrations of 0.33mg/l and 0.49 mg/l with corresponding electrical conductivity (EC) values of 374 and 370 mS/m, respectively. The 33% difference between TP concentrations from the two samples was not expected.

On the 28th August 1998, one sampling bottle was used. The sample was divided into two and sent to the CSIR and Abbot & Associates laboratories. The results from the two laboratories came out differently. Results from the CSIR laboratory showed that the sample had a relatively high concentration of sediment-associated phosphorous **(0.201mg/l)**, whereas Abbot & Associates found that the sample had a very low concentration of sediment-associated phosphorous **(0.03 mg/l)**. The EC from the two laboratories was also different. One laboratory found that the EC in the sample was **569 mS/m**, whereas the other laboratory found that the EC was **724 mS/m**.

The CSIR laboratory is using a Skalar Auto Analyzer for marine and fresh water samples. This instrument was used in the analysis of samples collected by the researcher. A calorimetric technique was used in the analysis of the collected samples, with a detection limit for $P0_4$ of 0.01mg/l.

Most of the samples analysed routinely by Abbot & Associates are sewerage treatment works related samples. They use Lovybond products and technique to analyse these samples. Since the samples are related to sewerage treatment works, a higher detection limit should be expected, compared to the CSIR detection limit mentioned above. The $P0_4$ detection limit Abbot & Associates are using is 0.1mg/l of $P0_4$. The same products, technique and $P0_4$ detection limit were used in the analysis of fresh water samples collected for this study. The higher detection limit might have affected the accuracy of the $P0_4$ concentration.

DWAF is using a Technicon Auto Analyzer for the analysis of grab samples. A calorimetric technique was used in the analysis of samples with a detection limit of 0.005mg/l of $P0_4$ concentration.

The $P0_4$ concentration results from the CSIR laboratory are comparable with those of DWAF towards the end of August and September 1998. The reasonable correspondence of the abovementioned results may be attributed to the low detection limits used by the two laboratories and the respective techniques used in the analysis of samples. The $P0_4$ concentrations from Abbot & Associates were not comparable with the DWAF and CSIR $P0_4$ concentrations. This difference may be attributed to the detection limit used (0.1mg/l), which is higher than both the CSIR and DWAF detection limits (0.01mg/l and 0.005mg/l of $P0_4$, respectively) and the technique used in the analysis of samples.

From the above laboratory results, it is evident that laboratory errors should always be taken into account when interpreting the final results, because the reliability of the observed $P0_4$ concentration may depend on the analytic method and the instrument used in the analysis of samples.

CHAPTER 7

MODEL CALIBRATION PROCEDURE AND RESULTS

In order to enable the model output to match field observations as close as possible, model parameters of the calibrated models need to be adjusted. The process in which these parameters are adjusted is called calibration. This chapter outlines calibration procedures of selected models and the calibrations results.

7.1 CALIBRATION PROCEDURE

The following criteria were used to measure the goodness-of-fit between simulated and observed monthly phosphorous loads and flows.

- ☆ error in monthly and annual mean
- ☆ error in standard deviation
- ☆ error in seasonal distribution
- ☆ daily and monthly coefficients of determination
- ☆ daily and monthly coefficients of efficiency, and
- ☆ visual inspection.

In the case of the first two criteria (i.e. mean and standard deviation), the objective would be to obtain simulated values that are as close as possible to that of the observed data. The objective functions, mean and standard deviation (STD), do however have severe disadvantages in that they represent aggregate values for the total data set. For instance, severe exceedence of simulated values over observed values for a specific year may well be offset by the simulated values being far lower than the observed values in a subsequent year. This should be kept in mind and visual fitting of both the seasonal distribution and the one-to-one correspondence should be used as further checks. The coefficients of efficiency and determination, should be as close to unity as possible. The abovementioned calibration procedure was implemented in all the models.

7.1.1 Calibration Procedure for the HSPF Model

7.1.1.1 Calibration Procedure for the Hydrology in the Pervious Land Segment

The following calibration procedure for the HSPF hydrology module was proposed by Johanson (1998)

Step 1 Estimate the active groundwater recession parameter (AGWRC) from the observed flow data for the dry period by plotting seven days of data on a semi-log plot for a number of cases. The general equation is:

$$(AGWRC)^7 = Q_o\,(N + 7)/Q_o(N)$$

Where: Q_o is the observed flow.

Step 2 Estimate the interflow recession constant (IRC) parameter from five days of record immediately after a storm event for a number of cases. The general equation is :

$(IRC)^5 = Qo(N + 5)/Qo(N)$.

Step 3 balance the monthly and annual volumes (it is important not to use periods which have missing streamflow data).

The parameters to adjust in the PERLND module are:

- ☆ LZETP : Lower Zone Evapo-Transpiration,
- ☆ LZSN : Lower Zone Nominal Storage,

Compare simulated and observed volumes.

Step 4 Specify the months representing the wet and dry seasons in the study area and calibrate the seasonal distribution. The relevant parameter to adjust is:

- ☆ INFILT : Infiltration rate,

If the model is producing too high dry season flows, then increase INFILT,

If the model is producing too high wet season flows, then decrease INFILT.

Step 5 Calibrate storm events using the interflow parameter (INTFW). If simulated flows are too high in a typical storm event, then increase INTFW and vice versa.

Step 6 If early season storms are under-simulated, then decrease the upper zone nominal storage (UZSN) parameter.

After completing all the steps above, go through steps 3 to 6 to check the water balance. This procedure was followed in the calibration of the model.

Alternatively :

The hydrological calibration could be done using software, HSPEXP, which uses 35 rules, involving 80 conditions, to recommend parameter adjustments. These rules are based on the experience of experts in the use of HSPF model in a wide range of climates and physiographic regions. The rules are divided into four phases (Bicknell, 1997), viz :

- ☆ annual volumes
- ☆ low flows
- ☆ storm flows
- ☆ seasonal flows.

This procedure was not used in this study due to time constraints and the fact that the present version of the software could only operate in Imperial units.

7.1.1.2 Hydraulic Calibration Procedure

Hydraulic results should be calibrated by adjusting values in the FTABLE. The FTABLE specifies values for surface area, reach volume and discharge for a series of selected average depths of water in each reach. When adjusting values in the FTABLE, particular attention should be given to the following:

- ☆ The approximations of the channel geometry which were used to develop the depth/volume relationship.
- ☆ The channel roughness coefficients selected for normal depth calculations.
- ☆ The interpretation and extrapolation of discharge data.

If both the hydrology results and the input data to the FTABLES are reasonable, then little or no hydraulic calibration will be required.

7.1.1.3 Sediment erosion calibration procedure in the pervious land segment

The sediment calibration process follows the hydrological calibration and must precede water quality calibration (Donigian, 1984). Generally, sediment calibration involves the development of an approximate balance between the accumulation and generation of sediment loads on one hand and the washoff or transport of sediment on the other hand. Thus, the accumulated sediment should neither be continually increasing nor decreasing throughout the calibration period.

The guidelines for sediment calibration are as follows:

- ☆ The availability of sediment on the land surface is controlled by the KRER and NVSI parameters. KSER and JSER parameters control the sediment washoff to prevent continually increasing or decreasing sediment on the land surface.

- ☆ Sediment availability for surfaces with high cover factors (COVER) is dominated by daily removal or accumulation of sediments.

- ☆ In order to get approximate balance between the accumulated and generated sediment particles on one hand and the washoff of sediment on the other hand, a balance must be established between the KRER and NVSI parameters, and the KSER and JSER parameters.

- ☆ If available sediment is limiting in a pervious land segment, increasing JRER will tend to increase peak values and reduce low values in the sediment graph. Decreasing JRER will have the opposite effect tending to reduce the variability of simulated results.

- ☆ When available sediment is not limiting in a pervious land segment, JSER will produce the same effect as in d) above.

- ☆ The following parameters receive major consideration during sediment calibration:

  - ◇ the rate at which sediment enters detached storage from the atmosphere (NVSI)
  - ◇ detachment coefficient of the soil matrix dependent on the soil properties (KRER)
  - ◇ coefficient of sediment washoff (KSER).

- ☆ It is recommended that sediment calibration be performed per land use at a time (if data allows), in order to correctly evaluate contributions from each land use (Donigian, 1984).

7.1.1.4 Sediment Transport Calibration Procedure

The following considerations apply to any sediment transport calibration:

- ☆ Since sediment transport processes are strongly linked to hydraulic processes, a sound hydraulic calibration is a necessity for successful simulation of sediment transport.

- ☆ The user must first ensure that sediment erosion is modelled reasonably accurately.

The instream sediment transport is calculated based on the three component fractions of sediment (sand, silt and clay). If sand transport is modelled as a power function of stream velocity, the user can control the process to a certain extent by adjusting the values for the coefficients (KSAND and EXPSND) of the transport equation.

The calibration procedure of the instream sediment transport processes for cohesive sediments (silt and clay) is as follows:

- ☆ Identify periods containing events which have a good fit between observed and simulated flows
- ☆ Identify values of the shear stress (TAU) which are characteristic of periods exhibiting significant suspension of sediment in the historical data
- ☆ Set values of the critical shear stress for erosion (TAUCS) of cohesive sediments which include the period of increased suspended load
- ☆ Select values for critical shear stress for deposition (TAUCD) of cohesive sediments which allow deposition during appropriate periods only
- ☆ Adjust the erodibility coefficient, M, to obtain the best overall correspondence between observed and simulated sediment loads for events with good hydraulic fit.

7.1.1.5 Water Quality Calibration in a Pervious Land Segment

HSPF gives the user the option of using either a more detailed routine, or a general routine, for simulating water quality constituents.

i. Calibration Procedure for General Water Quality Constituents

The calibration procedure of the general water quality constituents or pollutants vary, depending on whether the water quality variable simulated is sediment-associated or flow-associated (it may be associated with surface, interflow or groundwater flow).

Successful calibration of sediment-associated pollutants depends on a satisfactory calibration of sediment washoff. Inconsistent simulations can indicate that sediment is not a transporting mechanism for the particular pollutant or that the potency factors have been incorrectly applied. It is therefore of vital importance to ensure that if sediment is under-simulated, then the pollutant concentration should also be under-simulated and vice versa. If there is no correlation between the shapes of recorded sediment and pollutant concentration graphs, then pollutant transport is not directly linked to sediment transport, hence any adjustment will not impact the simulation. The parameters to adjust in the calibration of sediment-associated constituents are:

- ☆ Washoff potency factor (POTFW), and
- ☆ Scour potency factor (POTFS).

The potency factors are calibrated as follows:

- ◊ They must be adjusted by comparing simulated and observed pollutant concentrations for selected storm events.
- ◊ Storms that are well simulated for both flow and sediment should be used in the calibration of the potency factors.
- ◊ If the pollutant concentration graphs are uniformly low, then the initial values of the potency factors must be increased and vice versa.

ii. Calibration Procedure for Pollutants Related to Overland Flow (SURO)

The calibration procedure of pollutants associated with overland flow is based on three parameters, viz :

- ☆ the pollutant accumulation rate (ACQOP). If simulation of storms following long periods without rain is satisfactory, but too much washoff is simulated for storms occurring in close sequence to earlier storms, then the value of the ACQOP parameter is probably too high and should be adjusted accordingly, and vice versa.

- ☆ the maximum pollutant storage on the land surface (SQOLIM). If too much pollutant washoff is simulated for all storms, the value of SQOLIM is too high and vice versa.

- ☆ the last parameter is washoff rate parameter (WSQOP).

If too much pollutant washoff is simulated for small storms, but not for large storms, the value of WSQOP may be too low.

iii. Calibration Procedure for Pollutants Related to Interflow (IFWO) and Active Groundwater (AGWO)

In the study catchments where pollutants are related to sub-surface flows, the user may assign initial pollutant concentration values for both interflow and active groundwater.

7.1.1.6 Calibration Procedure for Nutrients Only (e.g Phosphorous)

The recommended order and the calibration procedure for nutrients are as follows (Donigian, 1984):

- ☆ use the information available from the literature or field studies to evaluate initial soil nutrient parameters
- ☆ calibrate initial mineralization rates so that annual amounts of plant-available nutrients corresponds to expected values
- ☆ adjust leaching factors based on any data available for a tracer such as chloride
- ☆ adjust plant uptake rates to develop the expected nutrient uptake distribution during the growing season and the estimated total uptake amount expected for the crop
- ☆ adjust nutrient partition coefficients based on the available runoff data
- ☆ refine the leaching, plant uptake and partition parameters based on observed runoff data and the expected sources of nutrient runoff.

7.1.2 Calibration Procedure for the PEM Model

7.1.2.1 Calibration Procedure for the Hydrology

If the observed flow record is used as the input to the model, then no hydrology calibration will be required; if not the Pitman model is used to generate runoff and the general procedure for calibrating the model must be followed.

7.1.2.2 Calibration Procedure for Phosphorous

Calibration of the model to simulate phosphorous export is done by comparing the observed and simulated phosphorous loads. The following steps are recommended:

- ☆ determine the USLE parameter values from topographic maps and/or the literature.
- ☆ if simulated particulate phosphorous is too high, then the parameter PPAR must be decreased or vice versa
- ☆ if simulated soluble phosphorous is too high, then the parameter SPAR must be decreased or vice versa.

Since the focus of this research was on soluble phosphorous, it was only SPAR which was calibrated in the model.

7.1.3 Calibration Procedure for the CWM Model

7.1.3.1 Calibration Procedure for the Hydrology

The model may use either monthly streamflows from the general system analysis models (WRPM and WRYM), or an observed flow record as the input. The system analysis models use the runoff generated by the Pitman model, hence the general calibration procedure for the Pitman model must be followed.

7.1.3.2 Calibration Procedure for Phosphorous

The following procedure is recommended in the calibration of the model to simulate phosphorous export :

- ☆ determine USLE parameters using topographic maps and/or literature
- ☆ get estimates of initial phosphorous parameters associated with different land use categories from the literature
- ☆ if baseflow concentration for a specific land use is too low, then increase parameter alpha (α) for that land use unit or vice versa
- ☆ if surface flow concentration for a specific land use is too low, then increase the parameter beta (β) for that land use unit or vice versa
- ☆ if sediment production from a specific land use is under-simulated, then increase the parameter gamma (γ) for that land use unit.

Since the focus was on soluble phosphorous, it was only parameters α and β which were adjusted in the calibration.

7.2 CWM

The model was applied to the selected pilot catchments in the Western and Eastern Cape.

7.2.1 Model Calibration : Western Cape Catchments

When interpreting the results from the model, the following points must be taken into account:

- ☆ Observed streamflow records were used as the input to the model.
- ☆ The focus of the research was on soluble phosphorous for reasons stated earlier (refer to **Chapter 6**), hence only soluble phosphorous loads are shown in **Table 7.1.**
- ☆ The model allows the user to break down the total flow in the catchment using the SCS curve numbers according to a variety of land use types.
- ☆ The model allows the user to estimate soluble and particulate phosphorous parameters for each land use type.
- ☆ Soluble phosphorous parameters may be calibrated for each land use type in the catchment.

☆ Soluble phosphorous parameters are divided into baseflow (α) and surface flow (β) components.

☆ Universal Soil Loss Equation parameters are estimated per land use type.

Table 7.1 summarises calibration results for the CWM model in the Western Cape catchments.

Table 7.1 Summary of the CWM Model Goodness-of-fit for Calibration in the Western Cape Catchments (Phosphorous Loads Expressed in kg/annum)

Subcatchment	River name	Period (hydrological years)	Mean Annual Observed PO_4 (kg)	Mean Annual Simulated PO_4 (kg)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H028	Twenty-Four Rivers	1984 - 1994	2055	2219	0.893	0.870
G1H029	Leeu	1983 -1994	192	213	0.839	0.808
G1H039	Doring	1983 - 1993	992	828	0.954	0.891
G1H041	Kompanjies	1983 - 1993	1200	1373	0.961	0.927

The Twenty-Four Rivers Catchment

In this catchment, the model overestimated the mean observed soluble phosphorous load by about 8% as shown in **Table 7.1.** and there is a reasonable statistical comparison between the observed and simulated soluble phosphorous loads.

Figure 7.1(A) shows that the model could mirror most of the changes in the observed data set. In most of the events throughout the calibration period, the model reproduced both the falling and rising limbs of the observed pollutograph successfully. As shown in **Figure 7.1(A)**, the model could not reproduce baseflow events successfully. These events were slightly overestimated.

The observed unpatched soluble phosphorous data in **Figure 7.1,** represents phosphorous data analysed from one, two, three and/or four samples per month, depending on the sampling frequency in the catchment

The Leeu River Catchment

There is reasonable correlation between the mean observed and simulated soluble phosphorous loads. The statistical comparison is also reasonable as shown in **Table 7.1**.

There is a similar pattern between the observed and simulated soluble phosphorous loads with most of the peaks and troughs roughly superimposed. Most of the wet months were slightly overestimated and the dry months were reproduced successfully, as shown in **Figure 7.1(B)**.

Both the rising and falling limbs of the observed pollutograph were reproduced successfully.

The Doring River Catchment

A reasonable comparison was achieved between the mean observed and simulated soluble phosphorous loads. The statistical comparison was also reasonable as shown in **Table 7.1**.

The model reproduced most of the events as shown in **Figure 7.1(C).** Both the rising and falling limbs of the observed pollutograph were reproduced consistently throughout the calibration period. Some of the dry months were slightly underestimated and this resulted in the mean observed load being underestimated by about 17%. The model could not reproduce the 1989 event completely.

The Kompanjies River Catchment

A reasonable comparison was achieved between the mean observed and simulated soluble phosphorous loads. As shown in **Table 7.1**, the statistical comparison is also reasonable. The model overestimated the mean observed load by about 15%.

Figure 7.1(D) shows that, the model reproduced most of the patterns in the observed data sets. Both the rising and falling limbs of the observed pollutograph were reproduced consistently throughout the calibration period. Most of the dry months were simulated successfully, whereas some of the wet months were slightly overestimated.

Generally, the CWM model was successfully calibrated for the Western Cape catchments. However, a relevant question is whether or not the CWM model calibration parameters are transferrable. This question is addressed later.

7.2.2 Model Calibration : Eastern Cape Catchments

Table 7.2 summarises the calibration results for the Eastern Cape catchments.

