UTILISATION OF MODELS TO SIMULATE PHOSPHORUS LOADS IN SOUTHERN AFRICAN CATCHMENTS

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Report to the Water Research Commission on the Project
"Development of phosphorus export models for catchments"

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ISBN 1 874858 26 8
WRC Report No 197/1/92

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Executive Summary

BACKGROUND

The need for the project arose from a series of events related to attempts to control eutrophication in South African reservoirs. The major events include

(1) the identification of phosphorous (P) as the main controllable cause of eutrophication in reservoirs;

(2) the decision by the Department of Water Affairs and Forestry to address causes of eutrophication rather than symptoms. Toward that end the Department implemented a 1 mg P /L limit on effluent discharged from point sources within certain specified catchments;

(3) the granting of exemptions from the 1 mg P/L limit in catchments where point sources do not materially affect P concentrations in reservoirs. The need for exemptions arose from the often very high costs of implementation of additional control of P concentrations.

This chain of events created the need for models to integrate the effects of point and non-point sources of P and predict potential algal blooms in reservoirs. The models were considered necessary to improve the decision-making process in granting exemptions.

This project was therefore aimed at the prediction of phosphate export from catchments experiencing changing phosphate loadings from point and non-point sources.

It was originally envisaged that a model would be developed and tested on a small experimental catchment, then scaled up for application to larger catchments. Staff changes and difficulty in recruiting suitable staff members was experienced so that the project began two years later than was originally scheduled. This late start was fortunate in that the Decision Support System for eutrophication control was applied during this period to assess the effect of eutrophication control measures. Shortcomings in the existing P-export models were identified and led to several changes in the approach to achieve the aims of the current project.

Three limitations were identified which determined the course of the project. Those limitations were:

(1) Department of Water Affairs and Forestry presently uses the Pitman hydrological model for runoff prediction and would for the foreseeable future continue to do so. Since P

export is so dependent on runoff it would be advisable to use the same model as the basis for runoff estimations.

(2) A severe shortage of P-related data that could be used in model calibration was identified. Since all applications of the DSS had to be for larger catchments, it was realised that the data requirements of a model developed on a small research catchment could not be met for larger catchments. It was thus agreed that it would be more fruitful to start model development on those catchments for which they were intended.

(3) It was appreciated that, for many catchments, not even the information for such a deterministic model would be available and the need to also refine the statistical or stochastic models for the prediction of P export, was identified.

Effective water quality management requires predictions of the effects of catchment changes on eutrophication in reservoirs in both conditions of good and poor data availability. Hence these conditions require two distinct types of model for predicting P export from non-point sources, a deterministic model coupled to hydrology and a stochastic model based on measurements of P concentrations. The project was therefore divided into two parts; (1) analyses of and recommended improvements to current stochastic models and (2) development of a deterministic model with the required relation to hydrology. The use of the results from the two models were the same but the modelling approaches differed. In catchments with limited data on catchment characteristics, but available P measurements, the stochastic model would be appropriate but in catchments with adequate catchment data sets the deterministic model would be more applicable. The two models were developed independently.

OBJECTIVES

The overall aim of the project was :

To develop models to predict phosphate export from catchments experiencing changing phosphate loadings from point and non-point sources.

SUMMARY OF FINDINGS

Deterministic Model

A simple deterministic Phosphorus Export Model (PEM) was developed to simulate the accumulation, washoff and transport of phosphorus from a non-point source dominated catchment. Although the model was based on deterministic principles, it can more accurately be described as a physical conceptual model relying heavily on *a priori* parameter estimation followed by parameter optimization based on the results of several objective functions.

The PEM has been developed for use with data or information on record and accessible to the user. Essentially three categories of data are needed. The first category is the information which describes the areal characteristics of a source: its location within southern Africa, its size and its basic land uses. A second category of data is that which is characteristic of a source or area, independent of land use. This includes data describing soil characteristics and properties, topographic features of the land, rainfall, runoff, and drainage densities. The third category of data is a description of how the source is used, such as tillage methods and conservation practices.

The model operates on a monthly time scale and accepts as input observed or modelled streamflow (runoff), which is then disaggregated into surface and ground water components. The model uses observed streamflow as the process driver, however, provision was made for streamflow to be generated by any of a number of suitable hydrological rainfall-runoff models. The Pitman monthly model is suggested, due to its use and acceptability. Phosphorus is assumed to accumulate on the catchment at a uniform rate and to be removed in its soluble form by surface runoff. The surface runoff also drives soil erosion processes which transport adhered particulate phosphorus towards streams and rivers. Provision is made for the surface accumulation of phosphorus to be increased via a user-defined annual growth index.

Calibration and sensitivity of the model parameters is described and results of phosphorus load export simulations from nine southern African catchments, using the PEM is provided. Even though the PEM is a fairly simple model and the parameter demands are modest, the results show that phosphorus loads exported from non-point source dominated catchments can be simulated to an acceptable degree of accuracy.

The methods were designed to be appropriate for use by water quality managers and to account for changes in P export as a result of changes in relevant characteristics of the catchment as well as varying P loadings from non-point sources. These methods would then be incorporated into a deterministically based computer model (program), or supplied as a set of regional regression parameters or stochastically based P export coefficients, that could be used to simulate the non-point source additions of P from catchments.

Results of the application of the deterministic PEM to nine southern African catchments provide acceptable results with coefficients of determination greater than 0.80 for all but one catchment. Short observed P data records and inadequate catchment land-use and soil data, however, remain a problem which can only be improved with the passage of time.

Stochastic Model

In addition to the deterministic model, the uncertainty/inaccuracy associated with a number of stochastic models making up the Reservoir Eutrophication Management Decision Support System (REMDSS) suite of models was quantified. The models studied were the Pitman Monthly Model (Pitman, 1973), the stochastic non-point source Phosphorus Export Model (Grobler and Rossouw, 1988), the REMDSS Phosphorus Budget Model, the Chlorophyll Concentration Model (Jones and Lee, 1982; Walmsley and Butty, 1979), and the Reservoir Eutrophication Model (REM). Improvements to the suite of models comprising REMDSS were suggested, as were procedures for improved calibration of the Pitman Monthly model.

The REM is commonly used to simulate the trophic status of South African reservoirs. No uncertainty analysis is usually included in such modelling. This is unfortunate because a false sense of model accuracy may result. Uncertainty analyses conducted in this study suggested that the conventional REM model is too simple and too inflexible to accurately characterise the behaviour of individual South African reservoirs. More accurate Reservoir Specific Eutrophication Models (RSEM) were therefore developed. In the case of the

Hartbeespoort Dam, the newly developed RSEM model was compared to the conventional REM model using Monte Carlo simulation.

It was shown, by means of Monte Carlo simulation, that these improvements to the REM model resulted in greater sensitivity in the case of Hartbeespoort Dam. This suggested that changes to the REM model such as those mentioned above can be used to improve the efficiency of REM modelling as a tool for assessing the effects of phosphorus control on water quality.

The models developed in the project fully achieve the aim of predicting phosphate export from catchments experiencing changing phosphate loadings from point and non-point sources. Improved predictions can be made with the models for catchments with sufficient data on land use characteristics and for catchments with little land-use data, but phosphate concentration measurements.

FURTHER RESEARCH

One of the urgent needs for additional research is for accurate information regarding soil erosion and sediment loss from catchments in southern Africa. The USLE was originally designed for use with small agricultural plots and its use in large catchments is in doubt. The information required to use the USLE is also a problem area as parameters such as land-use, soil erodibility, slope length and slope gradient are not readily available in many areas of the region except in specific research or gleaned by intensive field survey.

A major task is consolidating the mass of often conflicting research concerning P processes in research areas that has been reported in the scientific literature and applying it to the P export problem. The time scales involved in eutrophication responses in reservoirs are commonly of the order of months and even years. The model thus should use a monthly time scale with the associated problem that most of the research reported in the literature involves continuous or daily time scales.

The Reservoir Eutrophication Model is an important tool for the assessment of the future trophic status of South African reservoirs. However, this tool is only as good as the sub-models used to simulate phosphorus export, phosphorus budgets and chlorophyll concentrations. It was shown that the conventional REM model does not portray accurately the behaviour of all South African reservoirs. The further development of reservoir specific eutrophication models (RSEM's) is recommended in order to produce a more reliable modelling tool.

It is suggested that the first priority should be the development of a dynamic (time series) chlorophyll concentration model. A cross-sectional chlorophyll concentration model is inappropriate in the context of REM modelling on account of differences in nutrient loadings for South African impoundments.

The best available chlorophyll model for Hartbeespoort at this stage uses only six nutrient concentrations (TP, KN, NH_4, NO_2, NO_3, PO_4). Analysis for Witbank Dam has indicated that water clarity has a dramatic effect on algal growth. This variable and perhaps silica concentration should be studied with a view to improving the chlorophyll concentration model. If such studies could be performed for several dams, it is likely that a general form for the chlorophyll model will emerge. Additional extension to include other nutrients should also be conducted, since phosphorus is certainly not the only growth limiting nutrient.

Finally, an uncertainty/sensitivity analysis was performed for only one South African reservoir, namely Hartbeespoort Dam. Such Monte Carlo simulations need to be performed for other dissimilar South African dams in order to confirm the conclusions reached here.

Acknowledgements

The research and results described in this report emanated from a project funded by the Water Research Commission and entitled :

"Development of phosphorus export models for catchments"

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

Mr H M du Plessis	Water Research Commission (Chairman)
Mr H C Chapman	Water Research Commission
Mr F P Marais	Water Research Commission (Secretary)
Dr A J Bath	Department of Water Affairs
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The financing of the project by the Water Research Commission and the contribution of the members of the Steering Committee is acknowledged with gratitude.

This project was only possible with the co-operation of many individuals and institutions. The authors wish to record their sincere thanks to the following :

Department of Environment Affairs, South African Weather Bureau, in particular Mrs L Rademeyer and Mrs G Swart for rainfall data;

Department of Agriculture and Water Supply, Soil and Irrigation Research Institute, particularly Mrs O Rilley and Mr F G Koch for evaporation and land-use data;

Department of Water Affairs, in particular Miss E Modise for runoff data;

The Computing Centre for Water Research, for monthly rainfall data;

Mr K Tarboton, for providing land-use information for the Umgeni catchments;

Mr G R Angus, formerly of the Department of Agricultural Engineering, University of Natal, who made available literature on soil loss estimation.

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ABSTRACT

A simple deterministic model was developed to simulate the accumulation, washoff and transport of phosphorus from a non-pint source dominated catchment.

The model operates on a monthly time scale and accepts as input observed or modelled streamflow (runoff), which is then disaggregated into surface and ground water components. Phosphorus is assumed to accumulate on the catchment at a uniform rate and to be removed in its soluble form by surface runoff. The surface runoff also drives soil erosion processes which transport adhered particulate phosphorus toward streams and rivers. Provision is made for the surface accumulation of phosphorus to be increased via a user-defined annual growth index.

Calibration and sensitivity of the model parameters is described and results of phosphorus load export simulations from nine southern African catchments, using the Phosphorus Export Model (PEM) is provided.

Even though the PEM is a fairly simple model and the parameter demands are modest, the results show that phosphorus loads exported from non-point source dominated catchments can be simulated to an acceptable degree of accuracy.

In addition to the deterministic model, quantification of uncertainty/inaccuracy associated with a number of stochastic models making up the Reservoir Eutrophication Management Decision Support System (REMDSS) suite of models is attempted. The models studied are the Pitman Monthly Model (Pitman, 1973), the stochastic non-point source Phosphorus Export Model (Grobler and Rossouw, 1988), the REMDSS Phosphorus Budget Model, the Chlorophyll Concentration Model (Jones and Lee, 1982; Walmsley and Butty, 1979), and the Reservoir Eutrophication Model (REM).

The REM is commonly used to simulate the trophic status of South African reservoirs. No uncertainty analysis us usually included in such modelling. This is unfortunate because a false sense of model accuracy may result. Uncertainty analyses conducted in this study suggest that the conventional REM model is too simple and too inflexible to accurately characterise the behaviour of individual South African reservoirs. More accurate Reservoir Specific Eutrophication Models (RSEM) were therefore developed. In the case of the Hartbeespoort Dam the newly developed RSEM model was compared to the conventional REM model using Monte Carlo simulation.

1. INTRODUCTION

The original aim of this project, requisitioned and funded by the Water Research Commission, was to develop models to predict phosphorus (P) export from catchments experiencing changing P loadings from both point and non-point sources. The models were to have included transport of the P from the site of export to the receiving reservoirs. The aim, however, was changed during the course of the project to exclude the point source contributions and in-river transport processes, and to concentrate on the non-point source contribution of P exported from mainly non-point source dominated catchments.

Effective water quality management requires predictions of catchment changes on eutrophication in reservoirs in both conditions of good and poor data availability. Hence these conditions require two distinct types of model for predicting P export from non-point sources, a deterministic model coupled to hydrology, and a stochastic model. The project was therefore divided into two parts; analyses of and recommended improvements to current stochastic models, and development of a deterministic model. The objectives of the two models were to be the same but the approaches differed. In catchments with limited available data, the stochastic model would be appropriate but in catchments with adequate data sets the deterministic model would be more applicable. The two model types were developed independently.

The methods were to be appropriate for use by water quality managers and should account for changes in P export as a result of changes in relevant characteristics of the catchment as well as varying P loadings from non-point sources. These methods would then be incorporated into a deterministically based computer model (program), or supplied as a set of regional regression parameters or stochastically based P export coefficients, that could be used to simulate the non-point source additions of P from catchments.

1.1 Background

The enrichment of waterbodies with plant nutrients, eutrophication, causes many water quality problems as a result of excessive blooms of algae and/or macrophytes (Walker, 1983). Non-point source derived Total Phosphorus (TP) loads make up a significant part of the total TP load exported from several of the sensitive catchments in South Africa (Grobler and Silberbauer, 1984 ; Bath, 1989). The Department of Water Affairs (DWA) identified seven catchments which they regarded as being particularly susceptible to eutrophication. In these catchments a 1 mg P/l standard has been enforced to control eutrophication. However, it is appreciated that although a uniform standard was promulgated to avoid legal and administrative problems, the standard will probably not be required in some cases and might not be strict enough to prevent serious eutrophication problems in others. The Directorate of Water Pollution Control therefore adopted a policy whereby they will grant permits to effluent dischargers to exceed the standard when it can be shown that the effluents will have an insignificant effect on the receiving waterbodies. At the same time additional eutrophication control measures are being considered for those cases in which the 1 mg P/l standard will be insufficient to prevent serious eutrophication-related water quality problems from arising.

In order to justify decisions related to the enforcement of the P standard, it is imperative that the best possible estimates of non-point source derived TP loads be obtained when considering alternative control strategies (Grobler and Rossouw, 1988). Eutrophication models are used to assist in making these decisions concerning the implementation of the 1 mg P/l standard in sensitive catchments (Grobler, 1985b ; Grobler and Silberbauer, 1985) and for evaluating other eutrophication control strategies such as the construction of pre-impoundments upstream of important water supply reservoirs (Twinch and Grobler, 1986). In these applications of eutrophication models, serious limitations in their ability to predict the trophic response of reservoirs have been identified (Grobler and Silberbauer, 1984 ; Grobler, 1985b ; Twinch and Grobler, 1986) and several research projects, funded by different organizations, have been or are being undertaken to address some of these limitations.

1.2 Phosphorus Export Model

Development of P export models in South Africa has never received a high priority status in recent research endeavours although a simple stochastic model was developed to relate P export to catchment runoff in South Africa for catchments containing mainly non-point sources (Grobler, 1985a ; Grobler and Silberbauer, 1985). Grobler and Rossouw (1988) developed regression parameters relating phosphorus export to runoff in seven non-point source dominated South African catchments and Bath (1989) has developed a dynamic phosphorus export model that describes the transportation of phosphorus through the Berg River drainage basin. With the increasing population has come associated problems of increased urban and rural sewage volumes, and increased need for crop and livestock agriculture. These have led to increasing contamination of natural waterways by a multitude of domestic, industrial and agricultural pollutants among which is phosphorus. The effect of the increase in P loads is graphically illustrated by the on-going battle against eutrophication in the Vaal River system and the Hartbeespoort Dam. The need to quantify P concentrations exported from catchments and to understand the processes of P loss from these catchments, in order to improve or maintain acceptable P levels in South Africa's natural waterbodies and water supply systems, remains an imperative requirement.

Water quality models which include P considerations are available from international concerns such as the American Environmental Protection Agency (EPA). However these models have been developed for local conditions in parts of the USA and their applicability to southern African conditions is often in doubt.

As a result of these arguments the logical approach to the problem of simulating P export from catchments was the development of a deterministic Phosphorus Export Model (PEM), as well as the evaluation of stochastic models comprising the Reservoir Eutrophication Model Decision Support System (REMDSS) currently used by the DWA to assess the P standard and implement control strategies in sensitive catchments.

A review of the literature pertaining to P export from catchments follows in Chapter 2. In Chapter 3 the structures of both the Pitman and P export models are described and Chapter 4 provides information on data acquisition and processing. Chapter 5 describes the selection of objective functions, calibration and simulation results as well as parameter sensitivity. In Chapter 6 a number of stochastic water quality simulation models comprising the REMDSS suite of models are discussed and Chapter 7 closes the report with a discussion and conclusions. The Appendices include information on parameter and data selection for the Pitman and PEM models, simulation results, a detailed description of the computer programs as well as sample inputs and outputs and a review of statistical tests used.

2. LITERATURE REVIEW

2.1 Introduction

Eutrophication, the excessive fertilization of natural water bodies, is manifested by the excessive growth of planktonic, attached algae and aquatic macrophytes, and can have significant deleterious effects on the beneficial use of these water bodies (Jones and Lee, 1982). Eutrophication can interfere with the use of waters for domestic and industrial water supply, irrigation, recreation, fisheries, etc. (Lee, 1973). Undesirable amounts of phytoplankton and/or macrophytes occur due to eutrophication and lead to increased water purification costs, and loss of livestock (Grobler, 1985a). Furthermore, it has been determined for some waterbodies that there is an apparent relationship between the degree of eutrophication and the amount of trihalomethanes formed during chlorination of the water during treatment for domestic use (Jones and Lee, 1982). Trihalomethanes are chloroform-like compounds which, if ingested in large amounts, are suspected to be carcinogenic to animals (Jones and Lee, 1982).

Eutrophication has increased markedly throughout the world during the last two decades. South Africa is no exception and eutrophication of major water storage systems is regarded as one of the most serious threats to water quality. Eutrophication must therefore be controlled by, amongst others, limiting the fertility of the water by controlling the nutrient supply to, or the nutrient concentration in, the water environment (Grobler, 1985a ; Bath, 1989).