Table 7.2 Summary of the CWM Model Goodness-of-fit for Calibration in the Eastern Cape Catchments (Phosphorous Loads Expressed in kg/annum)

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
R2H001	Upper Buffalo	1983-1985	170	151	0.931	0.921
R2H008	Cwencwe	1983-1985	140	133	0.973	0.961
R2H011	Yellowwoods	1983-1985	337	290	0.976	0.962
R3H001	Gqunube	1983-1994	605	532	0.935	0.931

The Upper Buffalo River Catchment

Reasonable correlation was achieved between observed and simulated soluble phosphorous loads. The observed load was underestimated by about 13% as shown in **Table 7.2.** The statistical comparison between the observed and simulated loads is also reasonable.

The model reproduced most of the events, with the exception of the 1985 event, in the observed data sets. The baseflow events were reproduced successfully (refer to **Figure 7.2(A)**), whereas high flow events were not reproduced successfully.

The Cwencwe River Catchment

The correlation between mean observed and simulated soluble phosphorous load is reasonable (refer to **Table 7.2**). The difference between the mean observed and simulated phosphorous load is negligible.

Figure 7.2(B), shows a similar pattern between the observed and simulated soluble phosphorous loads with most of the peaks and troughs roughly superimposed. Most of the events, both dry and wet period events, were successfully simulated. Almost all the falling and rising limbs of the observed pollutograph, were reproduced successfully.

The Yellowwoods River Catchment

The model underestimated the mean observed soluble phosphorous load by about 8% (refer to **Table 7.2).** The statistical comparison between the observed and simulated loads was reasonable.

The model could mirror most of the changes in the observed data sets as shown in **Figure 7.2(C)**. The baseflow events were undersimulated, whereas high flow events were simulated successfully (see **Figure 7.2(C)**).

The Gqunube River Catchment

There is reasonable agreement between the observed and simulated soluble phosphorous loads, with reasonable statistical comparison. The model underestimated the mean observed load by about 10% (refer to **Table 7.2**).

As show in **Figure 7.2(D)**, the model could mirror almost all the changes in the observed data sets with most of the troughs and peaks superimposed. Both the rising and falling limbs of the observed pollutograph were reproduced successfully. Most of the wet and dry period events were simulated successfully.

Generally, CWM was calibrated successfully for the Eastern Cape catchments.

7.3 PEM

The model was applied to the selected pilot catchments. It was applied in both lumped and distributed parameter format. No significant differences were discernable between the lumped and distributed approaches. Therefore, only the calibration results of the lumped case are shown.

7.3.1 Model Calibration : Western Cape Catchments

When interpreting the results, the following points must be taken into account:

- ☆ Observed streamflow records were used as the input to the model
- ☆ The focus of the research was on soluble phosphorous due to lack of observed total phosphorous data in some of the study catchments.
- ☆ The model does not allow the user to break down the total flow in the catchment according to contributions from the different land use types, even if the model is applied to the catchment as a distributed parameter model
- ☆ The model does not allow the user to estimate soluble and particulate phosphorous parameters for each land use type in the catchment
- ☆ There is one calibration parameter for soluble phosphorous and another for particulate phosphorous representing all the land use types in the catchment
- ☆ Universal Soil Loss Equation parameters are estimated per land use type
- ☆ The soluble phosphorous (SPAR) parameter represents only the surface flow component, because in the development of PEM, the contribution from the sub-surface drainage was ignored (Weddepohl *et al.*,1992).

Table 7.3 is a summary of PEM calibration results for the study catchments representing the Western Cape conditions.

Table:7.3 Summary of the PEM Model Goodness-of-fit for Calibration in the Western Cape Catchments (Phosphorous Loadings Expressed in kg/annum)

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Coefficient of determination (r^2)	Coefficient of efficiency
G1H028	Twenty-Four Rivers	1984-1994	2055	2163	0.924	0.914
G1H029	Leeu	1983-1994	192	185	0.975	0.974
G1H039	Doring	1982-1994	992	1018	0.992	0.987
G1H041	Kompanjies	1980-1994	1200	1178	0.932	0.925

The Twenty-Four Rivers Catchment

The model overestimated the mean observed soluble phosphorous load by about 6%. This is because the model could not reproduce the 1994 event. In general, there is a reasonable correlation between the mean observed and simulated soluble phosphorous loads with reasonable statistical comparison as shown in **Table 7.3.**

Figure 7.3(A), shows a similar pattern between the observed and simulated soluble phosphorous loads with most of the peaks and troughs roughly superimposed. There is only one peak recorded in June 1994 which the model could not reproduce. There is no clarity on why the model could not mirror the peak. In most of the events throughout the calibration period, the model reproduced both the falling and rising limbs of the observed pollutograph successfully.

The observed unpatched soluble phosphorous data in **Figure 7.3**, represents phosphorous data analysed from one , two, three and/or four samples per month, depending on the sampling frequency in the catchment. In most of the cases, four samples were collected per month. The sampling frequency was relatively similar, with four samples collected in most of the months in the Western Cape catchments.

The Leeu River Catchment

As shown in **Table 7.3**, there is a negligible difference between the mean observed and simulated soluble phosphorous loads. The statistical comparison between the loads is reasonable.

Figure 7.3(B), shows that the model reproduced almost all the observed events, with the peaks and troughs roughly superimposed. The rising and falling limbs of the observed pollutographs were consistently reproduced throughout the simulation period.

The Doring River Catchment

There is reasonable correlation between the mean observed and simulated soluble phosphorous loads with about 1.2% difference and reasonable statistical comparison.

As shown in **Figure 7.3(C)**, there is a similar pattern between the observed and simulated soluble phosphorous loads, with most of the peaks and troughs superimposed. The model could not reproduce the biggest event recorded in 1993. It is unclear why the model could not reproduce the 1993 event. The model reproduced both the falling and rising limbs through out the calibration period.

The Kompanjies River Catchment

The correlation between the mean observed and simulated soluble phosphorous loads, and the statistical comparisons between the loads are reasonable. The model underestimated the mean observed soluble phosphorous load by about 2.2%, as shown in **Table 7.3**.

Figure 7.3(D) shows that, the model reproduced most of the big events between 1984 and 1994 and could not reproduce completely, some of the events between 1980 and 1984. Both the rising and falling limbs of the observed pollutograph were reproduced consistently throughout the calibration period.

Generally, PEM performed well for the Western Cape catchments. However, it should be recognized that as PEM is driven by observed flows, and as the calibration process has a "*black-box*" character (i.e. calibration involves only one parameter and the catchment processes are not distinguished), achieving a reasonable goodness-of-fit during calibration is not difficult. A relevant question is whether or not the PEM model calibration parameters are transferrable. This question is addressed later in the thesis.

7.3.2 Model Calibration : Eastern Cape Catchments

Table 7.4 summarises PEM calibration results for the catchments representing the Eastern Cape conditions.

Table 7.4 Summary of the PEM Model Goodness-of-fit for Calibration in the Eastern Cape Catchments (Phosphorous Loadings Expressed in kg/annum)

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
R2H001	Upper Buffalo	1983-1985	170	187	0.937	0.932
R2H008	Cwencwe	1983-1986	140	136	0.964	0.963
R2H011	Yellowwoods	1983-1985	337	248	0.927	0.888
R3H001	Gqunube	1983-1994	604	565	0.978	0.977

The Upper Buffalo River Catchment

A reasonable correlation between the mean observed and simulated soluble phosphorous loads was achieved in this catchment. The statistical comparison between the mean observed and simulated loads was also reasonable.

Figure7.4(A), shows that the model could mirror most of the baseflow changes in the observed data sets. The 1984 and 1985 events, were reproduced with a slight overestimation and underestimation, respectively. The model reproduced rising limbs of the observed pollutograph throughout the calibration period. In contrast, it was not all the falling limbs of the observed pollutograph (e.g. the falling limb in the 1986 event) which were reproduced successfully.

The observed unpatched soluble phosphorous data in **Figure 7.4**, represents phosphorous data analysed from one, two, three and/or four samples per month, depending on the sampling frequency in the catchment. In most of the cases, four samples were collected per month.

The sampling frequency was relatively similar, with four samples collected in most of the months, in the Eastern Cape catchments.

The Cwencwe River Catchment

The mean observed and simulated soluble phosphorous loads show a reasonable correlation. The statistical comparison between the mean observed and simulated soluble phosphorous is also reasonable.

Figure 7.4(B) shows that the simulated and measured soluble phosphorous loads have similar or nearly identical time varying patterns in that almost all the simulated peaks and troughs are superimposed. It is only two events (i.e. the 1983 events) which the model could not reproduce completely. The big event, which was recorded in 1985, was reproduced successfully.

Both the rising and falling limbs of the observed pollutograph have been reproduced successfully throughout the calibration period.

The Yellowwoods River Catchment

In this catchment, the model underestimated the mean observed soluble phosphorous load by about 29%, as shown in **Table 7.4**.

As shown in **Figure 7.4(C)**, the model reproduced almost all the big events within the calibration period. The rising limbs of the observed pollutograph for the big events were reproduced successfully, whereas the falling limbs were reproduced with success in the 1983 and 1984 events, and not in the 1980 event. The time varying patterns between the observed and simulated soluble phosphorous loads during dry periods are similar, but the peaks could not be superimposed. This was a surprise in the light of the successful calibrations in the previous catchments. This surprising difference may be attributed to the inaccuracies in the routine for infilling the observed soluble phosphorous data.

The Gqunube River Catchment

There is reasonable comparison between the mean observed and simulated soluble phosphorous loads. The statistical comparison is also reasonable as shown in **Table 7.4**.The observed and simulated soluble phosphorous loads show a similar or nearly identical time varying patterns in that both the simulated peaks and troughs are superimposed as shown in **Figure 7.4(D)**.

Both the rising and falling limbs of the observed pollutograph were reproduced successfully throughout the calibration period.

Generally, PEM was successfully calibrated for the Eastern Cape catchments, with the exception of the Yellowwoods River catchment. However, a relevant question is whether or not the calibration parameters are transferrable. This question is addressed later in the thesis.

7.4 HSPF

The model was configured for all the study catchments and calibrated for streamflow. The streamflow calibration results were not encouraging. HSPF was designed to operate at an hourly or multi-hourly time interval, with the maximum number of hours being 24 hours. In most of the South African catchments, rainfall is measured on a daily basis and not on an hourly basis. If the modeller provides daily rainfall as the input, this quantity of rainfall would be distributed equally over 24 hours. This might not be true in practice, because it is rare to record the same quantity of rainfall every hour for a period of 24 hours.

7.4.1 Model Calibration : Western Cape Catchments

Table 7.5 summarises the model goodness-of-fit in for the Western Cape catchments.

Table 7.5 Summary of the HSPF Model Goodness-of-fit for Calibration in the Western Cape Catchments

Sub-catchment	River name	Period (hydrological years)	Mean Observed Runoff ($M.m^3$/ annum)	Mean Simulated Runoff ($M.m^3$/ annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H039	Doring	1982 to 1986	1.99	1.60	0.340	0.334
G1H028	Twenty-Four Rivers	1983 to 1987	118.97	84.06	0.22	-1.12
G1H029	Leeu	1983 to 1987	17.26	4.46	0.128	-0.25
G1H041	Kompanjies	1980 to 1984	23.18	13.31	0.083	-0.009

The Doring River Catchment

There is fairly reasonable agreement between the mean observed and simulated runoff for the selected calibration period, but poor statistical correlation. This might be attributed to the fact that HSPF was designed to operate on an hourly time step and require hourly data. The use of daily rainfall as the input instead of the average rainfall for 24 hours, might have had an impact on the simulated runoff, because the model distributes the daily rainfall into equal quantities of hourly rainfall for 24 hours. This might result in an overestimation or underestimation of rainfall in most of the hours, hence high runoff would be produced as shown in **Figure 7.5(C)**. **Figure 7.5(C)**, which represents 1983 events, shows that the model reproduced most of the events, but underestimated some peaks.

It is therefore, evident that with the availability of hourly rainfall data, better results might be obtained. The calibration procedure outlined earlier was followed, but could not produce reasonable results. This was an indication that even if the modeller follows the procedure, the modeller would be expected to have an extensive knowledge of the algorithms. Much time and effort was spent trying to refine the model parameters in this catchment.

A further attempt was made to calibrate the model for the Twenty-Four Rivers catchment which is located on the Eastern side of the Berg River.

The Twenty-Four Rivers Catchment

The statistical comparison between the observed and simulated mean runoff was poor as shown in**Table 7.5.** This could also be attributed to the reasons stated above. **Figure 7.5(A)** shows that the model overestimated almost all the peaks in the observed data set. The model could not reproduce both the rising and falling limbs of the observed hydrograph. The author decided to make a further attempt on a smaller catchment adjacent to the Twenty-Four Rivers catchment (i.e. the Leeu River catchment).

The Leeu River Catchment

The results in this catchment were also not promising as shown in **Table 7.5.** The statistical comparison was very poor and **Figure 7.5(B)** shows that the model could not mirror the changes in the observed data set. This could also be attributed to lack of representative hourly rainfall data. The last attempt was made in the Kompanjies River catchment, which is located on the western side of the Berg River.

The Kompanjies River Catchment

The results were also poor in this catchment. These poor results could be attributed to the reasons stated earlier. The model could not reproduce most of the events in the observed data set as shown in **Figure 7.5(D)**. It is quite evident from **Figure 7.5(D)** that lack of rainfall stations within the catchment boundaries had an impact on the simulated runoff.

Generally, the model was not successfully calibrated for the Berg River catchments. There is only one case, the Doring River catchment, where the model showed promise that if the relevant data (i.e. hourly data) was available coupled by the extensive knowledge of the algorithms, better calibration results could be achieved.

7.4.2 Model Calibration : Eastern Cape Catchments

A further attempt was made to calibrate HSPF in the Eastern Cape catchments. Model goodness-of-fit is summarised in **Table 7.6.**

Table 7.6 Summary of the HSPF Model Goodness-of-fit for Calibration in the Eastern Cape Catchments

Sub-catchment	River name	Period (hydrological years)	Mean Observed Runoff (Mm^3 /annum)	Mean Simulated Runoff ($M.m^3$/ annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
R3H001	Gqunube	1980 to 1981	3.87	4.45	0.465	0.448
R2H011	Yellowwoods	1981 to 1984	1.34	2.58	0.311	-0.989
R2H008	Cwencwe	1981 to 1983	1.37	0.45	0.207	-2.518
R2H001	Upper Buffalo	1981 to 1983	6.14	2.60	0.0	-1.262

The Gqunube River Catchment

The correlation between the observed and simulated runoff as shown in **Figure 7.6(D)** is promising. **Figure 7.6(D)**, which represents 1985 events, shows some promise that with the availability of hourly rainfall, coupled with extensive knowledge of the algorithms, the model might produce reasonable results.

The Yellowwoods River Catchment

The results show some promise that with the relevant rainfall data, the model could produce reasonable results. **Figure 7.6(C)**, which represents 1984 events, show that better results could be obtained if the hourly rainfall data was available.

The Cwencwe River Catchment

The model could not mirror most of the changes in the observed data set, but show promise that with the availability of the hourly rainfall, reasonable results might be achieved. **Figure 7.6(B)**, which represents 1985 events, show promise that with the availability of hourly rainfall data, better results might be achieved.

The Upper Buffalo River Catchment

The results in this catchment were not encouraging. There is no correlation between the mean observed and simulated runoff, hence the model could not mirror the changes in the observed data set. **Figure 7.6(A)**, which represents 1983 events, shows that the model could not reproduce every event. Since runoff is a primary driving factor of the water quality component of the model, water quality parameters for the study catchments could not be calibrated given the poor fit of simulated runoff. Hence, the investigation into HSPF was abandoned, and in its place, the ACRU daily phosphorous yield model was incorporated in this study.

7.5 ACRU MODEL VERIFICATION

The ACRU phosphorous yield model (refer to **Chapter 4, Section 4.4**) was included at a late stage of the research to explore the recently developed phosphorous component of the model. Due to time and budget constraints the model was configured and verified only for the Western Cape catchments.

When evaluating the results in **Table 7.7** and the corresponding figures, it is necessary to bear in mind the following:

☆ Unlike PEM, HSPF and CWM, the ACRU agrohydrological model is not a parameter fitting or optimising model and parameters are, by and large, supposed to be estimated from the physical characteristics of the catchment. The results in **Tables 7.7** were based on parameters which were not adjusted to improve the correlation between observed and simulated runoff.

☆ Rainfall stations used to generate runoff in all the catchments given in **Table 7.7**, are located outside the catchment boundaries. Some of the rainfall stations are in high- lying areas, while others are outside the catchment boundaries. This would obviously affect the runoff produced by the model in one way or another.

Table 7.7 Summary of the ACRU Model Goodness-of-fit in Terms of Runoff (unadjusted parameters)

Sub-catchment	River name	Period (hydrological years)	Mean Observed Runoff (M.m³/ annum)	Mean Simulated Runoff (M.m³/ annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H028	Twenty-Four Rivers	1980-1996	126.6	64.08	0.45	0.24
G1H029	Leeu	1980-1995	17.84	10.30	0.48	0.35
G1H039	Doring	1980-1994	1.90	2.70	0.34	-0.03
G1H041	Kompanjies	1983-1988	26.31	36.61	0.48	0.26

The Twenty-Four Rivers Catchment

The driver rainfall station is located in a low-lying area more than 20km outside the catchment boundary and was also adjusted to be representative of the catchment rainfall in the standard way encorded in ACRU.

The model could reproduce the patterns in the observed hydrograph as shown in **Figure 7.8(A)**, but under-simulated almost all the events. This under-simulation could be attributed to the rainfall data.

The Leeu River Catchment

The driver station data used in the Twenty-Four Rivers catchment was adjusted according to the catchment mean annual rainfall and used for modelling. The model reproduced the patterns in the observed time series as shown in **Figure 7.8(B)**, but under-simulated most of the wet months. Unlike in the Twenty-Four Rivers catchment, which is more than four times larger in size, the degree of under-simulation was less with a correlation coefficient of 48%.

The Doring River Catchment

The driver rainfall station used for modelling is located in a high-lying area outside the catchment boundary and its data was adjusted according to the catchment mean annual rainfall to be representative of the catchment rainfall. The adjusted rainfall data still produced high runoff, exceeded the mean observed runoff (see **Figure 7.8(C)**).

The Kompanjies River Catchment

The driver stations are located in high-lying areas near the catchment boundary and their data were adjusted using the catchment mean annual rainfall to be representative of the catchment rainfall. Despite the adjusted rainfall data, the model still produced high runoff with most of the events being overestimated as shown in **Figure 7.8(D)**.

Since runoff is the primary driving factor of the water quality constituents, poor fit of simulated runoff would obviously lead to poor fit of simulated soluble phosphorous loads.