Water resource management programs have been growing rapidly because of man's need to use his limited water supplies more efficiently. Phosphorus (P) is a constituent of waters that is of concern in most management programmes because it is one of the vital, growth or yield limiting nutrients that stimulates or supports excessive and undesirable growth of aquatic plant life that causes eutrophication. It may, at relatively high concentrations, interfere with the coagulation processes in the treatment of industrial and municipal water supplies (Keup, 1968). For this reason, control over P-containing compounds in aquatic ecosystems presents a means of controlling eutrophication (Toerien, 1977 ; Walker, 1983). P load control has been demonstrated internationally as one of the most effective ways of dealing with cultural (man-made) eutrophication, and is being successfully applied in the USA, Europe, Scandinavia and Japan (EWPCA, 1985). This strategy is generally regarded to be the most desirable since it eliminates the cause of eutrophication. However it is not always possible to limit nutrient supplies sufficiently to achieve control and in such cases additional control must be considered. The first step to controlling eutrophication in South African reservoirs was taken in 1984 when legislation was enforced (Government Gazette, 1984) which limits the phosphorus concentration in treated domestic and industrial wastewater, discharged to specified sensitive catchments, to 1 mg/l dissolved ortho-phosphate. Additional eutrophication control measures, such as reducing the phosphorus content of synthetic detergents and introducing stricter phosphorus standards for effluents, are also being considered. The 1 mg/l standard was selected as a result of an assessment of the technical and economic feasibility of phosphorus removal from wastewater at the time that the standard was promulgated. More recent technological developments allow the phosphorus concentrations in effluents to be decreased to 0.1 mg/l at the same cost previously required for removal to 1 mg/l. It was estimated that the 1 mg P/l would result in 80% to 90% reduction in the phosphorus load from sewage works, which were assumed to contribute 60% to 80% of the total phosphorus load. Considerable beneficial effects on the trophic status of reservoirs were consequently expected in catchments where the standard will be introduced (Grobler, 1985a).

The decision to introduce a universal standard of 1 mg P/l for all sensitive catchments has been criticised on the grounds that :

a) Differences in the capacity of reservoirs to absorb phosphorus from point sources without deterioration of their water quality were ignored.

b) In some catchments, the ratio between point and non-point source contributions to the total phosphorus load is such that removal of phosphorus contributed by point sources will have negligible effects on the trophic status of the reservoirs.

In some catchments, therefore, uncertainty about the benefits that would result from the introduction of, and the high cost of compliance with, the standard do not justify its enforcement on small local authorities. Personnel of the Division of Water Pollution Control of the Department of Water Affairs indicated that these criticisms may be considered when the standard is implemented and that final decisions about its enforcement will be based on quantitative assessments of the impact on the trophic status of reservoirs (Grobler, 1985a).

Mathematical computer modelling is one of several tools which can be used by managers of water resources faced with the challenge to protect and improve water quality at the lowest economical, environmental and social costs. Water quality variables result from the interaction between man's activities and the natural hydrological cycle and have a stochastic component which should be recognised in water quality management. The climate of South Africa is classified as arid to semi-arid. The summer rainfall region experiences a markedly seasonal distribution in precipitation, with 80% of the annual total falling during the summer months. A characteristic feature of South African hydrology is the large temporal variability in river flows. This variability is responsible for the stochastic nature of water quality variables and therefore effects the stochastic nature of nutrient loads and runoff. In order to attempt an understanding of the physical processes that combine to produce observed affects in nature, deterministic modelling of these processes is required. Deterministic models allow the results of changing catchment conditions and parameters to be observed and so can provide important insight into the impact that various envisaged and observed future scenarios will have on the P load emanating from catchments of interest. Deterministic model also allow the effects of envisaged environmental restoration programmes to be observed and so assist in the decision making processes regarding the most effective programme to implement.

In order to plan and implement a rational P load control program, it is necessary to know the sources of P as well as their relative contributions (Wiechers and Heynike, 1986). Man's impact on aquatic ecosystems by nutrient enrichment is not confined to the effect of discharge of nutrients directly into water bodies, but also through the indirect process of fertilizer application resulting in a pool of nutrients which may be leached into, and transported by, rivers to accumulate in impoundments (Furness and Breen, 1978). Sources of P may be divided into two categories, namely point and non-point sources. Point sources are those inputs that are considered to have a well defined point of discharge which, under most circumstances, is usually continuous. Point sources can be easily identified, quantified and controlled. Non-point sources are those for which the origin of the discharge is diffuse.

Phosphorus occurs naturally in soil from weathering of primary phosphorus-bearing minerals of the parent material. Additions of plant residues and fertilizers by man enhances the P content of the surface soil layer.

P in soils occurs either as organic or inorganic P. The relative proportion of the P in these two categories varies widely. Organic P is generally high in surface soils where organic matter tends to accumulate. Inorganic forms are prevalent in subsoils. Soil P is readily immobilized due to its affinity to certain minerals. In strongly acid soils, the formation of iron and aluminium phosphates, and in alkaline soils, the formation of tricalcium phosphate reduces the availability of soil P. Once it is lost to a stream, the nature of P existing in sediment or in solution becomes significant in the nutrition of aquatic micro-organisms.

P transport from a given site to a stream can occur either by erosion or leaching. The predominant mode of transport is via soil erosion (Logan, 1982 ; Römkens, Nelson and Mannering, 1973). Soil solution usually contains less than 0.1 μg of P per millimetre. The leaching losses are thus extremely low even in well drained soils. Exceptions are sands and peats which have little tendency to react with P (Beaulac and Reckhow, 1982).

2.2 Sources of Phosphorus

2.2.1 Point Sources

Domestic sewage, (from residences, businesses and institutions), and industrial effluents have been identified as the major point source contributors to the P load on the water environment in South Africa (Taylor, Best and Wiechers, 1984). The major sources of P in domestic wastewater are human excreta (50-65%) and synthetic laundry detergents (35-50%) (Wiechers and Heynike, 1986 ; Chapra, 1977). The average daily P derived from human excreta in South Africa has been estimated as 1.3 g P per capita and that derived from household synthetic detergents has been estimated to be about 1.0 g P per capita (Heynike and Wiechers ,1986). Industry can either add to, or in the case of P deficient discharges, dilute the P concentration in municipal wastewaters (WPCF, 1983). Industrial wastewaters typically high in P include those generated from fertilizer production, feedlots, meat processing and packaging, milk processing and commercial laundries. Certain pulp and paper manufacturing processes discharge P deficient wastewaters (Wiechers and Heynike, 1986).

Raw sewage contains a number of different P forms, *inter alia* organically bound and inorganic P. The latter includes simple ortho-phosphates and polyphosphates. The P-containing compounds may be in a particulate, colloidal or dissolved form. The concentrations and loads of these various P forms arriving at a municipal works may vary diurnally, daily and seasonally. Typically ortho-phosphate comprises 50% or more of the total P in raw sewage. Conventional activated sludge and biological filter wastewater treatment processes do not remove P to any significant extent, but increase the soluble ortho-phosphate content from 50% to about 90% by transforming the organic and polyphosphates to ortho-phosphate (WPCF, 1983). This form is the easiest to remove by both chemical and biological means and is also the most readily available form for assimilation by algae and aquatic plants (Wiechers and Heynike, 1986).

2.2.2 Non-point Sources

Non-point sources of P are comprised of effluents from non-sewered populated areas, urban runoff, runoff from both cultivated and uncultivated land, ground water, lake bottom sediments and both wet and dry atmospheric precipitation.

Groundwater comprises water that has percolated through soils, dissolving P compounds from minerals during its movement through the soil layers. This P enters surface waters via seepage or springs, and by the pumping of wells (Keup, 1968). Groundwaters contain relatively low quantities of P (Keup, 1968 ; Juday and Birge, 1931 ; Anon, 1966 ; Bath, 1989).

Vaporized and uncontaminated condensed water (rainfall) should contain no P, however Hutchinson (1957) and Wiebel *et al.* (1966) have reported, what they termed relatively high, concentrations of 49 and 80 μg P/l in rainfall. On the other hand Sonzogni and Lee (1974), Simpson and Kemp (1982) and Bosman and Kempster (1985) have reported concentrations of 0.02 to 0.08 g P m^{-2} yr^{-1}, which were described by Wiechers and Heynike (1986) as being generally low concentrations. This P must be the result of "washout" of atmospheric particulate material whose composition and quantity govern the concentration in rainfall (Keup, 1968).

Surface drainage is the major non-point source contributor of P to waterways (Keup, 1968 ; Bath, 1989). P loading from surface runoff is dependent on several factors which include P content of the soil, soil characteristics, topography, geology (Grobler and Silberbauer, 1985), vegetative cover, land use, manipulative practices, animal populations, pollution, precipitation and quantity and duration of runoff (Keup, 1968 ; Chapra, 1977).

The P content of soil is a function of the parent rock material from which the soil is evolved. The basic igneous rock source is apatite, $CaF_2 . 3 Ca_3P_2O_8$ (Hem, 1959). Wilde, Wilson and White (1949) give the following P percentages for representative rocks : sandstone, 0.02; gneiss, 0.04; unweathered loess, 0.07; andesite, 0.16; diabase, 0.03; and limestone, 1.32. In most soils the upper horizons become enriched through the accumulation of organic humus which contains P that was bought to the surface from deeper horizons through the root systems of plants. Higher than average concentrations are usually the product of biological accumulation of ancient plant and animal remains (Keup, 1968).

Topography plays a vital role in the quantity of P discharge in land runoff. Flat lands with little runoff and relatively high infiltration rates would contribute the least P to streams. As the land gradient increases, the potential for erosion also increases thus increasing the potential movement of sediment bound P. Sheet erosion is more effective in moving this P than is gully erosion (Keup, 1968).

Land vegetation determines the quantity of P in the land runoff as it controls the rate of runoff and the subsequent erosion. Crop lands may be fertilized thereby increasing the P load in the soil. Streams in forested or fallow areas discharge less P than in areas subjected to agricultural or urban development (Keup, 1968).

Urbanization is accompanied by an increase in P discharged to the surface waters (Keup, 1968). Stormwater runoff from urban areas is generally recognized to be a greater non-point source of P than runoff from most types of rural land use (Simpson and Kemp, 1982). Generally speaking, a denser population adds more P to the streams draining the catchment (Keup, 1968). Sylvester (1961) reported a wide range in P concentrations in urban street gutter drainage and attributed this variability to length of dry weather periods, frequency of street sweeping and the presence or absence of leaves from trees.