It was therefore decided to adjust some of the parameters in the ACRU agrohydrological model in order to obtain reasonable estimates of the soluble phosphorous loads. **Table 7.8** summarises parameters which were adjusted in order to obtain a reasonable comparison between the mean observed and simulated runoff.

Table 7.8 Summary of the Adjusted Parameters in the ACRU Agrohydrological Model

Sub-catchment	River name	Adjusted Parameters
G1H028	Twenty-Four Rivers	[1]DEPAHO, [2]DEPBHO, [3]COFRU
G1H029	Leeu	DEPAHO, DEPBHO
G1H039	Doring	DEPAHO, DEPBHO
G1H041	Kompanjies	DEPAHO, DEPBHO

[1]DEPAHO :- thickness of the topsoil of the soil profile
[2]DEPBHO :- thickness of the subsoil of the soil profile
[3]COFRU :- coefficient of baseflow response

Model goodness-of-fit for adjusted parameters is summarised in **Table 7.9**.

Table 7.9 Summary of the ACRU Model Goodness-of-fit in Terms of Runoff (adjusted parameters)

Sub-catchment	River name	Period (hydrological years)	Mean Observed Runoff ($M.m^3$/ annum)	Mean Simulated Runoff ($M.m^3$/ annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H028	Twenty-Four Rivers	1980-1996	126.6	78.97	0.465	0.344
G1H029	Leeu	1980-1995	17.84	13.45	0.586	0.527
G1H039	Doring	1980-1994	1.90	2.10	0.306	0.078
G1H041	Kompanjies	1983-1988	26.31	28.73	0.359	0.186

The Twenty-Four Rivers Catchment

The depths of both the subsoil and topsoil were reduced from 250mm to 150mm and 150mm to 50mm, respectively, and the coefficient of baseflow response was also reduced from 2% to 1%. This resulted in an improved correlation between the mean simulated and observed runoff as shown in **Table 7.9**.

The Leeu River Catchment

The depths of the subsoil and topsoil were reduced from 250mm to 150mm and 150mm to 50mm, respectively, to obtain improved correlation between the simulated and observed mean runoff.

The Doring River Catchemnt

The depth of the subsoil was increased from 800mm to 1020mm to obtain an improved comparison between the mean observed and simulated runoff as shown in **Table 7.9.** The depth of the topsoil was not increased.

The Kompanjies River Catchment

The depths of both the topsoil and subsoil were increased from 250mm to 400mm and 400mm to 600mm, respectively, to obtain improved correlation between the mean observed and simulated runoffs.

Table 7.10 summarises the model goodness-of-fit in terms of phosphorous yield.

When evaluating the results in **Tables 7.10** and the corresponding figures, it is necessary to bear the following in mind:

☆ **The focus of this research was on soluble phosphorous, due to a lack of observed total phosphorous data in some of the study catchments**. The soluble and adsorbed phosphorous loads generated from the ACRU phosphorous yield model are catchment delivered. Once in the streams one can assume that the liquid to solid ratios are high enough that most of the adsorbed phosphorous would desorb and go into solution. So if the measured data comprises stream sampled soluble phosphorous, one should ideally add the dissolved and adsorbed phosphorous loads from the model and compare these with measured loads (Lorentz, 2000). Observed soluble phosphorous loads were compared with the sum of the dissolved and adsorbed phosphorous loads from the model in **Table 7.10** and **Figures 7.9 (A-D).**

☆ Since the ACRU phosphorous yield model is still under development and has been applied to the Mgeni catchment only, it was incorporated into this study as part of its exploratory development.

☆ The ACRU phosphorous yield model is not a parameter-fitting or optimising model and input parameters are, by and large, estimated from the physical characteristics of the catchment. The algorithm for estimating a constant in the adsorption isotherm(PADC) and maximum sorbed concentration(PADM) in the adsorption isotherm for soils in each land use was not available from the developers of the model (i.e.University of Natal, Pietemaritzburg). These parameters were estimated with reference to the isotherm parameters from the Mgeni Study (Kienzle,1997).

☆ Since the model does not have particular routines for simulating phosphorous yield from areas dominated by wheat and grapes, the routines for simulating phosphorous yield from areas dominated by maize and sugarcane were used, respectively.

☆ Phosphorous from natural vegetation, grassland and forestry was assumed to be a result of both dry and wet atmospheric depositions, hence dry and wet deposition parameters were estimated with reference to the parameters used in the Mgeni Study (Kienzle,1997).

Table 7.10 Summary of the ACRU Model Goodness-of-fit in Terms of Phosphorous

Sub-catchment	River name	Period (hydrological years)	Mean Observed Soluble Phosphorous (kg/annum)	Mean Simulated Phosphorous (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H028	Twenty-Four Rivers	1984 to 1994	2055	905	0.29	0.082
G1H029	Leeu	1983 to 1994	192	154	0.29	-0.25
G1H039	Doring	1983 to 1988	751	25	0.292	0.040
G1H041	Kompanjies	1983 to 1988	1074	299	0.41	0.23

Because the algorithm for estimating land use parameters PADM and PADC in the isotherm equation, was not available these parameters had to be estimated with reference to parameters used in the Mgeni study. The results for each catchment are discussed below:

The Twenty-Four Rivers Catchment

The model under-simulated the observed loads. This was expected, because the driving factor of the water quality component of the model is the simulated runoff, which was also under-simulated due to a lack of representative rainfall data. Despite the under-simulation, the model shows promise (refer to **Figure 7.9 (A)**) that it could predict reasonable soluble phosphorous loads.

The Leeu River Catchment

The model under-simulated some of the peak events. This was expected because the simulated runoff peak events were also under-simulated. A comparison between observed and simulated soluble phosphorous loads in **Figure 7.9 (B)**, show promise that the model is capable of predicting reasonable soluble phosphorous loads.

The Doring River Catchemnt

The relationship between observed and simulated soluble phosphorous loads is shown in **Figure 7.9 (C)**. This relationship does not show promise that the model could perform well in catchments with low runoff coefficients. Unlike the other three Western Cape catchments, the Doring River catchment is the only one with low a runoff coefficient (refer to **Tables 5.1 and 7.9**). In the model, sediment production is driven by the storm volume for the event. In this catchment, very low sediment loads were produced resulting in relatively low adsorbed phosphorous loads. Generally, the model produced low soluble phosphorous loads. Since relatively low adsorbed as well as dissolved phosphorous loads were produced, the sum would obviously be low (refer to **Table 7.10** and **Figure 7.9(C)**).

The Kompanjies River Catchment

A comparison between observed and simulated soluble phosphorous loads in **Figure 7(D)**, show promise that the model could produce reasonable loads if the perfect fit is achieved in the runoff simulation.. Unlike most of the peak events, the peak event for 1986 was highly under-simulated. This was expected because the runoff event for the same period was also under-simulated.

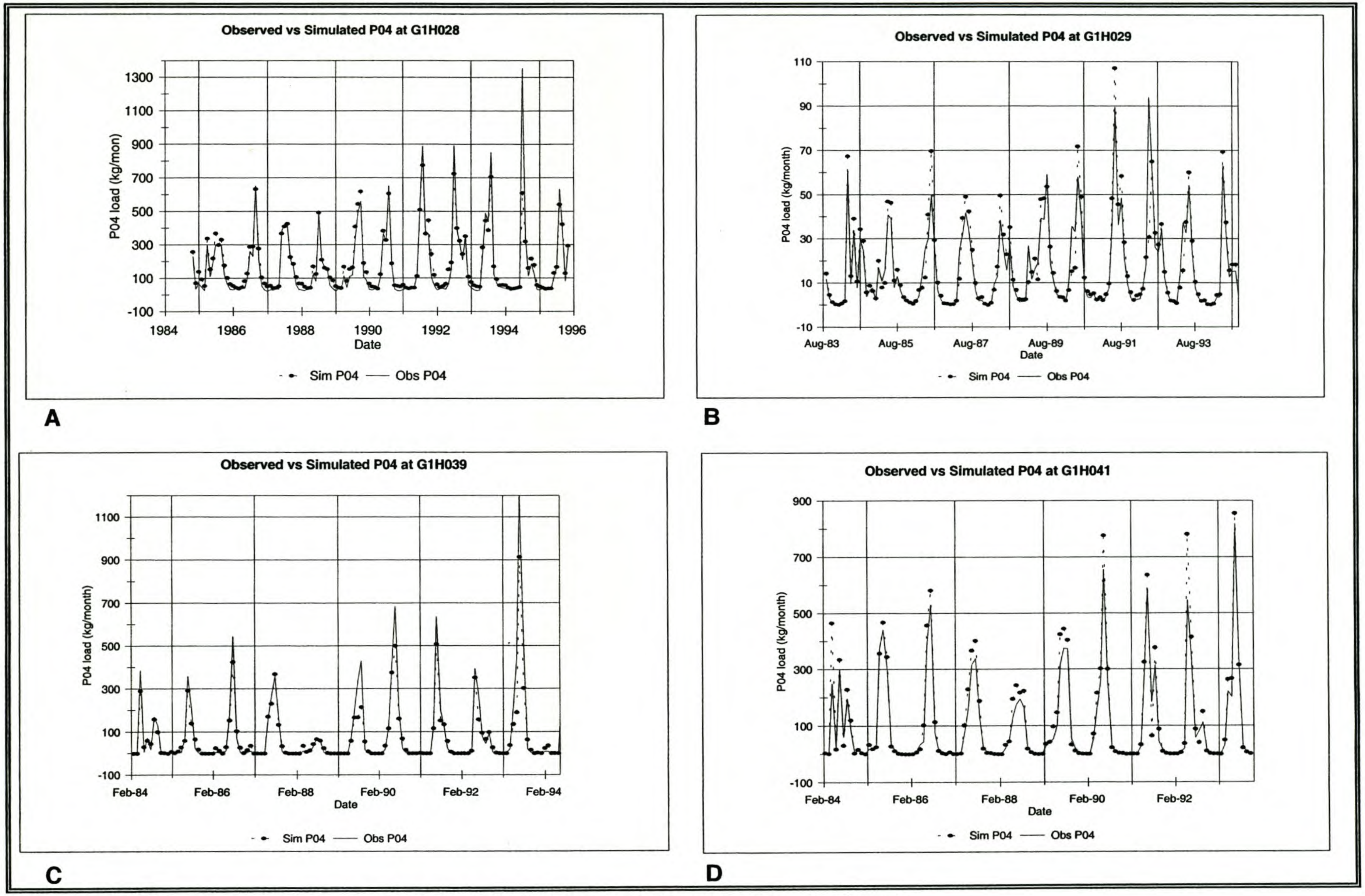


Figure 7.1 : The Goodness-of-fit for the CWM Model Calibration in the Western Cape Catchments

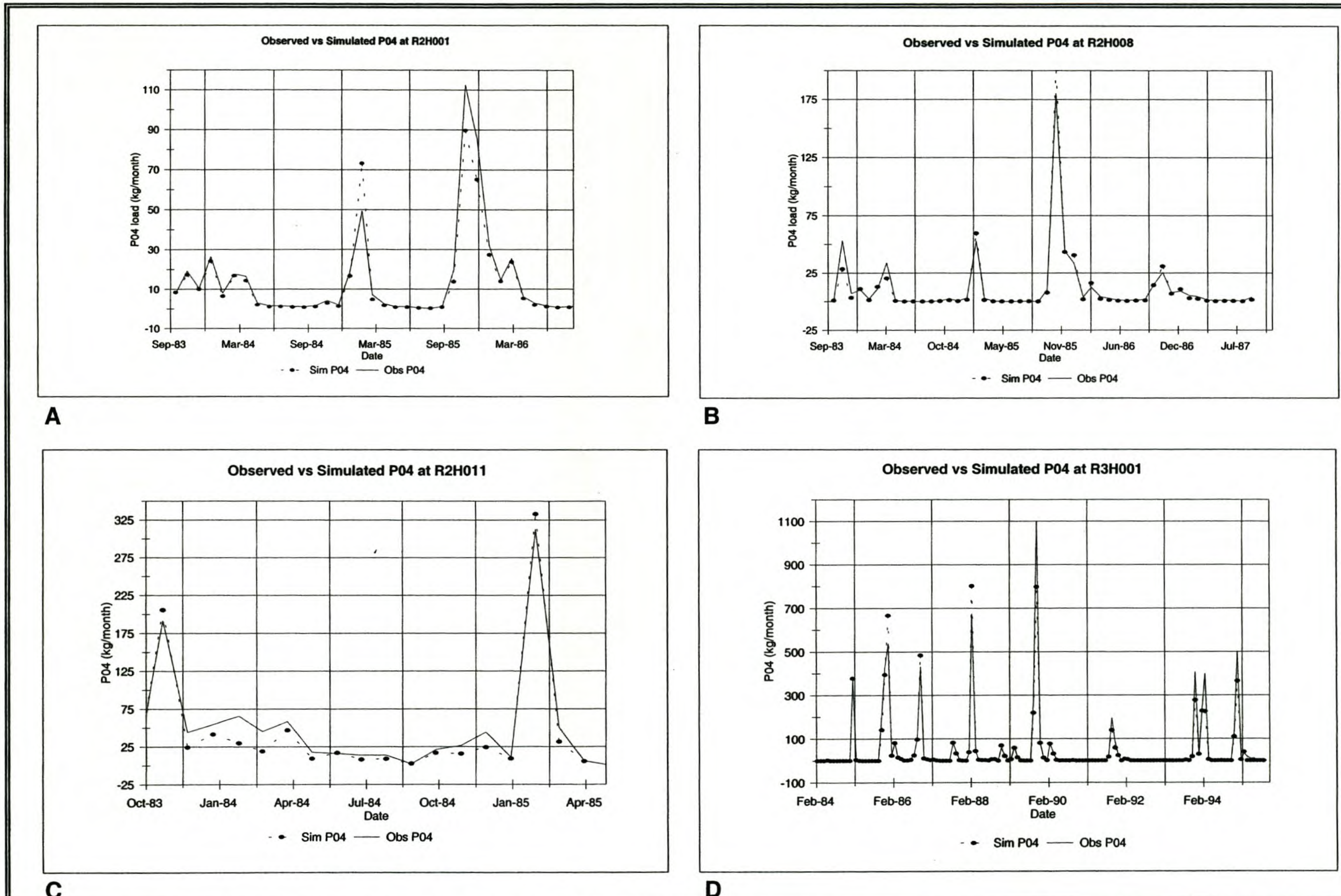


Figure 7.2 : The Goodness-of-fit for the CWM Model Calibration in the Eastern Cape Catchments

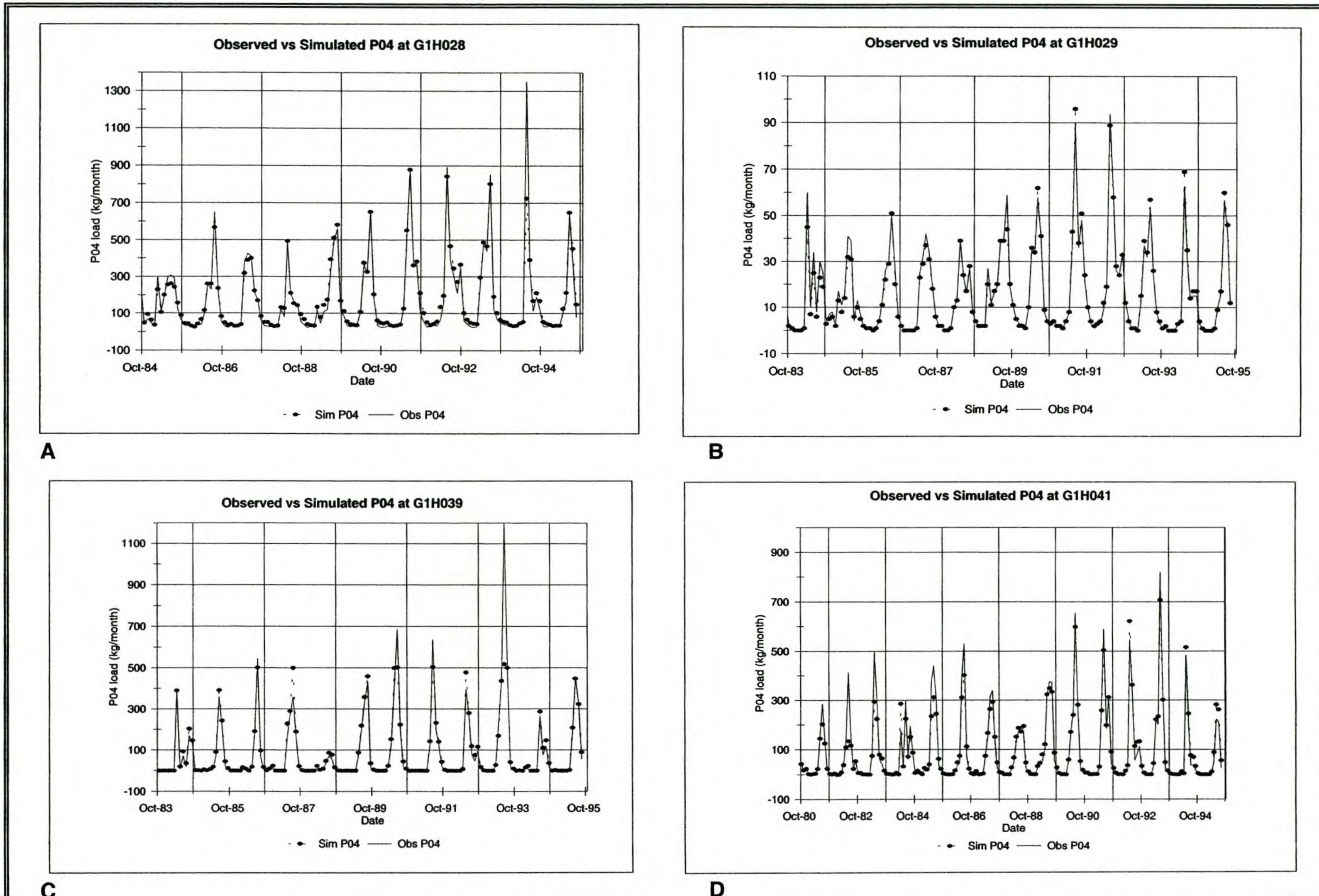


Figure 7.3 : The Goodness-of-fit for the PEM Model Calibration in the Western Cape Catchments

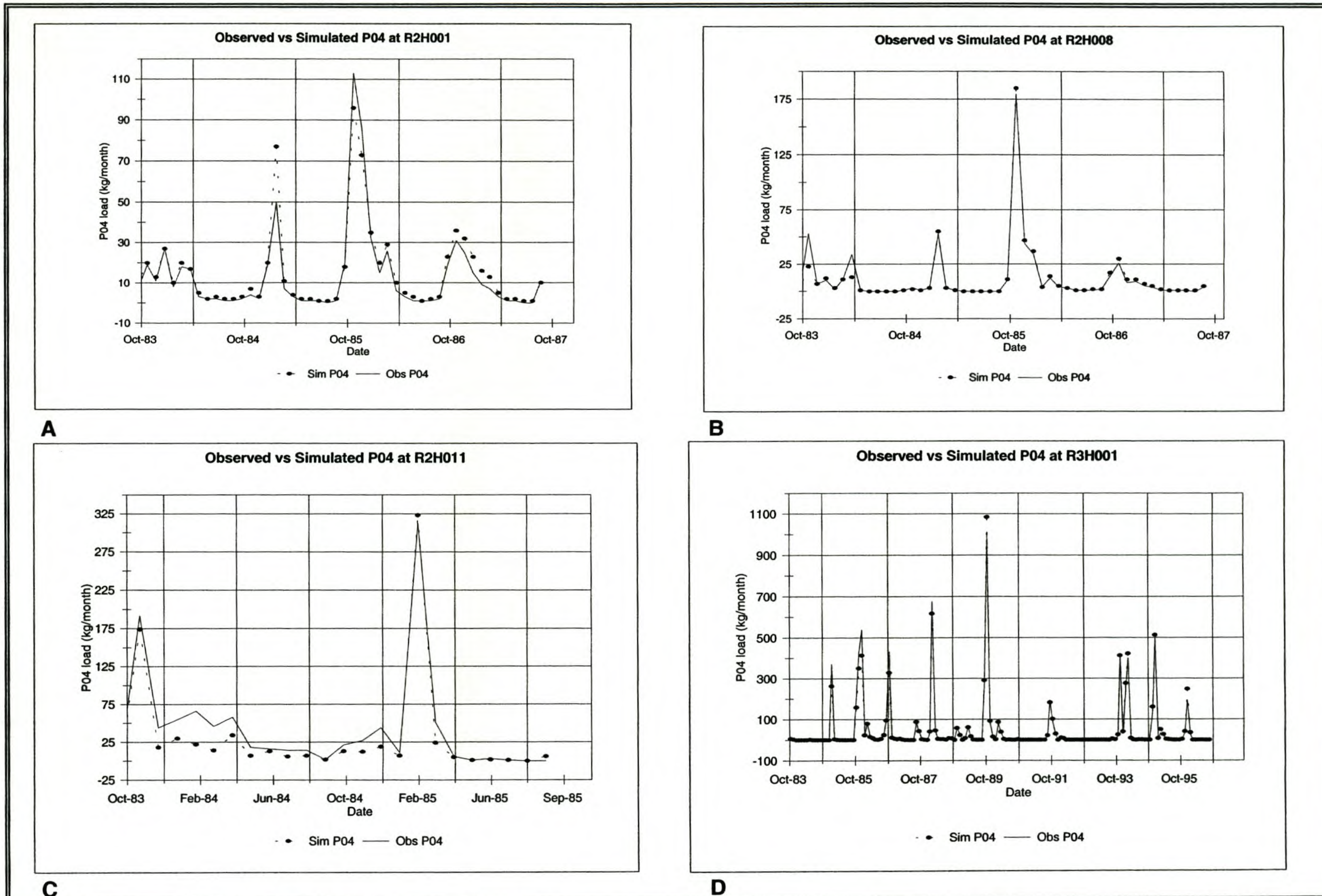


Figure 7.4 : The Goodness-of-fit for the PEM Model Calibration in the Eastern Cape Catchments

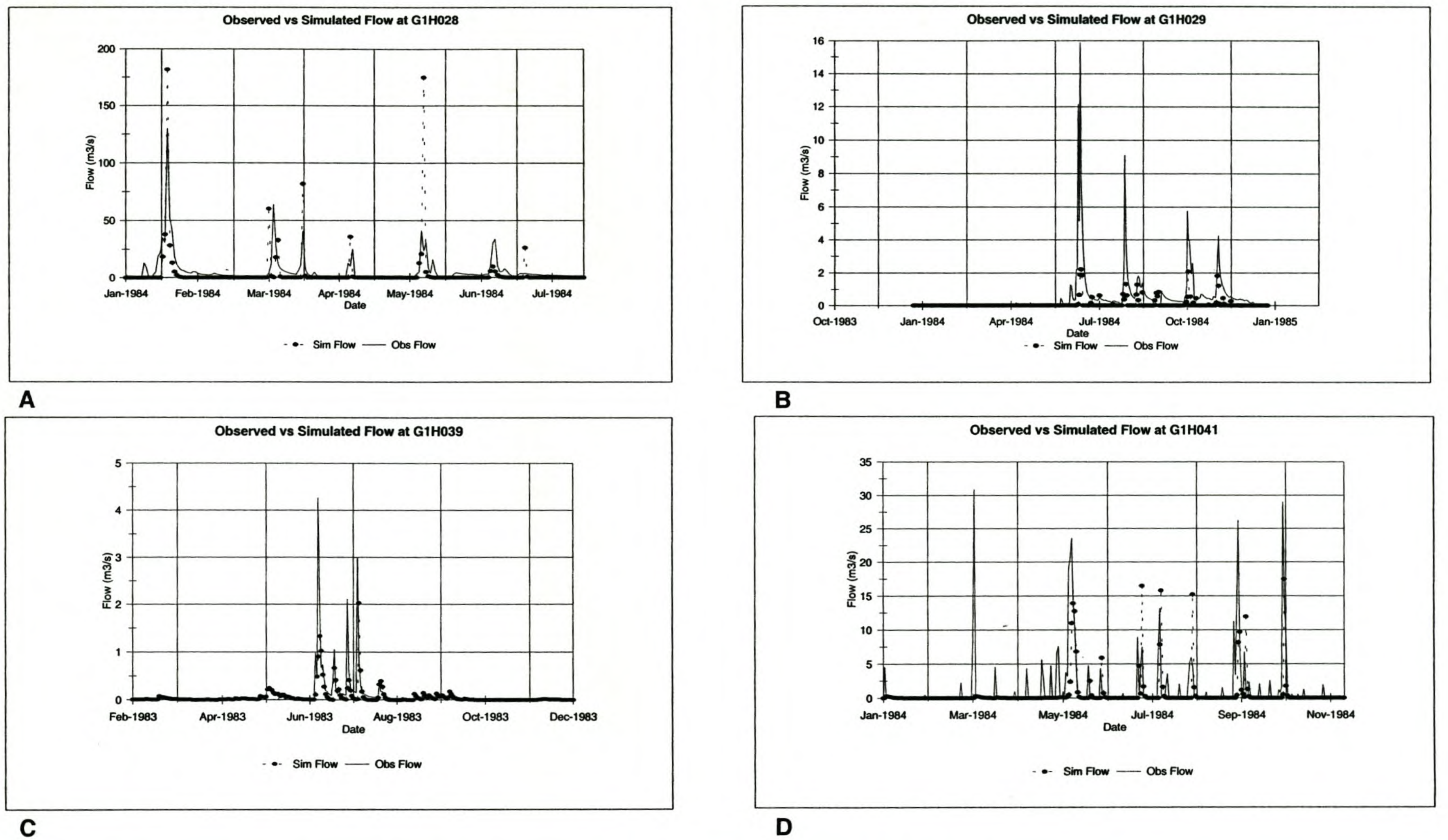


Figure 7.5 : The Goodness-of-fit for the HSPF Model Calibration in the Western Cape Catchments (Selected Events)

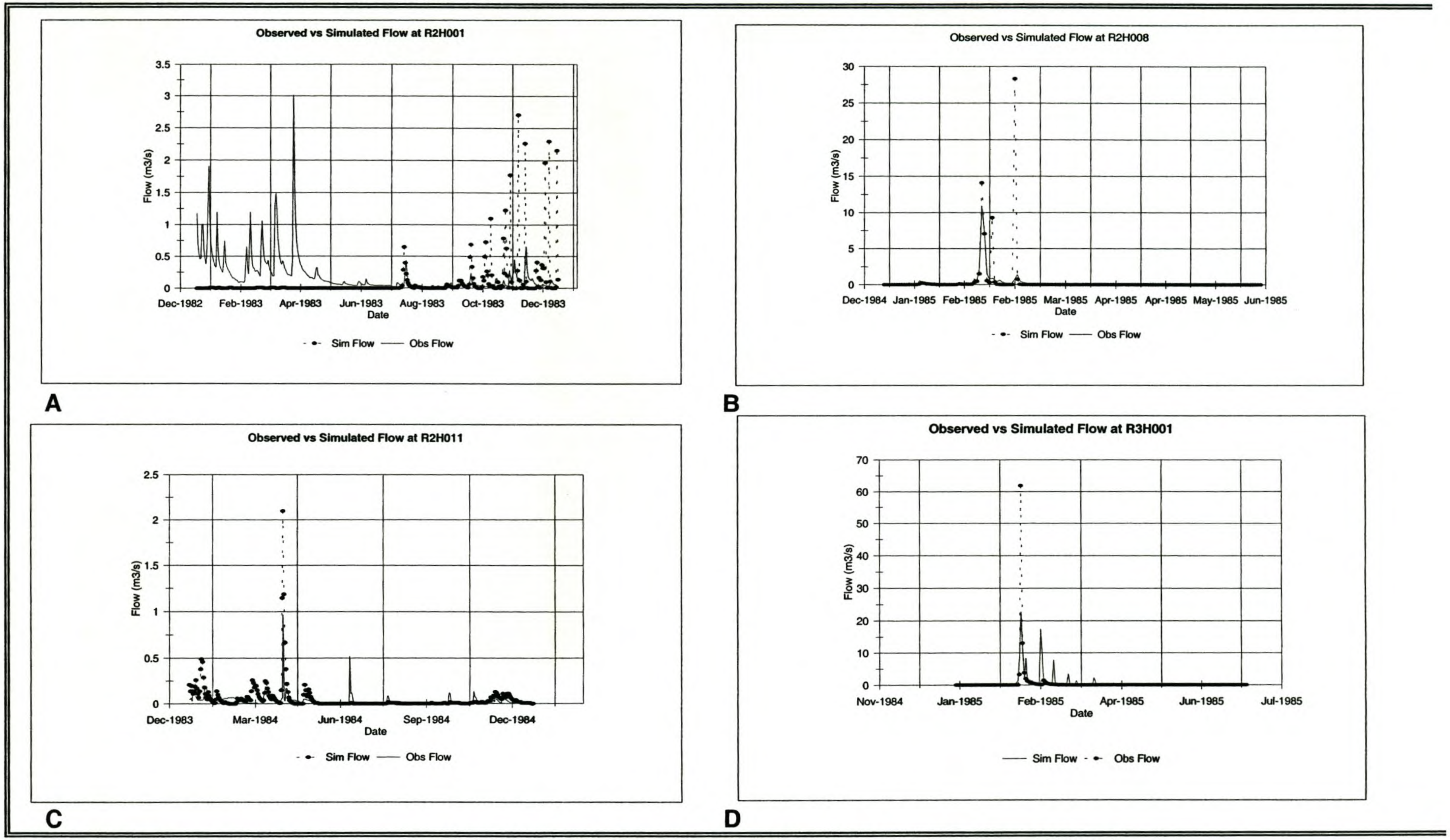


Figure 7.6 : The Goodness-of-fit for the HSPF Model Calibration for the Eastern Cape Catchments (Selected Events)

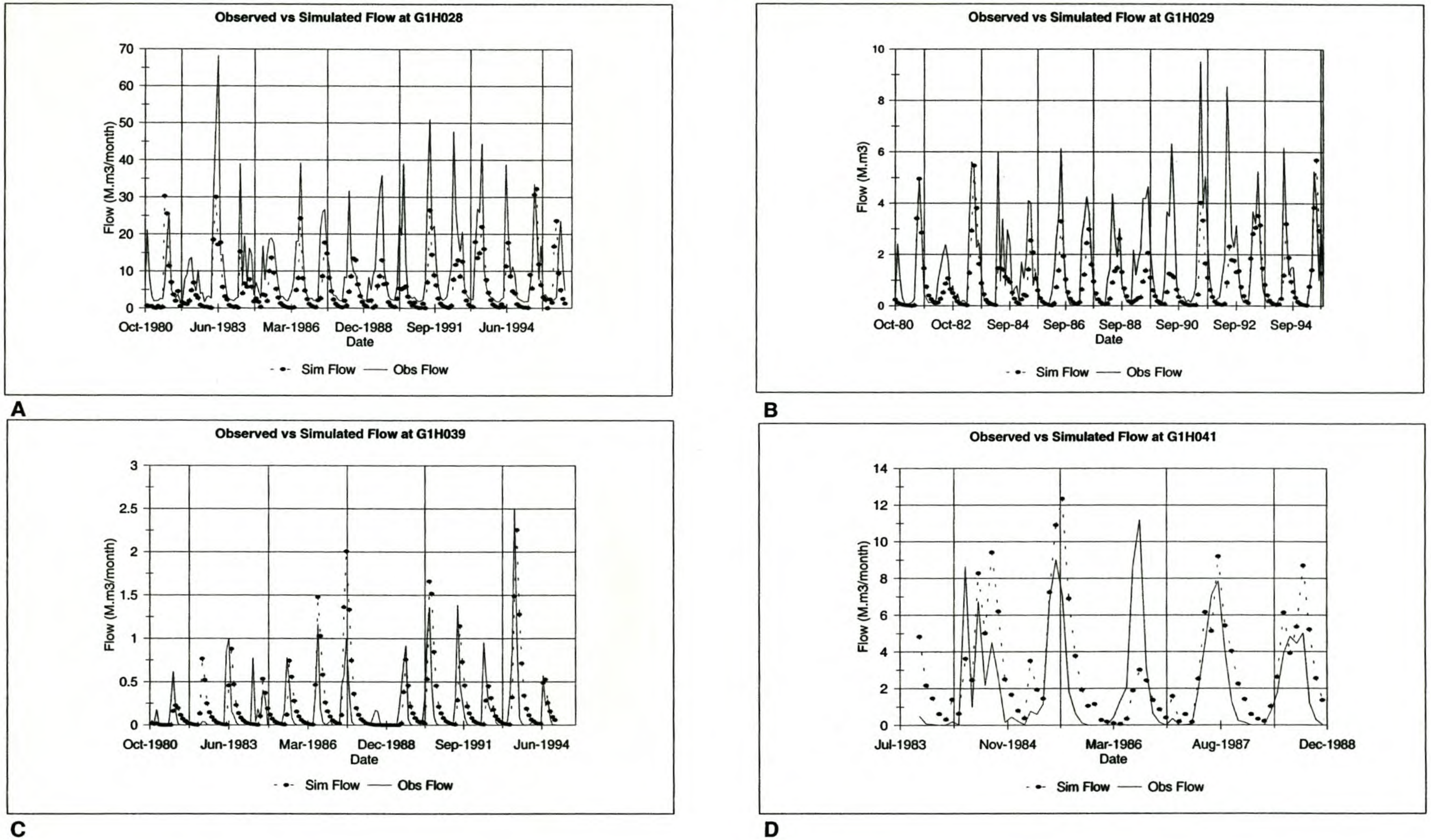
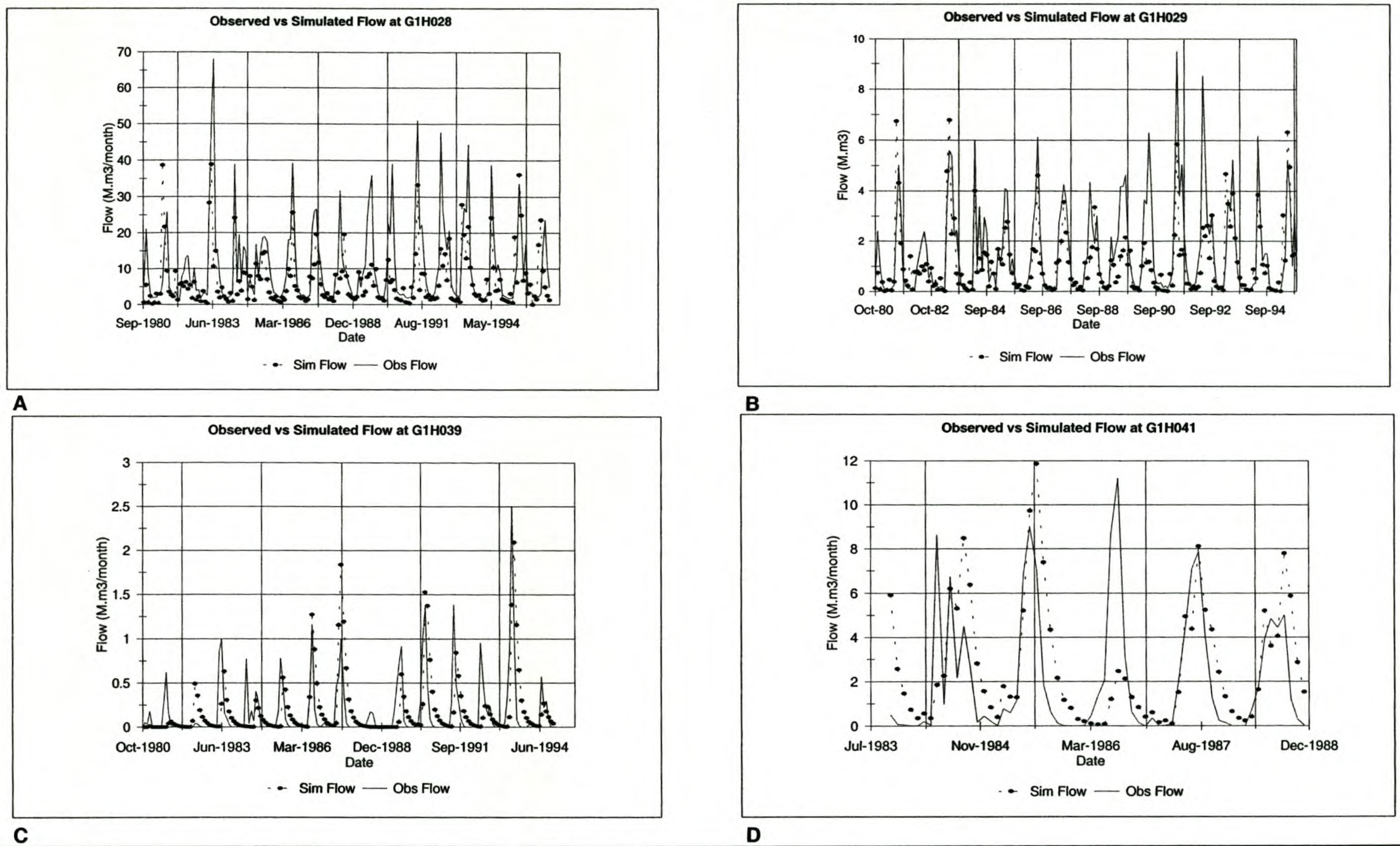