2.3 Transport of P

Most P is transported through the water hydrological cycle. The point where the P enters the hydrological cycle depends not only on the type of source and its location but also on the form in which the P occurs (Bath, 1989). Gaseous, emulsified and dispersed air-borne P enters the water route following deposition on the surface by precipitation and/or dry fallout. Soluble P mixes directly with the water. Relatively insoluble P is either dispersed or picked up during rain storms through subsequent surface runoff. Some P is adsorbed onto soil particles and transported by water in the particulate phase (Bath, 1989). Novotny *et al.* (1978) describe an idealized hydrological routing of P through the environment explaining transport of P in four categories :

a) atmospheric transport from air movement, wind erosion, dust fallout and precipitation,
b) overland flow transport resulting from surface runoff, erosion and sediment pickup, infiltration and contamination of groundwater, dissolution of deposited soluble P, adsorption and transformation of P in soil,
c) channel flow of P including convection, dispersion, sedimentation, scour, adsorption, release, degradation and transformation, and
d) deposition of P at estuaries where flow velocity decreases. The suspended particulate P and adsorbed fractions are subject to sedimentation during overland and channel transport and are able to settle out in sections of low water velocity or to be resuspended during high flows. Consequently the suspended and adsorbed materials lag behind the water movement and a portion of the P may be incorporated into alluvial deposits in the stream (Novotny *et al.*, 1978).

Logan (1982) explains the overland flow transport from a field during a runoff-producing rain as follows :

a) Precipitation strikes the soil surface and a fraction infiltrates while another portion runs off.
b) Part of the water that infiltrates continues to percolate downwards and partially reacts with only a shallow zone of soil, below the surface, before leaving the field in the runoff. This zone of interaction is probably < 1 cm.
c) Precipitation striking the soil surface dislodges soil particles and runoff carries some of the eroded soil downslope with only a fraction actually leaving the field as sediment. During the erosion and sediment transport process, there is

a selective removal of clay-sized mineral particles and organic matter, and both of these materials contain higher levels of P than the coarser sand and silt fractions.

d) As water reacts with the soil surface, dissolved P held in soil pores is removed, water soluble soil P compounds are dissolved, and some of the inorganic P sorbed on soil surfaces is desorbed into the water. Also some dissolved P is contributed from any decaying vegetation.

e) The final concentration of dissolved P in runoff leaving the field will be determined by the equilibrium between dissolved P and the sediment.

The paths and processes acting in the export of P from catchments to receiving waterbodies is shown in Figure 2.1.

2.4 Physical/Chemical Characteristics of P

P may be grouped into two physical fractions i.e. dissolved and particulate P. Dissolved inorganic P (mainly $H_2PO_4^-$ or HPO_4^{2-}) is the directly bioavailable form. Other forms are dissolved condensed P (P-O-P bonds) and dissolved organic P (P-O-C bonds) which are bioavailable only through conversion to inorganic P. Dissolved condensed P includes both natural compounds and the P compounds found in P detergents, and usually have a short lifetime in natural waters due to hydrolysis to dissolved inorganic P (Sonzogni *et al.*, 1982). The dissolved organic P released from soils is more stable and is usually present in lower concentrations than dissolved inorganic P in urban and rural runoff (Browman *et al.*, 1979).

Particulate P often comprises a high proportion of the total P input to waterbodies. The particulate P fraction can consist of inorganic, organic and condensed forms (Sonzogni *et al.*, 1982). Inorganic P is the most significant as a source of bioavailable P in most natural waters (Sagher, 1976). The condensed particulate P compounds generally comprise a small portion of the total particulate P. Organic P in eroded soil particles (the major source of particulate P in streams) is relatively stable and the fraction converted to dissolved inorganic P in natural waters is probably small (Rodel, Armstrong and Harris, 1977).

2.5 Chemical Interaction between P and the Environment

Soil sediment and dust particles are the primary carriers in the movement of P from a catchment. The process of fixation of P by soil and dust particles can be accomplished either by precipitation or adsorption. Precipitation refers to a process in which P forms relatively insoluble compounds. The amount of P in the particulate fraction is governed by its solubility in the soil environment. Adsorption is a physio-chemical process by which molecules or ions are immobilized by soil particles. The removal of P from the soil solution depends on the concentration of P in the solution which, in turn, is in dynamic equilibrium with the soil adsorbed component. The soil sorptivity for P is controlled by several factors :

a) aluminium and iron oxides and hydroxides are responsible largely for P retention in acid soils (Hsu, 1965 ; Tandon, 1970 ; Vijayachandran and Harter, 1975),

b) calcium compounds fix P in calcareous soils (Hsu, 1965), and

c) organic matter may contribute to P adsorption (Vijayachandran and Harter, 1975).

Huettl, Wendt and Corey (1979) stated that the major portion of P carried in runoff is often attached to sediment and Wendt and Alberts (1984) stated that most labile (dissolved plus adsorbed) P contributed by soil to runoff is derived from soil particles that are detached and transported with runoff water.

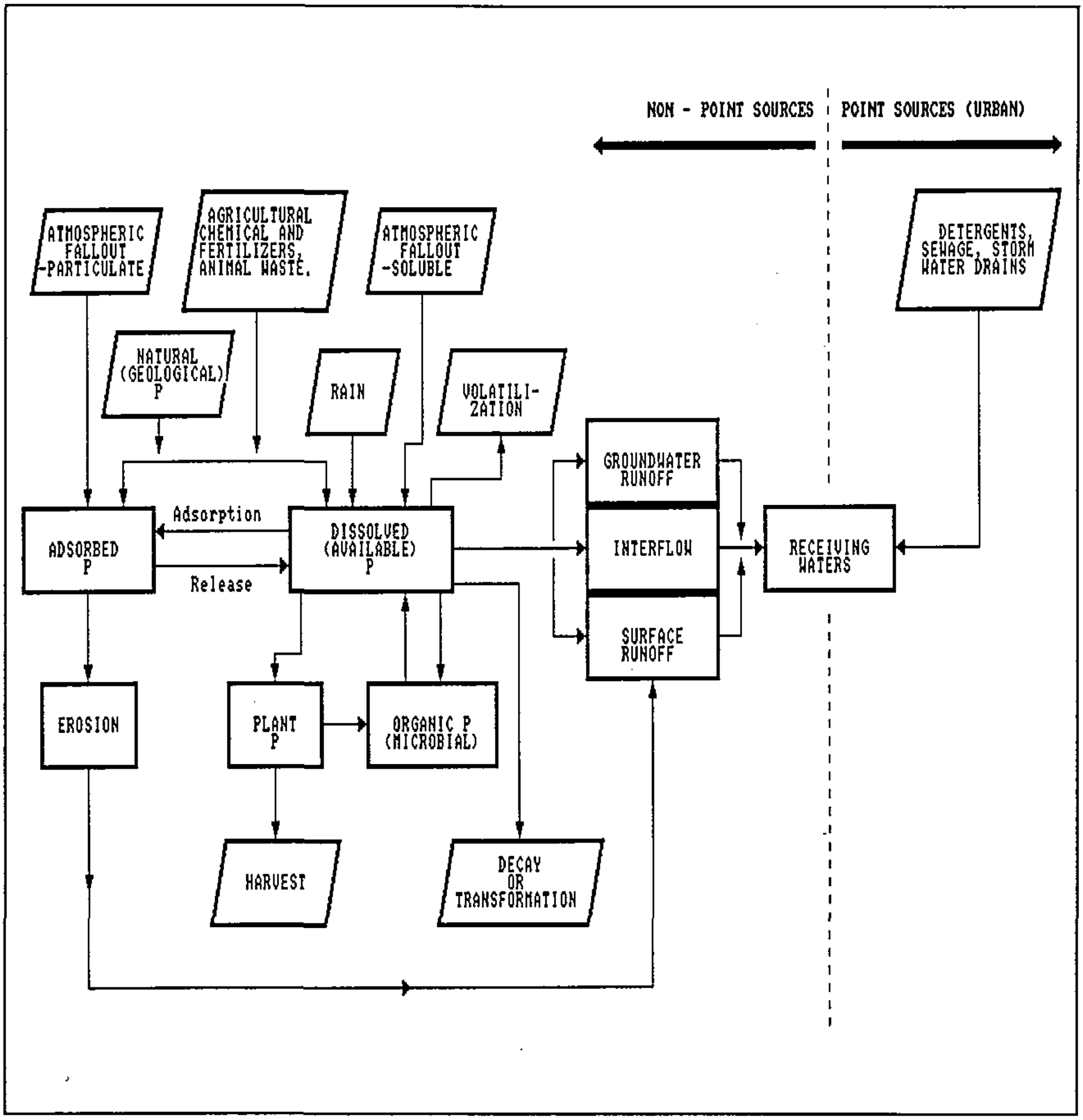

Figure 2.1 Paths and processes of non-point source P export

2.6 P Load in Streams

P is not a conservative element and it undoubtedly incurs several changes once it enters a flowing waterway. It can be taken up physically or assimilated biologically. Suspended solids in waste waters eventually settle to the bottom of receiving streams. Any P bound in these solids would be incorporated, at least temporarily, into bottom or bank deposits (Bath, 1989). Soluble P ions may combine chemically with metallic cations to form precipitates. Sorption of P by particulate material plays a vital role in the reduction of soluble concentrations. Subsequent settling and deposition of this particulate material will reduce the total quantity of P in the water mass. High proportions (80 %) of P fertilizers are rapidly and tightly fixed to inorganic soil particles (Miller and Turk, 1951). Hepher (1958) demonstrated that soils, especially those rich in calcium, can readily remove P from water. The majority of a waterway's P is tied up in organic materials (phytoplankton and attached littoral vegetation), probably not more than 10 % ever being in a soluble form at any one time (Odum, 1959).