Figure 7.7 : The Goodness-of-fit for the ACRU Agrohydrological Model Verification (Uadjusted Parameters)



Figures 7.8 The Goodness-of-fit for the ACRU Agrohydrological Model Verification (Adjusted Parameters)

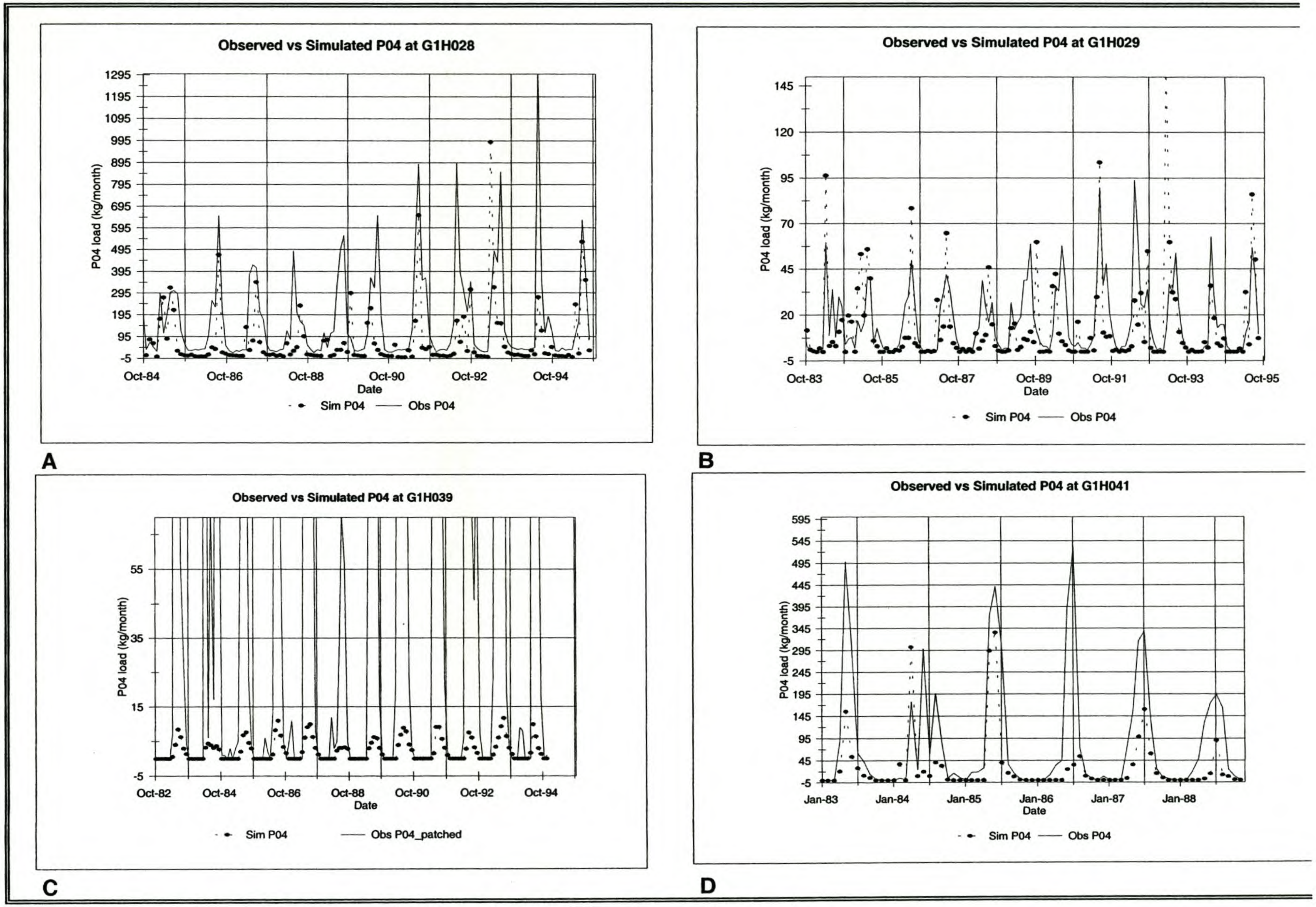


Figure 7.9 : The Goodness-of-fit for the Verification of the ACRU Phosphorous Yield Model

CHAPTER 8

COMPARISON OF THE CALIBRATED LAND USE PARAMETERS

This chapter presents a comparison of the calibrated land use parameters related to phosphorous production for study catchments in the Eastern and Western Cape. These parameters and dominant land use/cover in each of the catchments are summarised in **Table 8.1**. When evaluating the parameters in **Table 8.1**, it is necessary to bear the following in mind:

- ☆ ACRU phosphorous yield model is not a parameter fitting model. Land use parameters are based on the type of soils in each land use within the catchment. Since the parameters are not calibrated, they would not appear in **Table 8.1.**
- ☆ PEM has a "*black box*" nature
- ☆ The parameter SPAR in the PEM model does not necessarily represent a specific land use type in the catchment. It was calibrated for the whole catchment
- ☆ No information was available in the literature about the lower and upper limits of the SPAR parameter for specific land use types. Adjustment of this parameter was of a "*black box*" nature.
- ☆ α and β parameters in the CWM model represent each land use type in the catchment.
- ☆ No information was available in the literature about the lower and upper limits of the α and β parameters for specific land use types. Adjustment of these parameters was of a "*black box*" nature.

Table 8.1 Comparison of the Calibrated Parameters for Soluble Phosphorous

Catchment	Dominant Land Use/Cover	PEM	CWM	
		SPAR	α (baseflow parameter)	β (surface flow parameter)
Doring	Wheat	3.800	0.85	0.250
Kompanjies	Wheat	3.800	0.02	0.055
Leeu	Forest & natural vegetation	3.300	0.01	0.015
Twenty-four Rivers	Natural bush	1.400	0.020	0.013
Gqunube	Natural bush	1.000	0.035	0.010
Yellowwoods	Natural bush	11.50	0.085	0.030
Cwencwe	Forest	4.400	0.006	0.010
Upper Buffalo	Forest	4.500	0.006	0.016

8.1 CWM

In **Table 8.1**, only soluble phosphorous parameters representing dominant land use/cover types are shown. It is quite evident from **Table 8.1** that the surface flow and base flow concentration parameters for soluble phosphorous in the Yellowwoods River catchment are higher than in the Gqunube River catchment. The Gqunube River catchment is pristine, whereas in the Yellowwoods catchment there is a relatively high human presence.

The parameters for Upper Buffalo and the Cwencwe River catchments which are dominated by forestry are comparable. The soluble phosphorous parameters for natural vegetation in the Twenty-Four Rivers catchment are also comparable with the parameters in the Gqunube River catchment.

The surface flow parameters for the two Western Cape catchments dominated by wheat are comparable but not so are baseflow parameters. It should be noted that these two catchments are on different sides of the Berg River and soils are derived from different geological formations.

8.2 PEM

Soluble phosphorous parameters for Eastern Cape catchments dominated by forestry are comparable, but parameters for the catchments dominated by natural vegetation (i.e. the Gqunube and Yellowwoods catchments) are not comparable. In the PEM model, SPAR does not necessarily represent the dominant land use only. It represents all other land use types. It should therefore be noted that the Gqunube River catchment is a pristine catchment, whereas the Yellowwoods catchment is not. In the Yellowwoods catchment, there are lots of human activities which might have impact on the phosphorous production.

There is a reasonable comparison between land use parameters for the Western Cape catchments which are dominated by wheat.

8.3 ACRU

The ACRU phosphorous yield model is not supposed to be a parameter fitting or optimising model and parameters are, by and large, supposed to be estimated from the physical characteristics of the catchment. Some of the land use parameters in the model are PADC and PADM (refer to **Chapter 7**, **Section 7.5**), which are estimated from the soil characteristics in each land use type within the catchment.

CHAPTER 9

VERIFICATION OF THE MODELS IN TIME AND SPACE

It is important to be confident that calibrated models can be used in comparable un-monitored catchments or for periods different to those that reigned during the calibration period. To test for such robustness, verification of the model output is performed in both space and time.

Parameter transfer in time

Parameter transfer in time within the same catchment, provides the modeller with the information about the model parameters which are affected by different events within different records of length. These parameters can be identified by calibrating land use (wheat, sugar, maize cultivation etc.) parameters for a specific period and then transferring them to another period outside the calibration period.

Model verification in time is done by transferring parameters calibrated for the specific land use type in the catchment within a certain period, to another period falling outside the calibration period.

Parameter transfer in space

Parameter transfer in space provides the modeller with information about the model parameters which are not variable from one catchment to another. Such parameters are not dependent on the size of the catchment, meteorological, topographical and hydrological characteristics of the catchment, but are dependent on the land use types (i.e. forestry, wheat, maize, grapes etc.) in the catchment. These parameters can be identified through transfer of model parameters in space between catchments with similar land use types.

In this study, model verification in space was done by transferring parameters calibrated for a specific land use type in one catchment to another catchment which has the same land use type, and for which records of observed flows and phosphorous loads were available.

For this study, one catchment which is not part of the study catchments was selected from each region to be used for verification of the model parameters in space. The Toise River catchment, which is dominated by natural vegetation, was selected for model verification in the Eastern Cape region, while the Sandspruit River catchment, which is dominated by wheat, was selected to verify model parameters in the Western Cape region.

9.1 MODEL VERIFICATION IN SPACE

For the CWM model verification in space, the observed flows at both the Toise River and Sandspruit River catchments were used as the input.

9.1.1 CWM

9.1.1.1 The Toise River catchment

Characteristics of the Toise River catchment are given in the table below:

Table 9.1 The Eastern Cape Catchment Selected for the Model Verification in Space (i.e. The Toise River Catchment)

Station No.	Place	Dominant land use	Catchment area (km^2)	MAP (mm) DWAF,1995)	MAR (mm) (DWAF, 1995)	MAE (mm) (DWAF,1995)
S6H003	Forkroad	Natural vegetation	217.1	672	80.0	1500.0

The flow gauging station (S6H003) is located at Forkroad. The CWM model was configured for the Toise River catchment to investigate the reliability of parameter transfer in space. Model parameters (α and β with values 0.035 and 0.01, respectively) calibrated for natural vegetation in the Gqunube catchment were transferred to this catchment. **Table 9.2** summarises results of the model verification

Table 9.2 Summary of the Goodness-of-fit for the CWM Model Verification in Space in the Toise River Catchment

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
S6H003	Toise	1977 - 1990	649	409	0.926	0.826

The model underestimated the observed soluble phosphorous load by about 37% as shown in **Table 9.2**.The coefficient of efficiency is about 83%, which implies that a small systematic error was introduced when parameters were transferred in space.

Figure 9.1(A) shows that the model could reproduce almost all the changes in the observed data set. Most of the dry period events were under-simulated, whereas some of the wet period events were slightly overestimated. However, these results show promise that land use parameters for the CWM model could be transferred from the catchments which are gauged to those which are not gauged.

9.1.1.2 The Sandspruit River Catchment

Catchment characteristics of the Sandspruit River catchment are given in the table below:

Table 9.3 The Western Cape Catchment Selected for the Model Verification in Space (i.e. The Sandspruit River Catchment)

Station No.	Place	Dominant land use	Catchment area (km^2)	MAP (mm) (DWAF, 1993)	MAR (mm) (DWAF,1993)	MAE (mm)
G1H043	Vrisgewaagd	Wheat	149.46	437	30.1	1605

The flow gauging station (G1H043) is located at Vrisgewaagd. The model was configured for the Sandspruit River catchment, which is a tributary of the Berg River catchment, located on the Western side. The catchment is dominated by wheat farming.

Land use parameters (α and β with values 0.02 and 0.055, respectively) were transferred from the Kompanjies River catchment which is located on the eastern side of the Berg River to the Sandspruit River catchment, to investigate the reliability of parameter transfer. **Table 9.4** contains a summary of results obtained.

Table 9.4 Summary of the Goodness-of-fit for the CWM Model Verification in Space in the Sandspruit River Catchment

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H043	Sandspruit	1980 - 1994	357	163	0.839	0.586

In the light of the mean observed soluble phosphorous load being overestimated in the Kompanjies River catchment, as shown in **Table 7.1**, it was hoped that land use parameters would result in the mean observed load being overestimated in the Sandspruit River catchment. However, the model underestimated the mean observed soluble phosphorous load by about 54% and the coefficient of efficiency is about 59%. This implies that when land use parameters were transferred in space, a large systematic error was introduced.

Figure 9.1(B) shows that the model could mirror almost all the changes in the observed data set, but underestimated almost all the peaks. These results do not show promise that land use parameters for catchments located in the winter rainfall region could be transferred in space.

9.1.2 PEM

For the PEM model verification in space, the observed flows at the Toise River and Sandspruit River catchments were used as the input.

9.1.2.1 The Toise River Catchment

The PEM model was also configured for the Toise River catchment. Land use parameters calibrated for the Gqunube catchment were transferred to this catchment to investigate the reliability of parameter transfer. As stated previously, the Toise River catchment is dominated by natural vegetation. **Table 9.5** summarises the model verification at the Toise River catchment.

Table 9.5 Summary of Goodness-of-fit for the PEM Model Verification in Space in the Toise River Catchment

Sub-catchment	River name	Period (hydrological years)	Mean Observed $P0_4$ (kg/annum)	Mean Simulated $P0_4$ (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
S6H003	Toise	1977 - 1990	649	237	0.95	0.48

Given the reasonable calibration that was achieved for the Gqunube River catchment, it was hoped that transferring calibration parameter to the adjacent Toise River catchment will result in a reasonable goodness-of-fit. However, the model underestimated the mean observed soluble phosphorous load by 64%. This might be an indication that the PEM model parameters might not be transferred from the gauged catchments to those which are not gauged in the summer rainfall region.

Figure 9.1(C) shows that the model could reproduce the patterns in the measured data set, with the coefficient of determination 95%, but both peaks and troughs were under-simulated. The coefficient of efficiency is 48% as shown in **Table 9.5**, this implies that a large systematic error was introduced when land use parameters were transferred from the gauged catchment to those which are not gauged. This could also be observed between pollutographs in **Figure 9.1(C).**

9.1.2.2 The Sandspruit River Catchment

The PEM model was further configured for the Sandspruit River catchment. Land use parameters for the catchment dominated by wheat (i.e. the Kompanjies River catchment) were transferred to the Sandspruit River catchment on the western side of the Berg River. **Table 9.6** summarises the PEM model verification in the Sandspruit River catchment.

Table 9.6 Summary of Goodness-of-fit for the PEM Model Verification in Space in the Sandspruit River Catchment

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H043	Sandspruit	1980 -1993	357	246	0.966	0.856

Given the reasonable calibration achieved in the Kompanjies River catchment, parameter transfer was expected to result in reasonable correlation between mean observed and simulated phosphorous loads. However, the model under-simulated the mean observed load by 31%. This was not bad as compared to the model results in the Toise River catchment.

Figure 9.1(D) shows that the model could reproduce the patterns in the observed data set, but the peaks could not be superimposed. A systematic error less than that for the Toise River catchment could still be observed in **Figure 9.1(D)** and in **Table 9.6** where the coefficient of efficiency is 86%. The model could reproduce both the rising and falling limbs of the observed pollutograph. These results indicated promise in that the land use parameters for catchments dominated by wheat, in the winter rainfall region, might be transferred (with small systematic error) from catchments which are gauged to those which are ungauged.

9.2 MODEL VERIFICATION IN TIME

The models were verified in time for both the Western and the Eastern Cape study catchments. **Table 9.7** summarises verification and calibration periods for the models.

Table 9.7 Summary of Verification and Calibration Periods in Hydrological Years

Station number	Model calibration period	Model verification period
G1H028	1983 - 1994	1980 - 1982
G1H029	1983 - 1994	1980 - 1981
G1H039	1983 - 1994	1980 - 1981
G1H041	1983 - 1994	*No verification period
R2H001	1983 - 1986	1992 - 1994
R2H008	1983 - 1986	1977 - 1980
R2H011	1982 - 1984	*No verification period
R3H001	1983 - 1994	1977 - 1982

*phosphorous data exists for the calibration period only.

9.2.1 CWM

The land use parameters of the CWM model were transferred from the calibration period to the period for which the model was not calibrated, in order to investigate the validity of parameter transfer in time. **Table 9.8** summarises model verification results for the Western Cape catchments.

Table 9.8 Summary of the Goodness-of-fit for the CWM Model Verification in Time in the Western Cape Catchments

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H028	Twenty-Four Rivers	1980 - 1982	2036	2099	0.987	0.941
G1H029	Leeu	1980 - 1981	80	105	0.992	0.918
G1H039	Doring	1980 - 1981	226	202	0.929	0.864

Twenty-Four Rivers Catchment

The model overestimated the mean observed soluble phosphorous load by about 3%. This is because the model overestimated the dry months events between 1981 and 1982, as shown in **Figure 9.3(A)**.

The statistical comparison between the mean observed and simulated soluble phosphorous load is also reasonable. The results in this catchment show better promise that the CWM model parameters could be transferred in time

The Leeu River Catchment

In this catchment, the model could mirror all the changes in the observed data set, but overestimated the mean observed load by about 31%. This is because the model overestimated almost all the dry and wet month events, as shown in **Figure 9.3(B)**.

Figure 9.3(B) shows that a small systematic error was introduced when land use parameters were transferred in time in this catchment. Nevertheless, the results show some promise that model parameters could be transferred in time.

The Doring River Catchment

The model reproduced the changes in the observed data set, but underestimated the mean observed soluble phosphorous load by about 11%. This could be attributed to the fact that the model underestimated most of the wet month events, as shown in **Figure 9.3(C)**.

The coefficient of efficiency is about 86%, which implies that a small systematic error was introduced when land use parameters were transferred in time. Despite the small systematic error, the results show better promise that land use parameters could be transferred in time.

In general, the results have showed better promise that land use parameters for catchments in the winter rainfall region could be transferred in time.

Table 9.9 Summary of the Goodness-of-fit for the CWM Model Verification in Time in the Eastern Cape Catchments

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
R2H001	Upper Buffalo	1992 - 1994	155	91	0.994	0.853
R2H008	Cwencwe	1977 - 1980	375	101	0.712	0.303
R3H001	Gqunube	1977 - 1982	787	536	0.961	0.705

The Upper Buffalo River Catchment

The model underestimated the mean observed soluble phosphorous load by about 41%. This could be attributed to the fact that the model underestimated both dry and wet month events as shown in **Figure 9.4(A).** The coefficient of efficiency is about 85%, which is an indication of the small systematic error which was introduced when parameters were transferred in time.

The Cwencwe River Catchment

The model underestimated the mean observed soluble phosphorous load by about 73%. The coefficient of efficiency is about 30%, hence this is an indication that a large systematic error was introduced when land use parameters were transferred in time. **Figure 9.4(B)** shows that almost all the events in the observed data set were underestimated. The results from this catchment do not show any promise that land use parameters could be transferred in time.

The Gqunube River Catchment

In this catchment, the model underestimated the mean observed soluble phosphorous load by about 32%. This could be attributed to the fact that the model underestimated most of the wet month events (see **Figure 9.4(C)**). The coefficient of efficiency is about 70%, which implies that a smaller systematic error than the one in the Cwencwe River catchment occurred when parameters were transferred in time.

In general, the results from the Eastern Cape region (characterised by summer rainfall) do not show promise that land use parameters could be transferred in time.

9.2.2 PEM

The PEM land use parameters were transferred from the calibration period to the period for which the model was not calibrated in the study catchments listed in the tables below. The aim of the exercise was to investigate the possibility of transferring land use parameters of the PEM model in time.

Table 9.10 Summary of the Goodness-of-fit for the PEM Model Verification in Time in the Western Cape Catchments

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
G1H028	Twenty-Four	1980 - 1983	2036	2155	0.990	0.983
G1H029	Leeu	1980 - 1981	80	66	0.996	0.910
G1H039	Doring	1980 - 1981	226	238	0.982	0.981

The Twenty Four Rivers Catchment

When land use parameters calibrated for this catchment were transferred to the period for which the model was not calibrated, reasonable comparison between the mean observed and simulated soluble phosphorous loads was achieved, as shown in **Table 9.10**. The model under-simulated the mean observed soluble phosphorous load by about 6%, with reasonable statistical comparison.

The model could mirror most of the changes in the observed data set as shown in **Figure 9.5(A)**, and both the rising and falling limbs of the pollutograph, with the exception of the period between the middle of 1981 and the middle of 1982, were simulated successfully. The results showed promise that land use parameters for catchments dominated by natural vegetation might be transferred in time.

The Leeu River Catchment

In this catchment, where forests and natural vegetation are dominant land covers, reasonable comparison between the observed and simulated soluble phosphorous loads was achieved as shown in **Table 9.10.** There is also a reasonable statistical comparison between the observed and simulated soluble phosphorous loads.

The model could mirror the changes in the observed data set, but underestimated the wet months and overestimated the dry months to a lesser extend as shown in **Figure 9.5(B)**. Nevertheless, the model showed promise that model parameters could be transferred from the calibration period to a period for which the model was not calibrated.

The Doring River Catchment

Reasonable correlation was achieved between the mean observed and simulated soluble phosphorous loads, as shown in **Table 9.10**.There was also reasonable statistical comparison between the observed and simulated phosphorous loads.

Figure 9.5(C) shows that the model was not consistent during the wet months, because the first event was slightly underestimated and the second big event was slightly overestimated. Despite the inconsistency in the model, there was promise that model parameters for catchments dominated by wheat could be transferred from the calibration period to the period for which the model was not calibrated.

Generally, the results show promise that land use parameters for catchments in the winter rainfall region could be transferred in time.

Table 9.11 Summary of the Goodness-of-fit for the PEM Model Verification in Time in the Eastern Cape Catchments

Sub-catchment	River name	Period (hydrological years)	Mean Observed PO_4 (kg/annum)	Mean Simulated PO_4 (kg/annum)	Monthly coefficient of determination (r^2)	Monthly coefficient of efficiency
R2H001	Upper Buffalo	1992 - 1994	155	118	0.978	0.914
R2H008	Cwencwe	1977 - 1980	375	95	0.573	0.416
R3H001	Gqunube	1977 - 1982	787	474	0.969	0.772

The Upper Buffalo River Catchment

The model underestimated the observed soluble phosphorous load by about 24%. In spite of the 20% overestimation, there was reasonable comparison between the observed and simulated soluble phosphorous loads as shown in **Table 9.11**. The statistical comparison was also reasonable.

Figure 9.6(A) shows that the model could mirror the changes in the observed data set. However, most the wet months were under-simulated throughout the verification period. This was an indication that land use parameter transfer in time, in this catchment, could result in a small systematic error.

The Cwencwe River Catchment

The model underestimated the mean observed soluble phosphorous by about 75% as shown in **Table 9.11**. The coefficient of efficiency is about 42%, which implies that a large systematic error occurred when land use parameters were transferred to this catchment.

Figure 9.6(B) shows that the model underestimated most of the wet months, with the exception of the 1981 event. The model performance was not consistent throughout the verification period as shown in **Figure 9.6(B)**. This was an indication that the transfer of land use parameters in time, in this catchment, could result in a systematic error.

The Gqunube River Catchment

The model underestimated the mean observed soluble phosphorous load by about 40% as shown in **Table 9.11**. The coefficient of efficiency is 77%, this implies that systematic errors were introduced when land use parameters were transferred (this could be observed in **Figure 9.6(C)**).

Figure 9.6(C) shows that the model could reproduce changes in the observed data set, but underestimated most of the wet months. This was an indication that land use parameter transfer could result in systematic errors.

Generally, the results do not show promise that land use parameters could be transferred in time in the summer rainfall region.

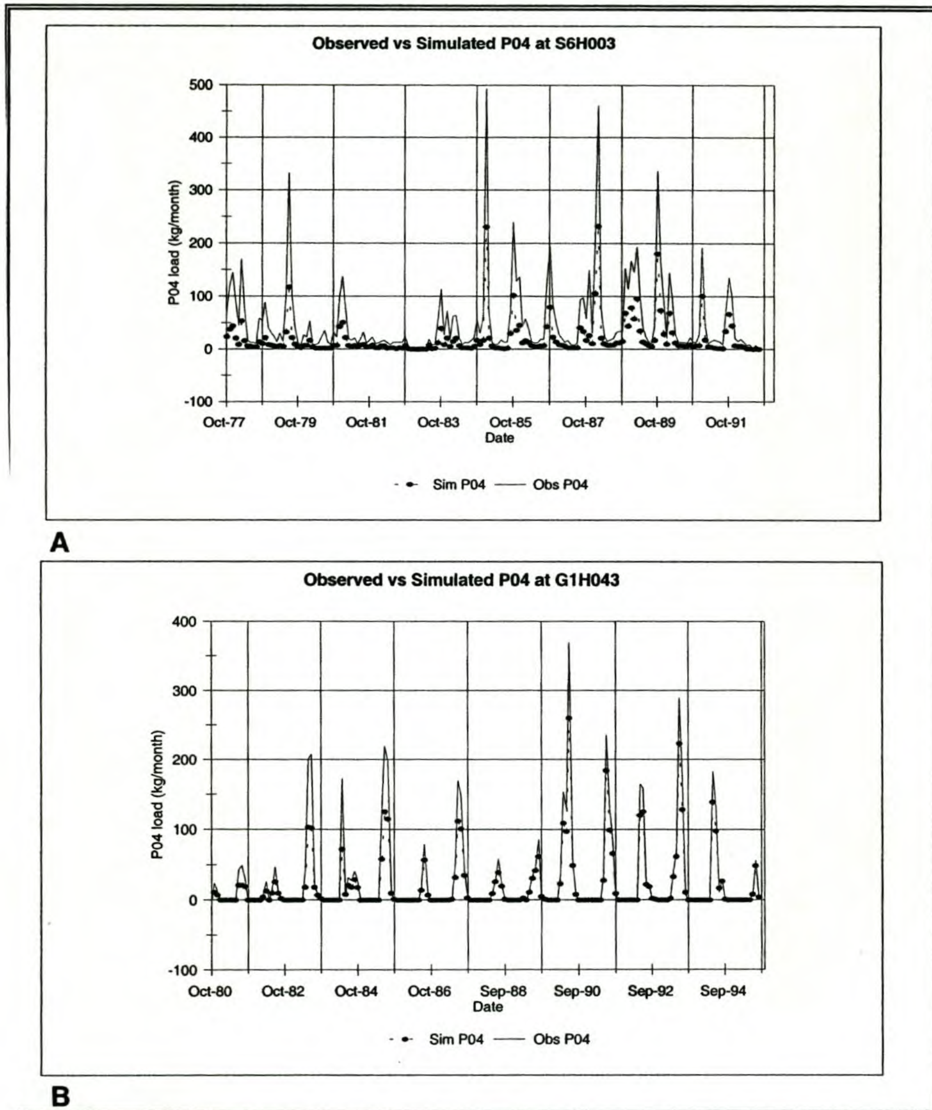


Figure 9.1 : The Goodness-of-fit for the PEM Model Verification in Space

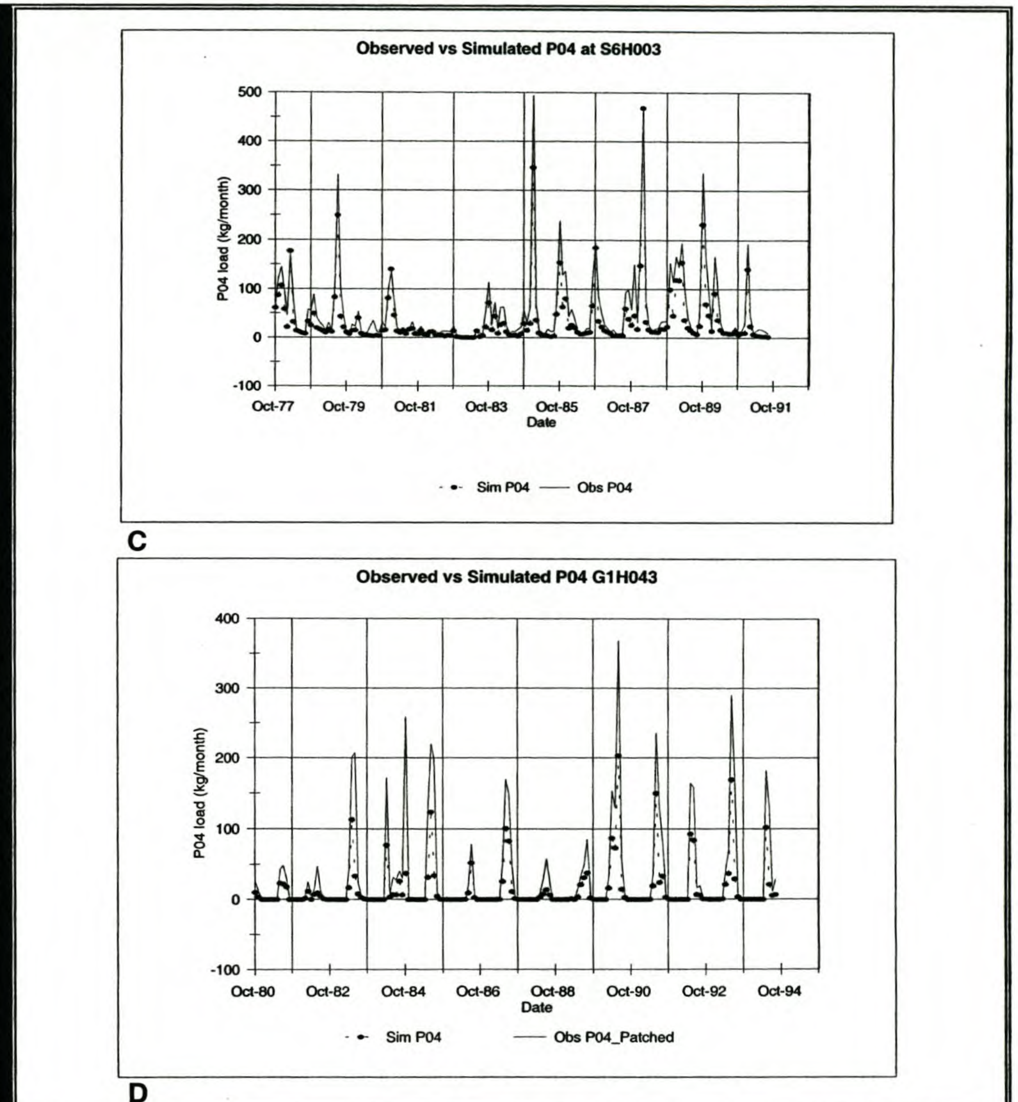


Figure 9.2 : The Goodness-of-fit for the CWM Model Verification in Space

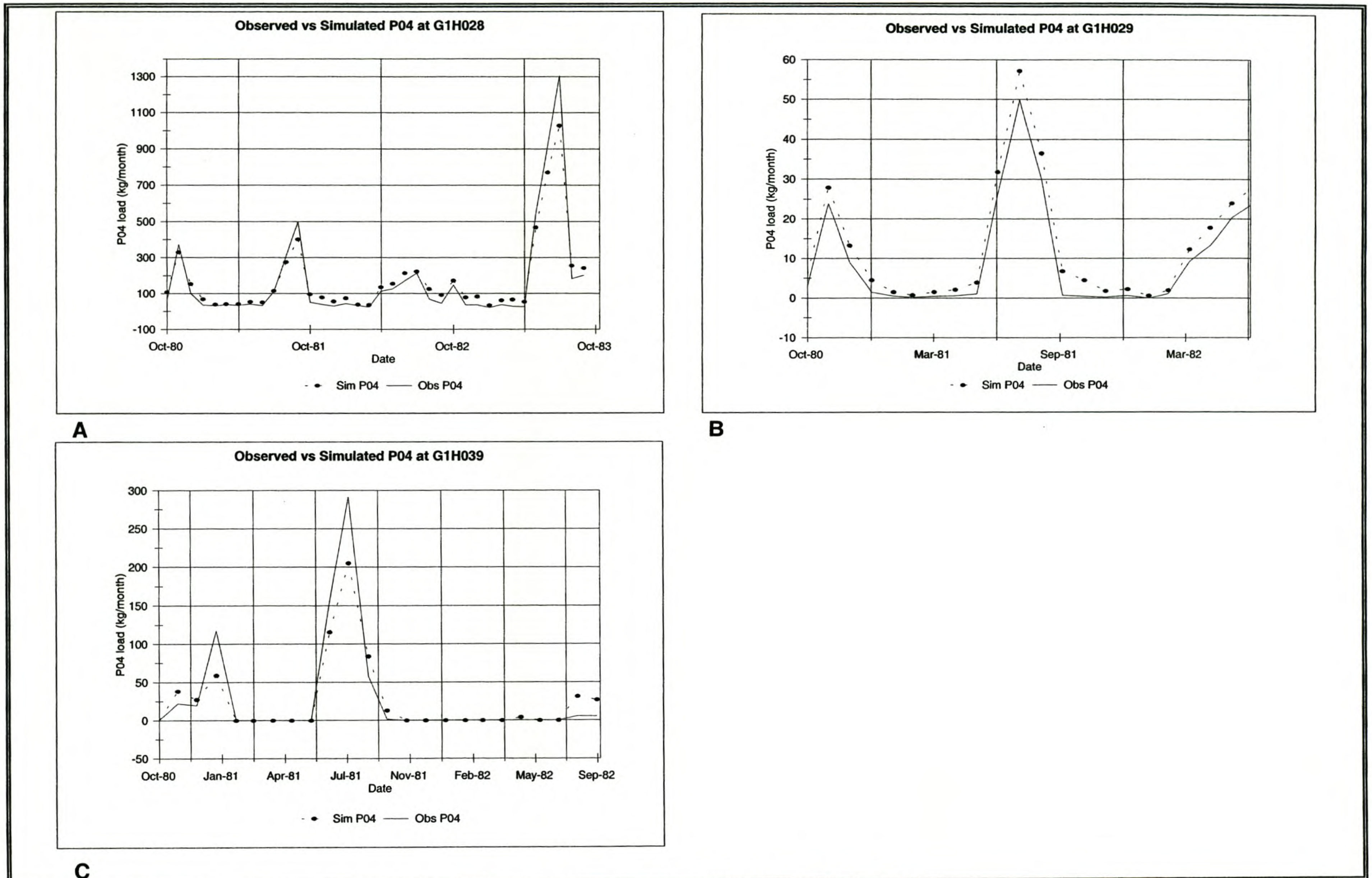


Figure 9.3 : The Goodness-of-fit for the CWM Model Verification in Time in the Western Cape Catchments

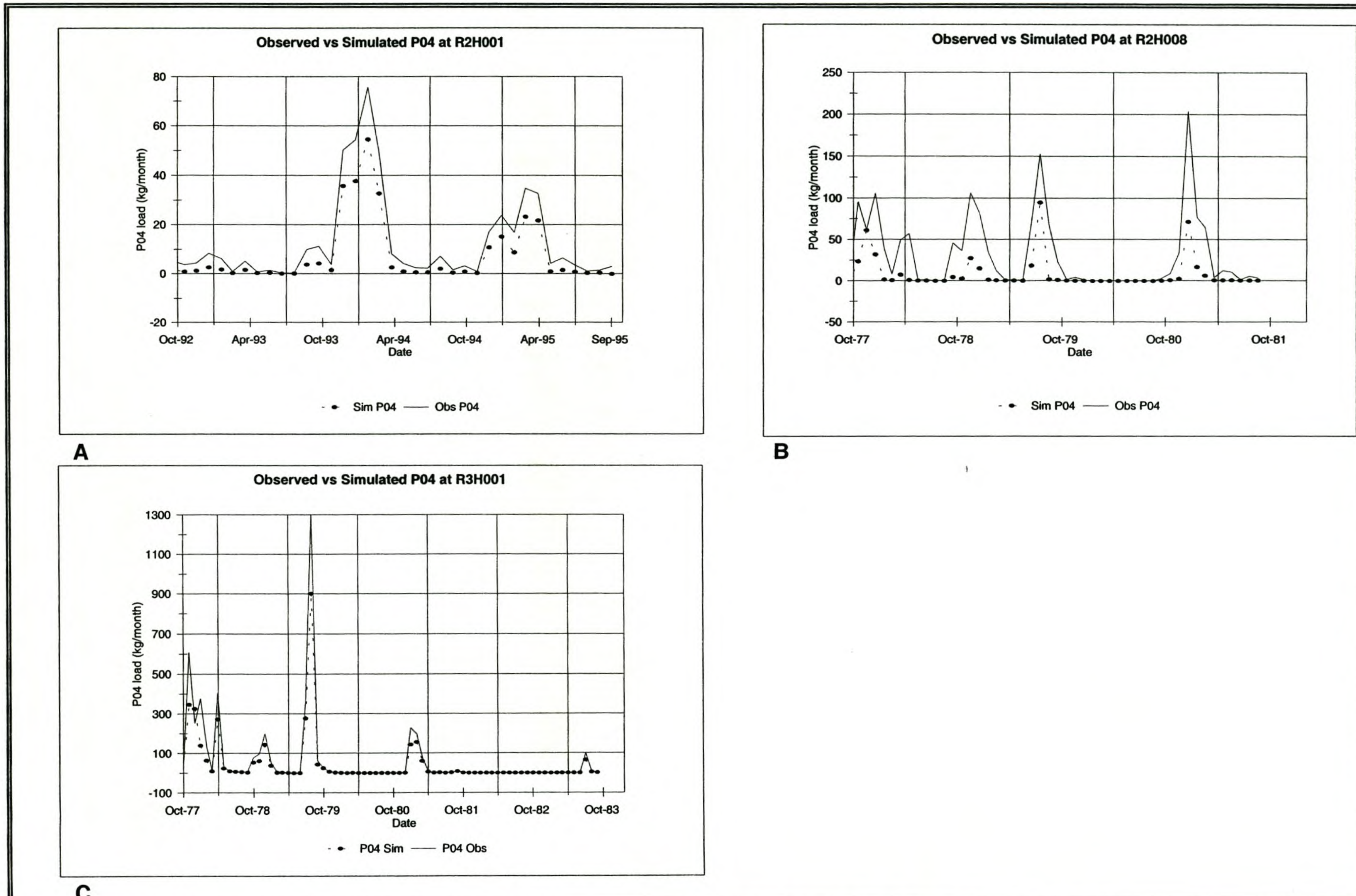


Figure 9.4 : The Goodness-of-fit for the CWM Model Verification in Time in the Eastern Cape Catchments