Significant quantities of P may pass downstream, unmeasured, as portions of bed loads or as floating materials. Substantial amounts of P may be temporarily stored in stream bottom deposits that are subsequently scoured from the channel and rapidly discharged during periods of rising water levels (Bath, 1989). Much of this resuspended P is ultimately deposited when, because of reduced velocities, settling occurs on flood plains during flood periods, or on the deltas in lakes, reservoirs and estuaries (Keup, 1968).

2.7 Simulation Modelling

The eutrophication process begins in the catchment of the waterbody where nutrients are produced either naturally or anthropologically. Nutrients are exported to the receiving waterbody, in which concentrations change according to the nutrient loads it receives and in response to the biological and chemical processes taking place in it. Eutrophication management models have to simulate the history of P export from the catchment to the receiving waterbody. The first, and probably the most important, step in this process is the simulation of P export from a catchment, into its drainage system (Bath, 1989). Eutrophication management is usually directed at phosphorus control because phosphorus is generally the growth limiting nutrient in fresh water systems and offers the best options for control (Grobler, 1985a).

The development of a model for simulating the P export from catchments should keep the following objectives in mind :

a) The model should be applicable to catchment systems in semi-arid and arid regions by not being limited to the steady state assumption which does not allow the effects of the large hydrological variability characteristic of the region to be simulated.

b) The model should be simple and should depend on data that are generally available for its input.

2.8 Phosphorus Modelling in South Africa

In southern Africa the need for reservoir eutrophication control strategies tied in with phosphorus modelling has its origin in the early 1970's. Toerien (1977) reviewed eutrophication in South Africa and provided tentative guidelines for its control. After several years of research using data from selected South African reservoirs Walmsley and Butty (1980) reported updated guidelines for the control of eutrophication in South Africa. On the basis of these reports the Department of Water Affairs decided to implement measures to control the causes of eutrophication and not the consequences. It was assumed that between 80% and 90% of the total P load from 'sensitive' catchments originated from point sources (Taylor *et al.*, 1984), however Grobler (1985a) showed that a large proportion of the P entering reservoirs originated from non-point sources. The need to quantify these non-point source additions thus became apparent.

In the mid 1980's a stochastic model was developed to relate P export to catchment runoff in South Africa, for catchments containing mainly non-point sources (Grobler, 1985a ; Grobler and Silberbauer, 1985). Grobler and Rossouw (1988) later improved the model and developed regression parameters relating phosphorus export to runoff in seven non-point source dominated South African catchments and Bath (1989) developed a dynamic phosphorus export model that describes the transportation of phosphorus through the Berg River drainage basin. The model accounts for export of P from non-point (diffuse) and point sources to the main drainage channel as well as transportation of P in the water column in the main channel taking due account of abstraction of P from the column by settlement, biological growth, etc., and remobilization of P into the water column by high flows. Non-point source P export is modelled empirically using a refined looped P-discharge rating method (Bath, 1989).

Stochastic and empirical models however are usually restricted to use in the areas of their development. More portable deterministic models to simulate non-point source P export from catchments are as yet not available for southern African conditions.

At present the REMDSS suite of models (Rossouw, 1990), is used to model the effects on phosphorus and other variables on eutrophication in southern African reservoirs. The model accepts as input, amongst others, P loads entering the reservoir. The P input is usually in the form of a monthly time series. Although stochastic regression-based P export models have, until now, been used to provide the P input data for REMDSS, it is envisaged that a suitable deterministic model could be used in catchments for which adequate data exist. This is an important consideration in the justification of the deterministic P export model development.

3. THE DETERMINISTIC MODEL

3.1 Introduction

Increasing contamination of waterways and reservoirs in southern Africa by excess phosphorus (P) has manifested itself in increasing eutrophication problems and the need for the quantification of the P entering southern African reservoirs. Unlike point sources, non-point (or diffuse) sources of P exported from catchments cannot be quantified directly. Although several stochastic and empirical models have been developed to simulate non-point source P export, these models are generally specific to the area of their development. Deterministic models, based on physical processes can be used in a far wider range of areas than can their stochastic and empirical counterparts and would provide a useful tool in the control of eutrophication. One such model is described in this chapter.

For the development of a deterministic Phosphorus Export Model (PEM) it was decided that the Pitman monthly runoff model would be used to generate monthly runoff values for input to the PEM. The Pitman model was developed to simulate monthly runoff hydrographs for any catchment in southern Africa, using available meteorological data (monthly rainfall and evaporation) as well as catchment parameters derived from catchment maps and information published by Pitman (1973).

The Pitman model does not calculate the export of nutrients/contaminants which reach the catchment waterway via runoff and pickup from non-point sources. The Pitman model computer program has been rewritten in PASCAL (as opposed to the original FORTRAN) and revised to ensure greater user-friendliness and a lower incidence of operator errors, whilst maintaining the integrity of the original program. The PEM accepts as input observed or simulated monthly catchment runoff values provided via the Pitman model and is based loosely on the monthly diffuse salt load model developed by Herold (1980).

It was decided that a time resolution of one month was adequate for development and use of the PEM, the reasons being :

a) for most water resource problems, a time resolution of one month has been found to be adequate (Pitman, 1973),
b) hydrologic input data is readily available over monthly intervals, and
c) the reservoirs and impoundments into which the P laden waterways eventually flow are large with long detention times (of the order of years) and it is anticipated that mixing is reasonably good. Accordingly, it could be assumed that the adopted time step of one month would be compatible with the availability of data, would ensure reasonable computational times (Herold, 1980), and would provide output of value to water quality managers.

Furthermore Pitman (1977 ; 1978) compared three of his own models of differing complexity with the Stanford Watershed Model using data from three temperate catchments. The Stanford Model and the most complex Pitman models required hourly rainfall inputs, while the other two models required respectively daily and monthly rainfall inputs. The outcome of the study was that the two simpler models produced monthly and annual outputs at levels of accuracy comparable with those of the complex models. Pitman concluded that his monthly model would be as suitable for water resources analysis as any of the more complex models. The implications of these findings are far-reaching. The choice of model that is just sufficiently complex in terms of input and structure to provide results at a level of accuracy that is adequate for the application in mind would minimize the cost of data collection and the time, effort and computer costs involved in familiarisation and calibration of the model (Görgens, 1983).

The aim of the project is the use of the Pitman monthly hydrological model to simulate runoff values or to use available observed streamflow values for input to a Phosphorus Export Model (PEM) for non-point source dominated southern African catchments. Equations and methods for the calculation of P export have been adapted from the available literature.

3.1.1 Choice of the Pitman Model

The Pitman model has been developed to simulate monthly runoff hydrographs for any catchment in southern Africa, on the basis of available meterological data (adequate monthly rainfall and evaporation data) as well as parameters that can be derived readily from catchment maps and information published by Pitman (1973).

The Pitman model is used by the Department of Water Affairs (DWA) as the standard model for the simulation of runoff hydrographs required for water resource planning and hydrological structure design in southern Africa. The choice of the Pitman model was based on three major considerations, namely :

a) The Pitman model is used by the DWA to simulate runoff from catchments. The simulated runoff data drives the water balance in the REMDSS. As P export is such a runoff dependent process, the same hydrological model used for generating runoff should be used to generate P export from catchments.

b) As the P export model will be used to assist in decision making concerning the implementation of the 1 mg P/l standard, it was deemed necessary to base the hydrology on a model which was well known in the southern African hydrological community. A further pre-requisite was that the model should have been well tried and tested over the years and thus instill confidence, through familiarity, in the user.

c) During recent years monthly and daily models developed by Pitman (1973 ; 1976) have been gaining a reputation in water resources engineering circles as the "standard" South African models (Hydrological Research Unit, 1981-1982).

d) Input requirements for the model are easily satisfied.

3.1.2 Improvements to the Pitman Monthly Model Program

Pitman (1973) wrote the computer model using the FORTRAN programming language. The model was intended for use on a Mainframe computer system with input being read from punched cards or an input file and output being directed to a printer. The model contains the basic principles and mathematics as described by Pitman (1973). Recent improvements (Pitman, 1989) to the model include :

a) adaptation for use on IBM compatible PC's,
b) allowances for, and consideration of, irrigation usage of catchment flows, effects of farm dams and forest uptake of available water,
c) computation of several indices of river behaviour,
d) plots of several trends of the observed and simulated record, and
e) an interactive calibration option.

As PASCAL is the programming language used generally by the DWA and the Division of Water Technology of the CSIR, it was deemed to be in the best interests of the P export project that the Pitman model be translated from FORTRAN to PASCAL. This step was tackled and completed with emphasis being placed on increasing the user-friendliness of the computer program. The improved program includes the following modifications :

a) Improved input/output file selection handling - files that are requested by the program are input by the user and then checked for existence. If input files specified by the user do not exist in the drive directory the program will inform the user and provide options for ending the program, re-entering the requested file or displaying the current drive file directory through a link to the DOS. If output files specified by the user already exist the program informs the user and provides options to end the program, re-enter the requested file, overwrite the specified existing file or display the current drive file directory. This allows the user greater flexibility without the destruction of existing files or abortion of the program as was the case with the original program.

b) Improved parameter input handling - the option to input parameters from a file or from the keyboard is provided. After all the parameters have been input they are displayed and the user may change any parameters to a new value. This allows the user to check that the parameter values input are correct before the program is allowed to run.

c) Improved runtime sequential program execution information - messages to the user are displayed during execution of the program in order to inform the user as to the stage of the program.

d) Improved display information and requests - only that information that is of immediate use to the user is displayed, resulting in a less cluttered display and increasing the understanding of what is requested from the user.

e) Improved output presentation - the output file presentation has been restructured to provide the user with a neater and more readable hard copy of results.

3.1.3 PEM Criteria

In order to comply with the provisions of the funding organisation and the integration of the P export component with the Pitman runoff component, the PEM :

a) must be a physically based (deterministic), digital, monthly simulation model and must require a minimum of calibration for each application,
b) must be simple and easily understood,
c) must have as few parameters as possible,
d) must represent the physical system relatively accurately,
e) must have input requirements that can be satisfied easily,
f) must estimate surface runoff, groundwater runoff and total P loads exported from a catchment, and
g) must consider catchment characteristics such as size, topography, geology, soil type, land use and management practices.