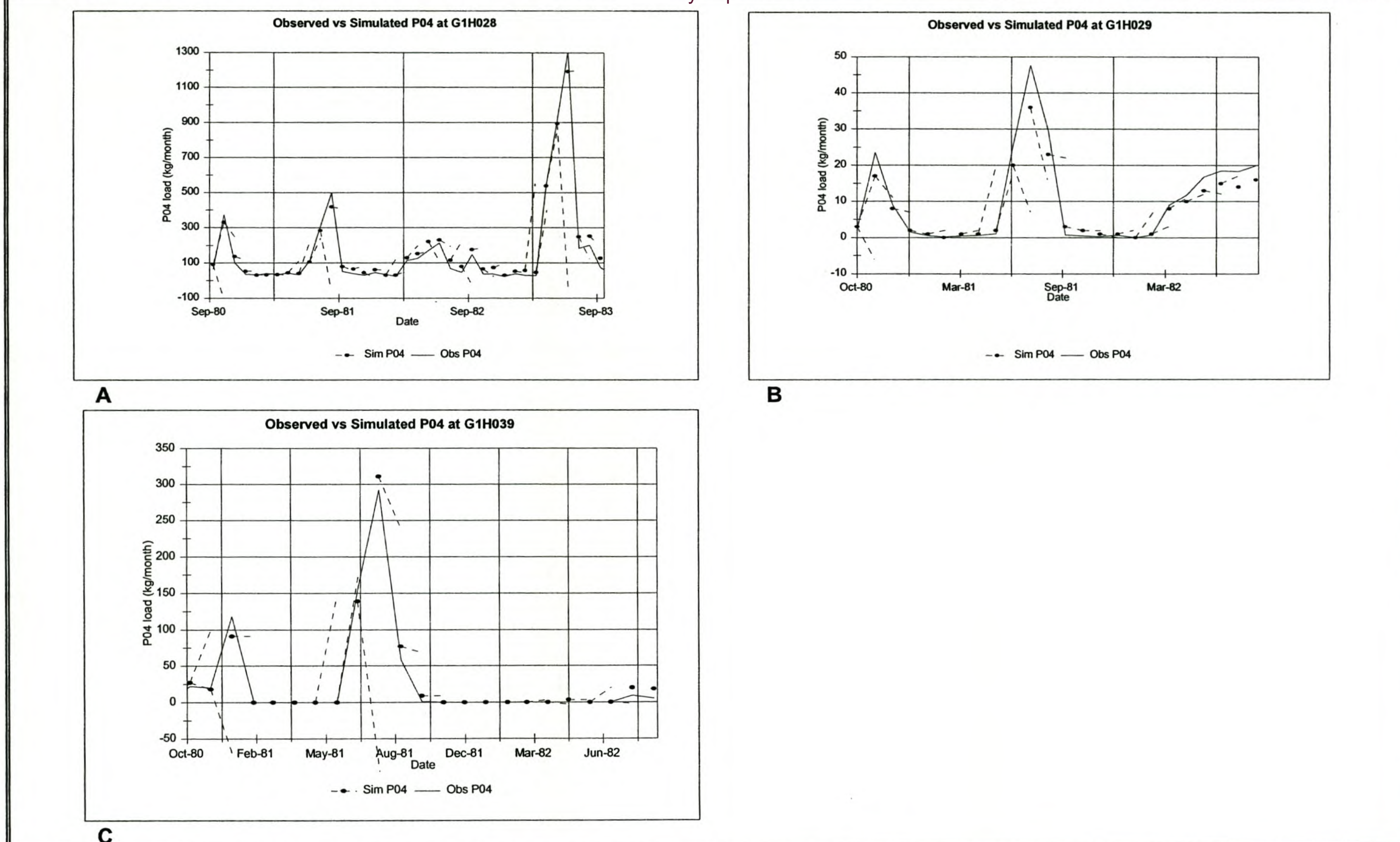


Figure 9.5: The Goodness-of-fit for the PEM Model Verification in Time in the Western Cape Catchments

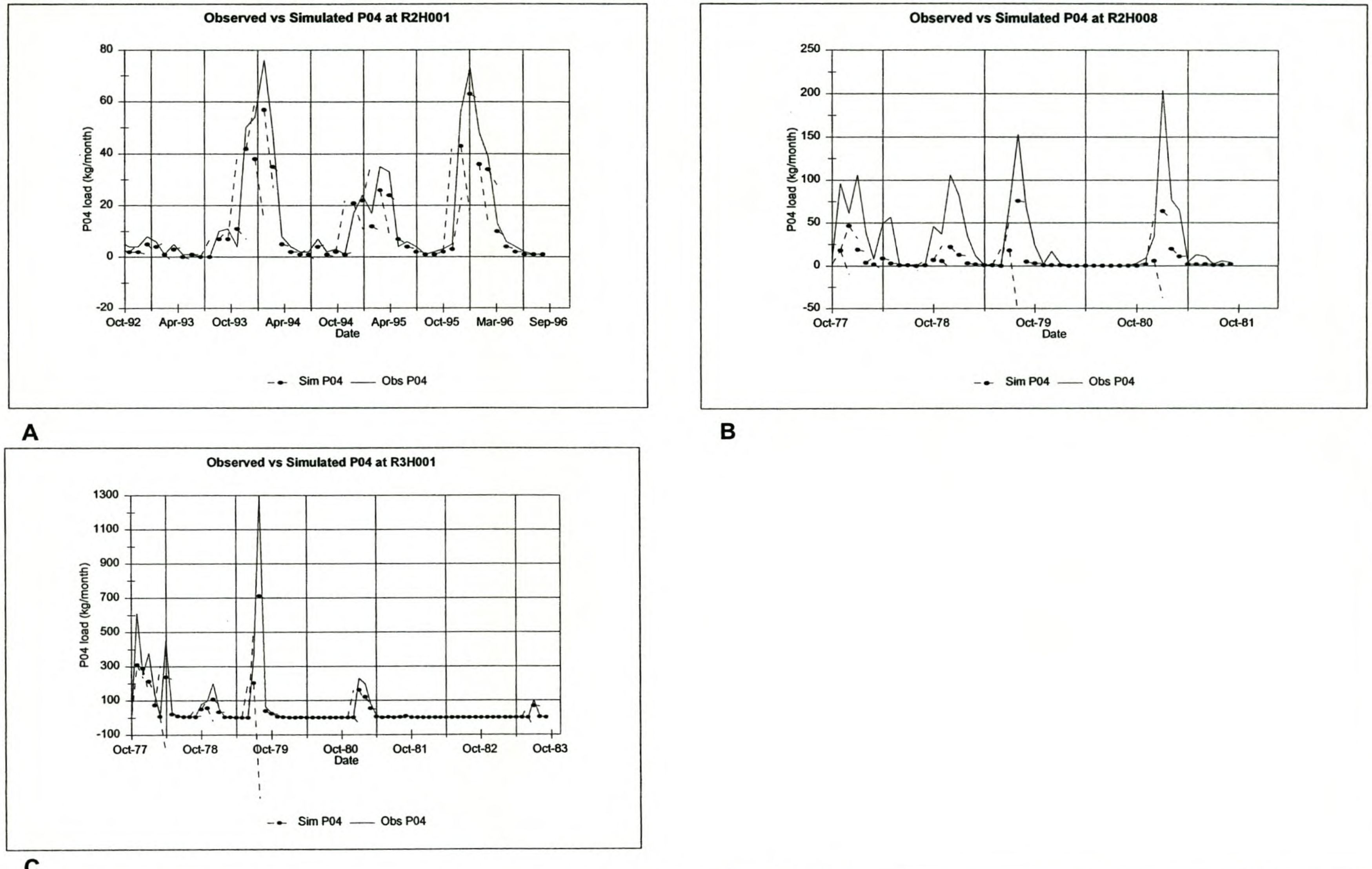


Figure 9.6 : The Goodness-of-fit for the PEM Model Verification in Time in the Eastern Cape Catchments

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

This chapter outlines the conclusions which are drawn regarding the extent to which the research objectives which were set at the beginning of the thesis were met (**refer** to **Chapter 1**) and recommendations are also made for further research.

10.1 CONCLUSIONS

- ☆ The CWM model results show promise that land use parameters for catchments located in the Eastern Cape could be transferred in space, whereas there is no promise for catchments located in the Western Cape.

- ☆ The CWM model results do not show promise that land use parameters for catchments located in the Eastern Cape could be transferred in time, whereas there is better promise for catchments located in the Western Cape.

- ☆ The CWM model, whose spatial resolution is finer compared to PEM, could be useful at the "*evaluation*" level of water quality assessment, because the model is capable of simulating phosphorous production per land use unit.

- ☆ The PEM model results do not show promise that land use parameters for catchments located in the Eastern Cape could be transferred in space, whereas there is better promise for catchments located in the Western Cape.

- ☆ The PEM model results do not show promise that land use parameters for catchments located in the Eastern Cape could be transferred in time, whereas there is better promise for catchments located in the Western Cape.

- ☆ The PEM model, whose spatial resolution is extremely coarse, could be useful at the "*screening/scoping*" level for assessing nonpoint source pollution, because of its ease of calibration stemming from its *black-box* character.

- ☆ The ACRU phosphorous yield model, whose temporal resolution is finer than the PEM and CWM models, could be useful at the "*prioritisation*" level for assessing nonpoint source pollution. The spatial resolution is finer than for PEM, but similar to that of the CWM model.

- ☆ Since the ACRU phosphorous yield model was included at a late stage of the research, the potential for parameter transfer in space and time was not investigated. The model verification results showed promise for catchments located in humid part of the Berg River bain, but did not perform as well in the catchment located in the semi-arid part.
- ☆ Unlike runoff-generating model parameters, it is a difficult task to calibrate water quality

model parameters related to phosphorous production in South African catchments, because of a lack of continuous phosphorous data. In most of the cases, the modeller is expected to infill phosphorous data which would then be regarded as the "observed" data in the calibration.

10.2 RECOMMENDATIONS

- ☆ Intensive research should be undertaken to develop a database of land use parameters/ export coefficients related to phosphorous production (and other non-conservative constituents) in South African catchments. Availability of these parameters would make phosphorous modelling much easier.

- ☆ HSPF should be configured and calibrated, more especially its water quality component, for catchments with hourly rainfall and rainfall stations located within/on the catchment boundaries, to investigate its performance under South African conditions. Given the complexity of the HSPF algorithms and the time required to familiarise oneself with the model, it is recommended that such an investigation be undertaken which is not inclusive of any other models.

- ☆ The spatial resolution of PEM is extremely coarse, and should be improved to allow the user to partition the total flow in the catchment according to contributions from the variety of land use types and to estimate soluble and particulate phosphorous parameters for each land use type.

- ☆ A study should be undertaken to investigate the potential for the ACRU phosphorous yield model parameter transfer in time and space.

- ☆ Sampling frequency of water quality data in South Africa should be improved, because it is difficult to assess the performance of the calibrated water quality models, more especially phosphorous export models, due to a lack of continuous data sets.

- ☆ Rainfall data collection in gauged catchments, more especially Western Cape catchments (e.g. Twenty-Four Rivers, Leeu, Kompanjies and the Doring River catchments), should be improved. There should be at least one rainfall gauging station located within the catchment boundaries. This would contribute towards achieving reasonable hydrological calibration or verification. Since runoff is the driving factor for water quality components, improved hydrological calibration/verification would result in reasonable water quality calibration/verification.

CHAPTER 11

REFERENCES

1. ANORLD, J.G, WILLIAMS J.R, NICKS A.O, SAMMONS N.B. (1989). *SWRRB : A Basin Scale Simulation Model for Soil and Water Resources Management*, Texas A & M University Press, College Station.

2. BATH, A.J. (1989). *Phosphorous Transport in the Berg River*, Western Cape, Report TR143, Department of Water Affairs, Pretoria.

3. BEASLY, D.B, HUGGINS. (1981). *ANSWERS user manual*, EPA 905/9-82-001, US EPA.

4. BRICKNELL, B.R, IMHOFF, J.C, KITTLE, J.L, DONIGAN, A.S, JOHANSON. (1993). *Hydrological Simulation Fortran Program* : Users Manual, Release 10, EPA, Report 600/R-93/174, Athens, GA.

5. BICKNELL, B.R, JOHANSON, R.C, BARNWELL T.O. (1996). *Hydrological Simulation Program-Fortran User's Manual for Release 11*

6. BICKNELL, B.R, IMHOFF, J.C, KITTLE, J.L, Jr., DONIGIAN, A.S, Jr., and JOHANSON, R.C. (1997). *Hydrological Simulation Program Fortran*: User's manual for version 11: U.S Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga, EPA/600/R-97/080, p755.

7. BODO, B and UNNY, T.E. (1983). *Sampling strategies for mass-discharge estimation.* Journal of Environmental Engineering Division, American Society of Civil Engineers, pp109:812-829.

8. CHAPMAN, T.G. (1975). *Trends in catchment modelling*. In: Chapman, T.G and Dunin, F.X (Eds.). Prediction in catchment hydrology. Australian Academy of Science, Canberra : 459-482.

9. CHITTENDEN NICKS PARTNERSHIP and NINHAM SHAND Ltd (Pty). (1999). *Kuils River Metropolitan Open Space System*, Volume 1, Final Report No. 2913/8070.

10. DEVOS, R. (1999). *Personal Communication*, Computing Centre for Water Research, HSPF User Consultant, Pietermaritzburg.

11. DISKIN, M. and SIMON, E. (1977). *A procedure for the selection of objective functions for hydrological simulation nodels*. Journal of Hydrology, 34 :129-149.

12. DONIGIAN, A.S, CRAWFORD, N.H . (1976). *NPS from the land surface*, EPA 600/3-76-083, Wasington DC.

13. DONIGIAN, A.S, Jr., IMHOFF, J.C, BICKNELL, B.R, KITTLE J.L. (1984). *Application Guide for Hydrological Simulation Program - Fortran (HSPF).*

14. DWAF (1990). *Hydrological Information Publication No.15, List of Hydrological Gauging Stations*. Volume 1.

15. DWAF (1993). *South African Water Quality Guidelines. Volume 4: Agricultural use.*

16. DWAF (1993). *Hydrology of the Berg River Basin*, prepared by R.R Berg of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis, DWAF report no. PG000/00/2491.

17. DWAF (1993). *Water Quality vol.1* :Prepared by A.J Bath of Ninham Shand Inc. in association with BKS Inc. as part of the Western Cape System Analysis. DWAF Report No. PG 000/00/2891.

18. DWAF (1995). *Amatole Water Resources System Analysis*, DWAF Report No. :PR 000/00/1395.

19. DWAF (1995). *Amatole Water Resources System Analysis*, Vol.2, Main report, DWAF Report No. Pr 000/00/0295.

20. DWAF (1997). *Amatole Water Resources System Analysis Phase 2*, Water quality modelling, volume 3 : WQT hydro-salinity calibration.

21. GARMONSWAY, G.N. (1969). *The Penguin concise English Dictionary.*

22. GöRGENS, A.H.M. (1983). *Conceptual modelling of the rainfall-runoff modelling process in semi-arid catchments*, HRU Report No. 1/83, Rhodes University, Grahamstown.

23. HAIPING Z. and YAMADA K. (1998). *Simulation of nonpoint source pollutant loadings from urban area during rainfall: An application of a physically-based model.*

24. HAITH, D.A., TUBBS, L.J. (1981). *Simulation model for agricultural non-point-source pollution.*

25. HAITH, D.A. (1985). *An event based procedure for estimating monthly sediment yields*, Transactions of the ASAE. Vol. 28(6):1916-1920.

26. HAITH, D.A, SHOEMAKER L.L. (1987). *Generalised watershed loading functions for stream flow nutrients*, Water Resources Bulletin, 23(3):471-478.

27. HEROLD, C.E. (1980). *A model to compute on a monthly basis diffuse salt loads associated with runoff*, HRU report No. 1/80, University of the Witwatersrand, Johannesburg, Republic of South Africa.

28. IBBIT, R.P and O'DONNELL, T. (1971). *Fitting methods for conceptual catchment models*, Journal of the Hydraulics Division of the ASCE, 97(HY9) : 1331-1342.

29. JEWITT, G.P.W and GöRGENS A.H.M. (2000). *Scale and model interfaces in the context of integrated water resources management for the rivers in the Kruger National Park*, WRC Report No 627/1/00.

30. JOHANSON R. (1998). *Personal communication.*

31. JONKER, V and GöRGENS, A.H.M. (1995). *Improvements of the DISA Hydrosalinity Model and its Application to the Vaalharts Irrigation Scheme*. Unpublished M.Eng. Thesis, Department of Civil Engineering, University of Stellenbosch.