3.1.4 PEM Components

Although hydrology is only one component of the total system, water is the principle element as it causes erosion, carries nutrients and is an uncontrolled natural input. Each climatic region and physiographic area has its own characteristics that affect the response of the system. These varied conditions must be kept in mind when considering wide-scale applicability of the model. The logic of the model is that runoff provides the transport medium for the export of P.

The hydrological component consists of the Pitman monthly runoff simulation model (Pitman, 1973). In this component rainfall and potential evaporation are the sole hydrological data inputs. Calculations begin from assumed soil water conditions and are terminated when input data are exhausted. Rainfall is stored as interception and as soil water and this is subject to evaporation and transpiration. The quantity of rainfall that is not absorbed by the soil is the source of surface runoff. A portion of the rainfall held as soil water finds its way, via percolation and interflow, to the groundwater and thereby to the river system. By suitably lagging the various components, one may compute the movement of surface and sub-surface water down a catchment.

The PEM accepts as input recorded or modelled monthly runoff volumes and model parameters. The runoff is split into surface and groundwater flow components. P loads derived from the groundwater flow are calculated as the product of the groundwater flow and P concentration while the surface P washoff is calculated as a function of surface runoff intensity and sediment yield.

3.2 The Pitman Monthly Runoff Simulation Model

3.2.1 Introduction

The most basic input into hydrologic systems is the surface runoff. With this in mind (Pitman, 1973) developed a FORTRAN hydrological model to simulate monthly river flows from southern African catchments. The model uses available meteorological data such as monthly rainfall and evaporation as well as catchment parameters which can be derived easily from available catchment maps.

Several mathematical streamflow simulation models to extrapolate sparse flow records both spatially and temporally exist, but most of them demand hydrological inputs of finer detail than are generally available in southern Africa. Pitman (1973) developed his model on the basis of readily available meteorological data and parameters that could be derived from catchment maps. The model was kept as simple as possible so as to minimize the number of parameters to be evaluated. Parameter values derived from calibration of the model were correlated with physical features of the respective calibration catchments and were regionally mapped. It is thus possible either to simulate river flow at ungauged sites or to extend the hydrology at gauged sites to cover the period of the meteorological record.

In viewing the hydrologic cycle as a system that transforms the input (rainfall) into an output (runoff), one sees that in a hydrological model one attempts to duplicate the transformation. Pitman (1973) has defined his model as a digital, parametric-type model. Digital computer models merely carry out the specified computations of a mathematical representation of the system elements and interactions. The major task of the parametric approach to modelling is the definition of parameters representing physical processes and the relationships between them. The parametric model, with it's unique response to a given input, is suited to short range analysis.

A basic explanation of the Pitman model follows.

3.2.2 Model Structure

The essential elements of the model are depicted in Figure 3.1. Precipitation and potential evaporation are the sole data inputs. Calculations begin from assumed soil water conditions, as determined from initial catchment discharge, and are terminated when input data are exhausted. Precipitation is stored as interception and as soil water which are subject to evaporation and transpiration. The quantity of precipitation that is not absorbed by the soil is the source of surface runoff. A portion of the precipitation held as soil water percolates to groundwater before entering the river system. The various components are suitably lagged and the total runoff volume at the catchment outlet is computed on a mass balance basis.

3.2.2.1 *Precipitation*

The model is designed to handle input data to one-month time resolution, however provision is made to solve the catchment water balance at daily time intervals. Figure 3.2 is a typical plot of cumulative rainfall for a given month.

The observed cumulative curve will generally differ markedly from the average rate, represented by the chain-dotted line in Figure 3.2. The range of maximum deviations above and below the uniform rate line, denoted by W, represents a convenient measure of the non-uniformity of rainfall input. It would be possible to synthesize a representative mass curve if there were to exist a relationship between W and P, the total precipitation for the month (mm).

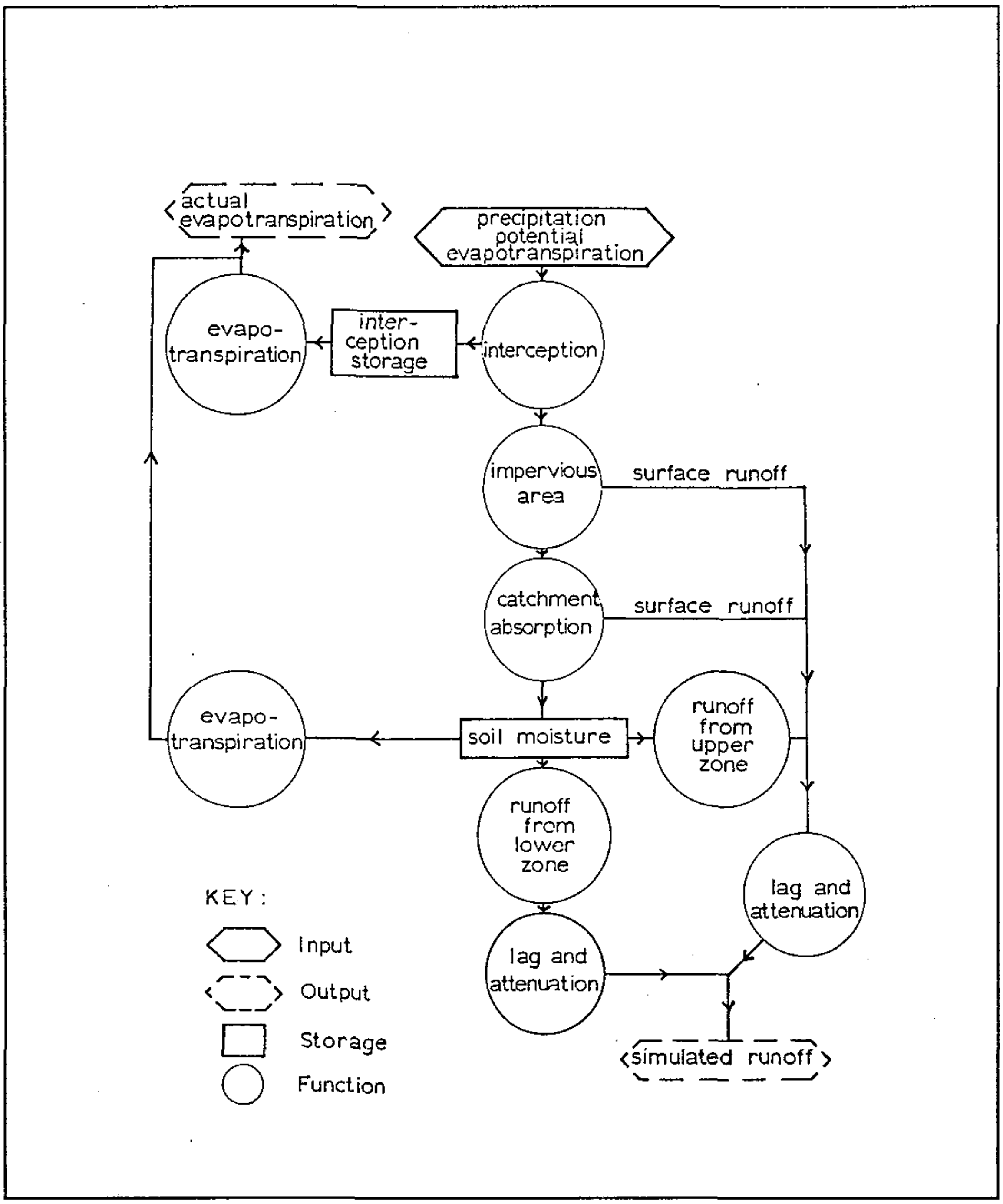

Figure 3.1 Pitman model flowchart (Pitman, 1973)

Using daily rainfall data abstracted from several widely-spread locations in South Africa, Pitman (1973) computed a P-W curve of best fit described by Equation 3.1 given below :

$$W = -2 + 1.3732*(P + 1.6)^{0.8} \qquad \text{Eq. 3.1}$$

Equation 3.1 satisfies the requirements that at $P = 0$, $W = 0$ and $dW/dP = 1$. Once the value of W has been established for a given month it is necessary to synthesize a mass curve having a range, or degree of non-uniformity, equal to W.

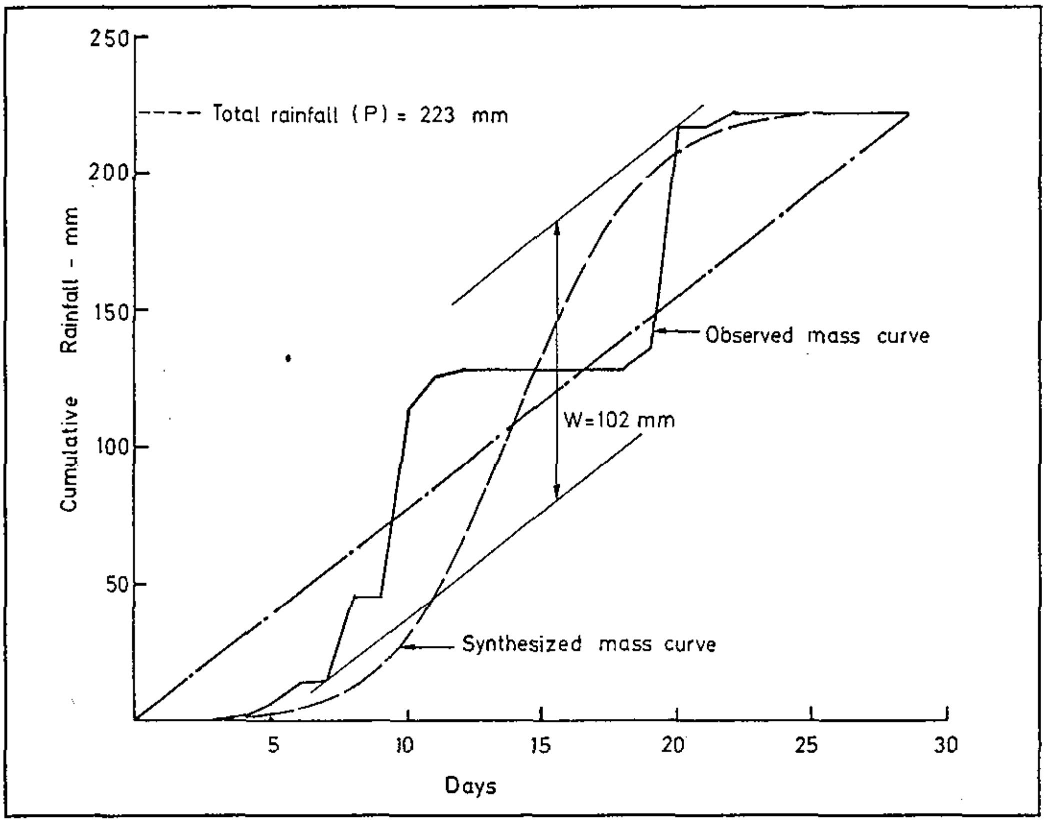

Figure 3.2 Cumulative rainfall curves (Pitman, 1973)

The equation of the mass curve was selected to satisfy the following requirements :

a) the month's precipitation is equally divided between the first and latter halves of the month, and
b) W is evenly divided above and below the line representing uniform rainfall distribution.

It follows that an equation yielding an 'S'-shaped curve is applicable. The following equation was adopted :

$$y = x^n/(x^n + (1 - x)^n) \qquad \text{Eq. 3.2}$$

in which : y = cumulative precipitation/total precipitation,
x = cumulative time/total time, and
n = exponent related to W.

The relationship between n and W within the range of likely values was approximated by the following equation :

$$n = 1.28/(1.02 - W/P)^{1.49} \qquad \text{Eq. 3.3}$$

3.2.2.2 *Interception*

Figure 3.3 displays mean curves relating monthly interception to monthly precipitation for given interception storages. Equations to these curves take on the form :

$$I = x^*(1 - e^{yP}) \qquad \text{Eq. 3.4}$$

in which : I = total interception for month (mm),
P = total precipitation for month (mm), and
x,y = constants.

For the range of interception storages considered to be applicable (0-8 mm), the empirical relationships between x, y and PI, the interception storage (mm), were found to be :

$$x = 13.08^*(PI)^{1.14} \qquad \text{Eq. 3.5}$$

and

$$y = 0.00099^*(PI)^{0.75} - 0.011 \qquad \text{Eq. 3.6}$$

3.2.2.3 *Surface runoff*

Surface runoff is taken to be derived from two components :

a) runoff from impervious areas, and
b) runoff resulting from rainfall that has not infiltrated into the soil.

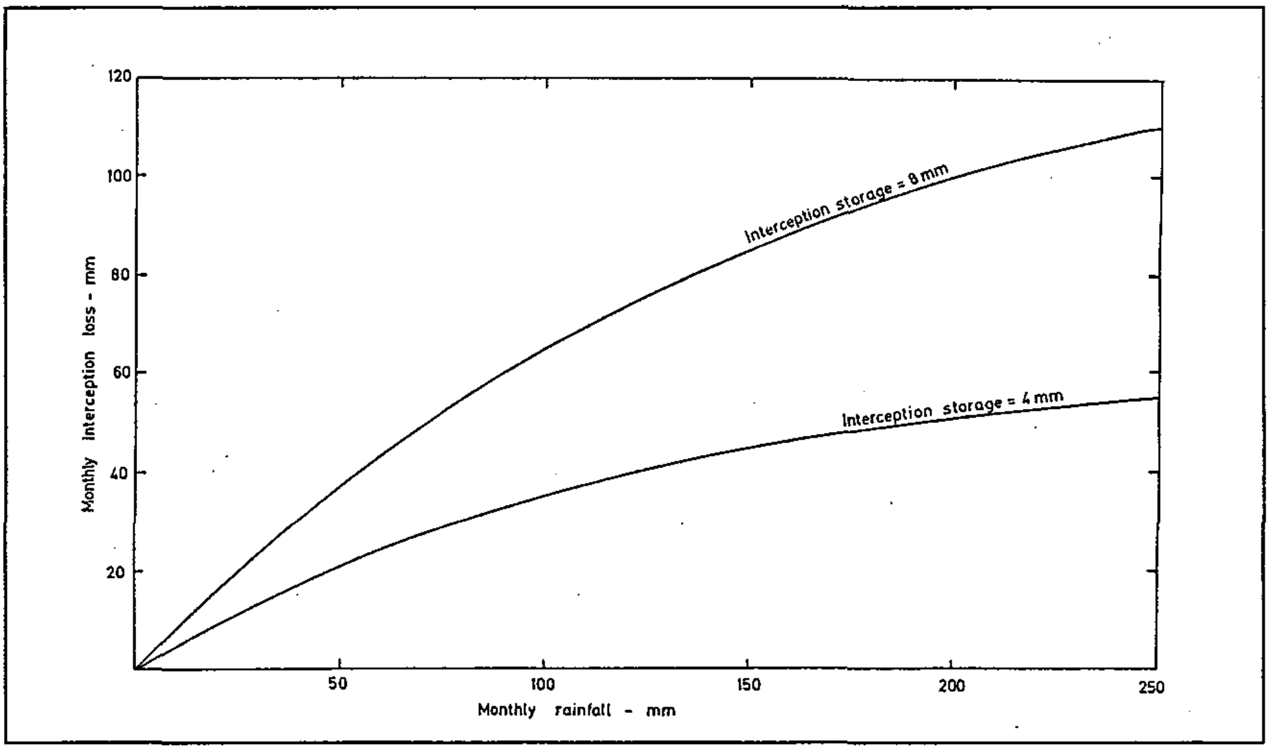

Figure 3.3 Monthly interception loss (Pitman, 1973)

Component a) is computed by multiplying the catchment rainfall available for infiltration and runoff by the area of the catchment that is impervious. In computing component b) it was recognised that infiltration would be highly unlikely to be uniform throughout the catchment and that the spatial distribution would be strongly influenced by physical features of the catchment. By assuming a symmetrical frequency distribution of infiltration rate, which appeared to yield the best combination of flexibility and mathematical simplicity, the parameters related to this phenomenon could be reduced to a manageable number. The distribution is shown in Figure 3.4a in which :

Z_1 = minimum infiltration rate (mm/month),
Z_3 = maximum infiltration rate (mm/month), and
Z_2 = mean infiltration rate (mm/month) = $0.5*(Z_1 + Z_3)$.

The cumulative frequency curve is plotted in Figure 3.4b below where :

for $Z \leq Z_2$: $y = (Z - Z_1)^2/((Z_3 - Z_1)*(Z_2 - Z_1))$ Eq. 3.7

for $Z \geq Z_2$: $y = 1 - 2*(Z_3 - Z)^2/(Z_3 - Z_1)^2$ Eq. 3.8

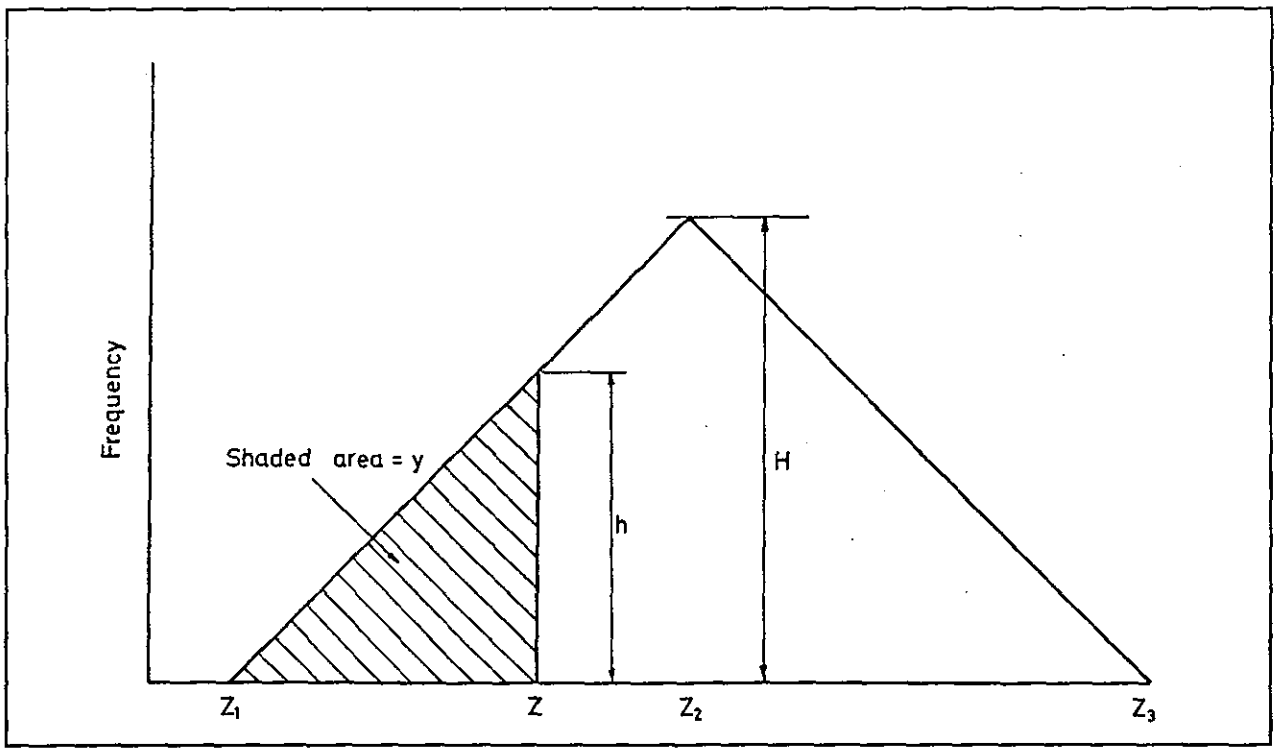

Figure 3.4a Assumed frequency distribution of catchment infiltration rate, Z (Pitman, 1973)