32. KIENZLE, S.W., LORENTZ, S.A. and SCHULZE, R.E. (1997). *Hydrology and Water Quality of the Mgeni Catchment*. Water Research Commission, Pretoria, Report TT87/97.pp88.

33. SMITHEN, A.A. (1981). *Characteristics of rainfall erosivity in South Africa*, Unpublished Msc.Eng. Thesis. Department of Agricultural Engineering, University of Natal, Pietermaritzburg:pp126.

34. KINNIBURGH, J.H, TINSLEY, M.R, and BENNET, J. (1997). *Orthophosphate concentrations in the River Thames*.

35. KNISEL (1980). *CREAMS, A field-Scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems,* US Department of Agriculture, Conservation Research report 26, Washington DC.

36. LORENTZ, S.A.(2000). *Electronic Communication*, University of Natal, Pietermaritzburg.

37. MAILHOT, A., ROUSSEAU, A.N., MAISSICOTTE, S., DUPONT, J., VILLENEUVE, J.P. (1997). *A watershed-based system for the integrated management of surface water quality*: The GIBSI system, Water Science Technology Vol. 36, No. 5, pp. 381-387.

38. MCELROY, A.D, CHIU, S.Y, NEBGEN, J.W, ALETI A and BENNET F.W. (1986). *Loading functions for the assessment of water pollution from nonpoint sources*, EPA report No.600/2-76-151.

39. Midgley, D.C, Pitman W.V, Middleton B.J. (1990). *Surface Water Resources of South Africa 1990*, Volume IV, WRC Report No.298/4.1/94.

40. MILLS, W.B, PORCELLA, D.B, UUNGS, M.J, GHERINI, S.A, SUMMERS, K.V, MOK L., RUPP G.L, BOWIE and HAITH D.A. (1985). *Water Quality Assessment: A screening procedure for toxic and conventional pollutants in surface and groundwater (Revised 1985)*, EPA report No.600/6-85/002.

41. NASH, J.E and SUTCLIFFE, J.V. (1970). *River forecasting through conceptual models. Part I - a discussion of principles*. Journal of Hydrology, 10:282-290.

42. NOVOTNY, V and OLEM, H (1994). *Water Quality: Prevention, Identification and Management of Pollution*, Van Nostrand Reinhold, New York.

43. PEGRAM, G.C, QUIBELL, G.E, GöRGENS, A.H.M. (1997). *A situation assessment of nonpoint sources in South Africa*, WRC report.

44. PEGRAM, G.G.S. (1994). *Patching Rainfall Data (A guide)*, Department of Water Affairs and Forestry, Directorate of Project Planning, Report No.H-6-6-0194.

45. PEGRAM, G.C, GöRGENS, A.H.M, OTTERMANN, A.B. (1997). *A framework for addressing the information needs of catchment water quality management*, Water SA Vol. 23, No. 1.

46. PITMAN, W.V. (1976). *A mathematical model for generating daily river flows from meteorological data in South Africa*, HRU Report No.2/76, University of the Witwatersrand, Johannesburg, Republic of South Africa.

47. THOMANN, R.V and MUELLER J.A. (1987). *Principles of Surface Water Quality Modelling and Control.*

48. RENARD, K.G, FORSTER, G.R, WEESIES, G.A and PORTER J.P. (1991). *RUSLE-Revised Universal Soil Loss Equation Journal of soil and Water Conservation* 46:30-33.

49. RICHARDSON, C.W, FOSTER G.R, WRIGHT D.A. (1983). *Estimation of erosion index from daily rainfall amount,Transactions of the American Society of Agricultural Engineers.*

50. SMITHERS, J.C. and CALDECOTT, R.E. (1994). *Hydrograph routing. In:Schulze R.E. Hydrology and Agrohydrology : A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System.* Water Research Commission, Pretoria, Report TT69/95. ppAT13-1 to AT13-16

51. WEDDEPOHL, J.P and MEYER, D.H. (1992). *Utilisation of models to simulate phosphorous loads in Southern African catchments*, WRC report.

52. TSIHRINTZIS V.A, FUENTES H.R, and GADIPUDI R.K. (1996). Water Resources Bulletin, American Water Resources Association, Vol. 32 No.2, *Modelling prevention alternatives for nonpoint source pollution at wellfield in Florid.*

53. WALKER, W.W. (1987). *Empirical methods for Predicting Eutrophication in impoundments* report 4 Phase III: Applications Manual, Technical Report E-87-9, U.S Army Corps of Engineers, Washington D.C.

54. WALLIS, J.R and TODINI, E. (1975). *Comment upon the residual mass curve coefficient*, Journal of Hydrology, 24 : 201-205.

55. WARD, R.C and ROBINSON, M. (1989). *Principles of hydrology.*

56. WHO (1975). *Intercomparison on conceptual models used in operational hydrological forecasting*, World Meteorological Organization, Operational Hydrology Report 7, Geneva.

57. WILLIAMS J.R. (1975). *Sediment Yield Prediction with Universal Equation Using Runoff Energy Factor*, U.S Department of Agricultural Research Services, Washington D.C., 244-252.

58. WISCHMEIER, W.H, and SMITH D.D. (1978). *Predicting rainfall Erosion Losses- A guide to Conservation*, Planning, Agricultural Handbook 537, U.S Department of Agriculture.

59. YOUNG *et al.* (1986). *Agricultural Nonpoint Source Pollution Model : A Watershed Analysis Tool, Agricultural Research service*". US Department of Agriculture, Morris, MN.

APPENDIX A

DEFINITIONS

a) *Pollution* means the direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it less fit for any beneficial purpose for which it may reasonably be expected to be used, or harmful or potentially harmful to the welfare, health or safety of human beings, any aquatic or non-aquatic organisms, the resource quality and property (Water Act, 1998).

b) *Water Quality Constituent* is a biological or chemical (organic or inorganic) substance or physical characteristic that describes the quality of a water body (DWAF, 1993)

c) *Water quality concerns* refers to the concerns which water users have on the quality of the water.

d) *Water quality variables* refers to *water quality constituents* (DWAF, 1993).

e) *Hardness* is defined as the sum of the calcium and magnesium concentrations, both expressed as the calcium carbonate, in milligrams per litre (DWAF, 1993).

f) According to the National Water Act (1998), *Resource quality* means the quality of all the aspects of a water resource including: the quantity, pattern, water level and assurance of instream flow; the water quality including the physical, chemical and biological characteristic of the water; the character and condition of the instream and riparian habitat; and the characteristics, condition and distribution of the aquatic biota. This definition has been adopted for this study.

g) *Fitness for use* : is the suitability of the quality of water for one of the following five recognised *water uses* : domestic use, agricultural use, industrial use, recreational use and water for the natural environment (DWAF, 1993).

h) *Nutrient* : water quality constituents such as nitrogen and phosphorous.

i) *Eutrophication* is defined as the enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorous. This causes an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned (Kinniburgh, 1997).

j) *Salinisation* is the process which determines the salt content of the soil or water (DWAF,1993).

k) *Trophic state* of a water body is defined as its degree of eutrophication or lack thereof (Thomann,1987, p387).

l) *Macrophyte* : refers to macroscopic forms of aquatic vegetation and encompasses certain species of algae, mosses and ferns as well as aquatic vascular plants (DWAF, 1993).

m) *Source area character* refers to the characteristics of the catchment which is acting as the source of nonpoint source pollution.

n) *Management goals* refers to, inter alia, investigation of the magnitude of the water quality pollution in the catchment, the sources of point and nonpoint source pollution and how they can be managed, etc.

o) *Production* refers to the generation or production of wastes at their point of origin. This may be a single industry, wastewater treatment works, or include nonpoint source generation in urban and agricultural areas (DWAF, 1995).

p) *Trace metals* are defined as water quality contaminants which tend to be easily adsorbed by soils, and usually accumulate within the surface layer and once adsorbed cannot be easily removed. Excessive concentrations may cause undesirable accumulations of plant tissue, followed by growth reductions and/or toxicity to animals (DWAF, 1993). Examples of trace metals are Iron, Zinc, Manganese etc.

q) *Micro pollutants* are any substances that make an environment harmful or unpleasant to micro-organisms.

APPENDIX B

LABORATORY RESULTS

(Reg. No. 82/04379/07)

Consulting Analytical & Industrial
Chemists Specialists in Water & Waste
Water Treatment.
Telephone (021)448 6340/1
After Hours (021)72 0940
Telefax (021)448 6342
e-Mail Address: alabbott@iafrica.com

No. 1, Vine Park
Vine Road
7925
P.O. Box 483
WOODSTOCK, CAPE
7915
SOUTH AFRICA

Certificate of Analysis

NINHAM SHAND (PTY) LTD

SAMPLE : Two Samples of Water

DATE RECEIVED : 12th August 1998

YOUR REF. : -

OUR REF. : 222/1/1729
13th August 1998

LAB DATA SHEET NO. : 98/649

Sample Marked :	A dd 7/8	B dd 7/8
Conductivity (mS/m)	370	374
	mg/l	mg/l
Total Phosphorus (as P)	0,49	0,33
Ortho Phosphorus (as P)	Nil	Nil

....
R. VAN DER MEULEN Pr.Sci.Nat.
DIRECTOR

Messrs Ninham Shand (Pty) Ltd
P O Box 1347
CAPE TOWN
8000

Attention : MR M.P. MATJI

P O Box 320 Stellenbosch 7599 South Africa
Telephone : (021) 888 2400
International + 27 21 888 2400
Telefax : (021) 888 2693
International + 27 21 888 2693

CERTIFICATE OF ANALYSIS

Our ref: C:\LET\CERT_059

Report Number: MALR059

31 August 1998

Water, Environment and Forestry Technology

CSIR

NINHAM SHAND
81 Church Street
Cape Town
8001

Attention: Mr Maselaganye Matji

CHEMICAL ANALYSIS - Water samples
Order No: 6816/7/ww/ROO

Samples received: 28 August 1998
Analyses completed: 31 August 1998

Sample ID:	Water sample
Sample Date:	21/08/98
Lab No:	1048
Conductivity in mS/m:	505
Reactive PO_4 as P in μg/l:	154
Total P in μg/l:	375
Sample ID:	Water sample
Sample Date:	28/08/98
Lab No:	1049
Conductivity in mS/m:	569 ✗
Reactive PO_4 as P in μg/l:	151
Total P in μg/l:	352

(11)

TO N Shand
INITIAL
NS. CT 1998-09-04
FILE No:
ACTION M Matji

Andrew Pascall
MARINE ANALYTICAL SERVICES

Sebastian Brown
MARINE ANALYTICAL SERVICES

Page 1 of 1

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P O Box 320 Stellenbosch 7599 South Africa
Telephone : (021) 888 2400
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CERTIFICATE OF ANALYSIS

Our ref: C:\LET\CERT_059

Report Number: MALR059

31 August 1998

NINHAM SHAND
81 Church Street
Cape Town
8001

Water, Environment and Forestry Technology

CSIR

Attention: Mr Maselaganye Matji

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Andrew Pascall
MARINE ANALYTICAL SERVICES

Sebastian Brown
MARINE ANALYTICAL SERVICES

(Reg. No. 82/04379/07)

Consulting Analytical & Industrial
Chemists Specialists in Water & Waste
Water Treatment.
Telephone (021)448 6340/1
After Hours (021)72 0940
Telefax (021)448 6342
e-Mail Address: alabbott@iafrica.com

No. 1, Vine Park
Vine Road
7925
P.O. Box 483
WOODSTOCK, CAPE
7915
SOUTH AFRICA

Certificate of Analysis

NINHAM SHAND (PTY) LTD

SAMPLE : **One Sample of Water (dated 28/8/98)**

DATE RECEIVED : **2nd September 1998**

YOUR REF. : **6816/71/WW/ROO - WRC projek**

OUR REF. : **222/1/1920**
3rd September 1998

LAB DATA SHEET NO. : 98/782

Conductivity (mS/m)	*724*
	mg/l
Total Phosphorus (as P)	*0,26*
Ortho Phosphorus (as P)	*0,23*

R. VAN DER MEULEN Pr.Sci.Nat.
DIRECTOR

Messrs Ninham Shand (Pty) Ltd
P O Box 1347
CAPE TOWN
8000

Attention : MR M.P. MATJI

1998 -09- 0 3
FILE No:
ACTION

A L ABBOTT AND ASSOCIATES (PTY) LTD
(Reg. No. 82/04379/07) Established1964

Consulting Chemists & Chemical Engineers Specialists in Water & Waste Water Treatment

No. 1, Vine Park
Vine Road
WOODSTOCK, CAPE
7925
P.O. Box 483
WOODSTOCK, CAPE
7915
SOUTH AFRICA
Telephone (021)448 6340/1
After Hours (021)72 0940
Telefax (021)448 6342

TELEFAX MESSAGE

MESSAGE TO : Ninhon Ground (PTY) Ltd

ATTENTION : Mr M.P. Maaji

MESSAGE FROM : **A.L. ABBOTT & ASSOCIATES (PTY) LTD**

TELEFAX REF. NO. : 98/1920

SUBJECT : 1X Water Sample

DATE TELEFAX SENT : 04-09.98

NO. OF PAGES BEING SENT : **PAGE** : 1 **OF** 2 **PAGES**

PLEASE NOTE : IF YOU DO NOT RECEIVE ALL PAGES IN LEGIBLE CONDITION, PLEASE CONTACT SAMANTHA OR BEVERLEY AT (021) 448-6340/1.

(Reg. No 82/04379/07)

Consulting Analytical & Industrial
Chemists Specialists in Water & Waste
Water Treatment.
Telephone (021)448 6340/1
After Hours (021)72 0940
Telefax (021)448 6342
e-Mail Address: alabbott@iafrica.com

No. 1 Vine Park
Vine Road
7925
P.O. Box 489
WOODSTOCK, CAPE
7915
SOUTH AFRICA

Certificate of Analysis

NINHAM SHAND (PTY) LTD

SAMPLE :	**One Sample of Water (dated 28/8/98)**
DATE RECEIVED :	**2nd September 1998**
YOUR REF. :	**6816/71/WW/ROO - WRC projek**
OUR REF. :	**222/1/1920 3rd September 1998** — **LAB DATA SHEET NO. : 98/782**

Conductivity (mS/m)	*724*
	mg/l
Total Phosphorus (as P)	*0,26*
Ortho Phosphorus (as P)	*0,23*

R. VAN DER MEULEN Pr.Sci.Nat.
DIRECTOR

Messrs Ninham Shand (Pty) Ltd
P O Box 1347
CAPE TOWN
8000

Attention : MR M.P. MATJI

This report relates only to the samples tested and is issued subject to the conditions printed on the reverse hereof

P O Box 320 Stellenbosch 7599 South Africa
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CERTIFICATE OF ANALYSIS

Our ref: C:\LET\CERT_062

Report Number: MALR062

14 September 1998

Water, Environment and Forestry Technology

CSIR (1) M. Matji (2) LN.

NINHAM SHAND
81 Church Street
Cape Town
8001

TO: NG Shand
-09- 18
FILE No:

Attention: Mr Maselaganye Matji

CHEMICAL ANALYSIS - Water samples
Order No: 6816/7/ww/ROO

Samples received: 11 September 1998

Analyses completed: 14 September 1998

Sample ID:	Bergriver
Sample Date:	11/9/98
Lab No:	1118
Conductivity in mS/m:	610
Reactive PO_4 as P in μg/l:	193
Total P in μg/l:	268

Andrew Pascall
MARINE ANALYTICAL SERVICES

Sebastian Brown
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CERTIFICATE OF ANALYSIS

Water, Environment and Forestry Technology

CSIR

Our ref: C:\LET\CERT_065

Report Number: MALR065

21 September 1998

NINHAM SHAND
81 Church Street
Cape Town
8001

Attention: Mr Maselaganye Matji

CHEMICAL ANALYSIS - Water samples
Order No: 6816/7/ww/ROO

Samples received: 18 September 1998

Analyses completed: 21 September 1998

Sample ID:	Bergriver
Sample Date:	18/9/98
Lab No:	1129
Conductivity in mS/m:	664
Reactive PO_4 as P in μg/l:	144
Total P in μg/l:	207

Andrew Pascall
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CERTIFICATE OF ANALYSIS

Our ref: C:\LET\CERT_066

Report Number: MALR066

22 September 1998

Water, Environment and Forestry Technology

CSIR

NINHAM SHAND
81 Church Street
Cape Town
8001

Attention: Mr Maselaganye Matji

CHEMICAL ANALYSIS - Water samples
Order No: 6816/7/ww/ROO

Samples received: 22 September 1998

Analyses completed: 22 September 1998

Sample ID:	Bergriver
Sample Date:	21/09/98
Lab No:	1130
Conductivity in mS/m:	676
Reactive PO_4 as P in μg/l:	141
Total P in μg/l:	188

Andrew Pascall
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CERTIFICATE OF ANALYSIS

Our ref: C:\LET\CERT_067
Report Number: MALR067

29 September 1998

Water, Environment and Forestry Technology

CSIR

NINHAM SHAND
81 Church Street
Cape Town
8001

Attention: Mr Maselaganye Matji

CHEMICAL ANALYSIS - Water samples
Order No: 6816/7/ww/ROO

Samples received: 28 September 1998
Analyses completed: 29 September 1998

Sample ID:	Bergriver
Sample Date:	22/09/98
Lab No:	1131
Conductivity in mS/m:	704
Reactive PO_4 as P in μg/l:	160
Total P in μg/l:	230

Sample ID:	Bergriver
Sample Date:	28/09/98
Lab No:	1132
Conductivity in mS/m:	704
Reactive PO_4 as P in μg/l:	155
Total P in μg/l:	157

Ninham Shand
1998-10-08
FILE No:
ACTION M Matji

Andrew Pascall
MARINE ANALYTICAL SERVICES

Sebastian Brown
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Our ref: C:\LET\CERT_071

Report Number: MALR071

12 October 1998

NINHAM SHAND
81 Church Street
Cape Town
8001

Attention: Mr Maselaganye Matji

CHEMICAL ANALYSIS - Water samples
Order No: 6816/7/ww/ROO

Samples received:9 October 1998

Analyses completed: 12 October 1998

Sample ID:	Bergriver
Sample Date:	9/10/98
Lab No:	1188
Conductivity in mS/m:	840
Reactive PO_4 as P in μg/l:	80
Total P in μg/l:	86

(2) M. Matji
(1)st L. Nieuwoudt
+ account.

TO N Shand
INITIAL NJ
1998 -10- 29
FILE No:
ACTION

(S)

Andrew Pascall
MARINE ANALYTICAL SERVICES

Sebastian Brown
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