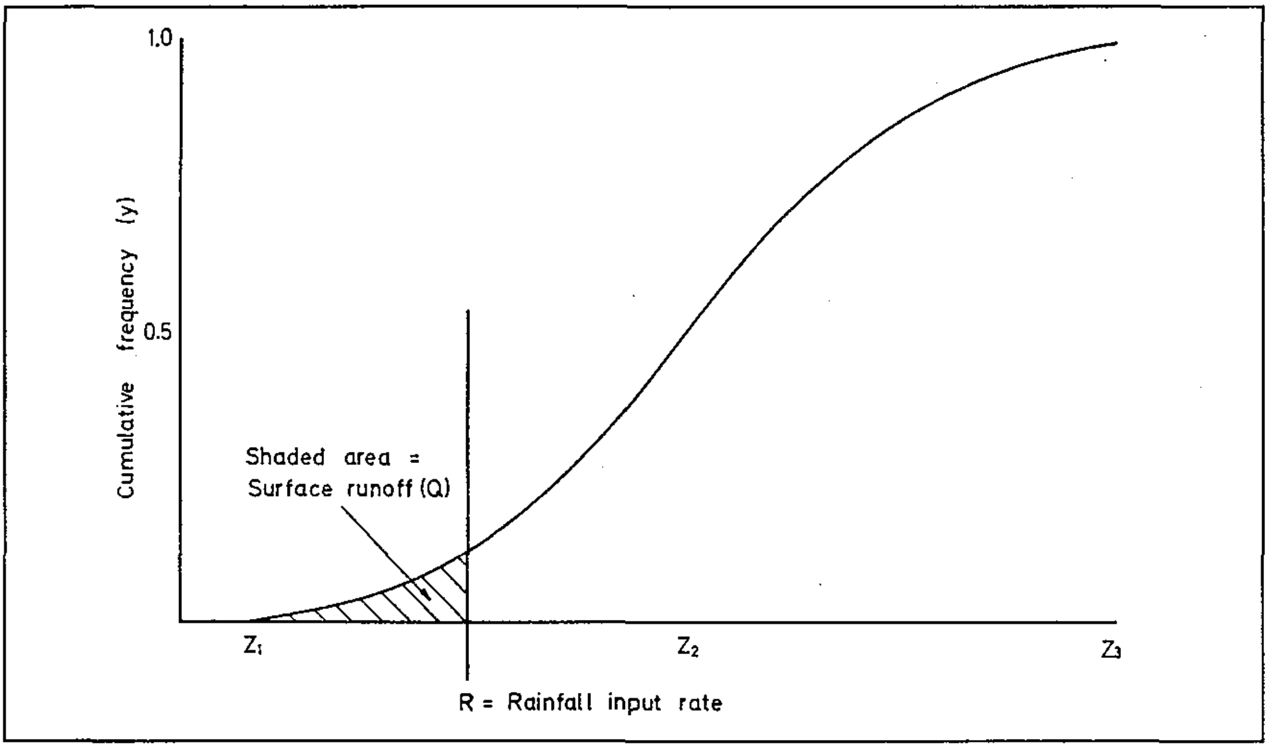

Figure 3.4b Cumulative frequency curve (Pitman, 1973)

The runoff rates, Q (m^3), for any given rainfall input rate, r (mm), are given below :

for $Z_1 \leq r \leq Z_2$: $Q = (2*(r - Z_1)^3)/(3*(Z_3 - Z_1)^2)$ Eq. 3.9

for $r = Z_2$: $Q = (1/12)*(Z_3 - Z_1)$ Eq. 3.10

for $Z_2 \leq r \leq Z_3$: $Q = r - Z_2 + (2*(Z_3 - r)^3)/(3*(Z_3 - Z_1)^2)$ Eq. 3.11

for $r = Z_3$: $Q = 0.5*(Z_3 - Z_1)$ Eq. 3.12

for $r \geq Z_3$: $Q = r - Z_2$ Eq. 3.13

3.2.2.4 *Evaporation - soil water relationship*

To achieve maximum simplification of the computational work and also to keep the number of parameters manageable, the evaporation - soil water relationship was assumed to lie anywhere between the limits depicted in Figure 3.5.

The catchment evaporation was calculated as :

$$E = PE * (1 - (1/(1 - R * (1 - PE/PEMAX))) * (1 - S/ST))$$ Eq. 3.14

in which : PEMAX = maximum potential evaporation for month (mm),
PE = potential evaporation for month (mm),
R = ratio of S at which evaporation ceases to the corresponding value of

S in Figure 3.5 for (R = 1),

S = soil water (mm), and

ST = soil water at full capacity (mm).

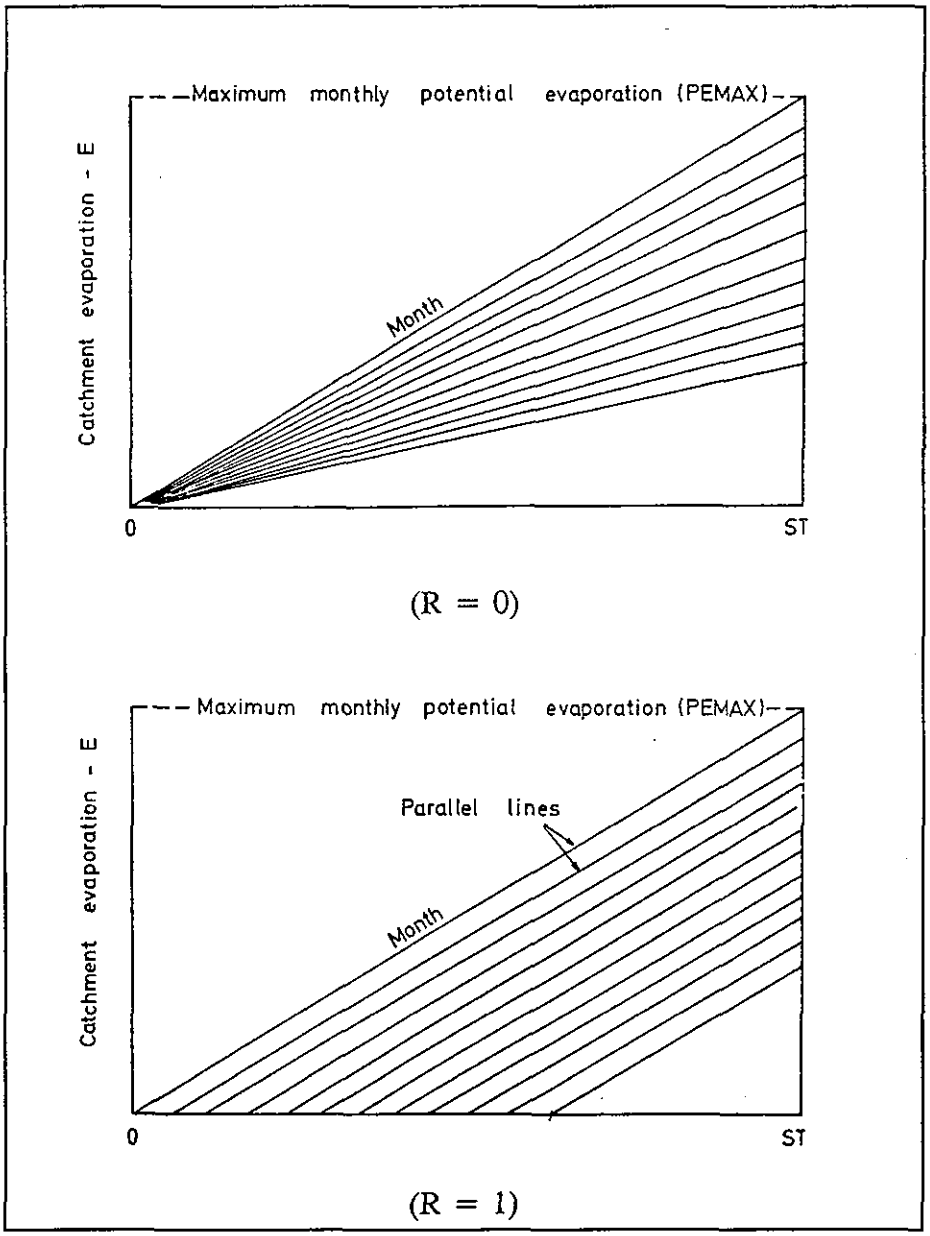

Figure 3.5 Limits of evaporation - soil water relationship (Pitman, 1973)

3.2.2.5 *Runoff - soil water relationship*

The generalized relationship between soil water and that component of runoff assumed to be directly related to soil water is depicted in Figure 3.6.

The Q - S relationship is a simple power curve which can be expressed by the following equation :

$$Q = FT*((S - SL)/(ST - SL))^{POW} \quad \text{Eq. 3.15}$$

in which : SL = soil water content below which no runoff occurs (mm),
ST = total soil water capacity (mm),
FT = runoff at soil water equal to ST (m^3),
POW = power of Q - S curve,
S = soil water (mm), and
Q = runoff (m^3).

The introduction of a further parameter, the maximum groundwater runoff rate (GW) is necessary in cases where the time lags of the different runoff components vary significantly. If the soil water storage is less than SG all associated runoff is considered to be groundwater and will be lagged accordingly. If the storage is greater than SG the quantity of groundwater will be equal to GW and the remainder, (Q - GW), will be lagged to a lesser degree than the groundwater component.

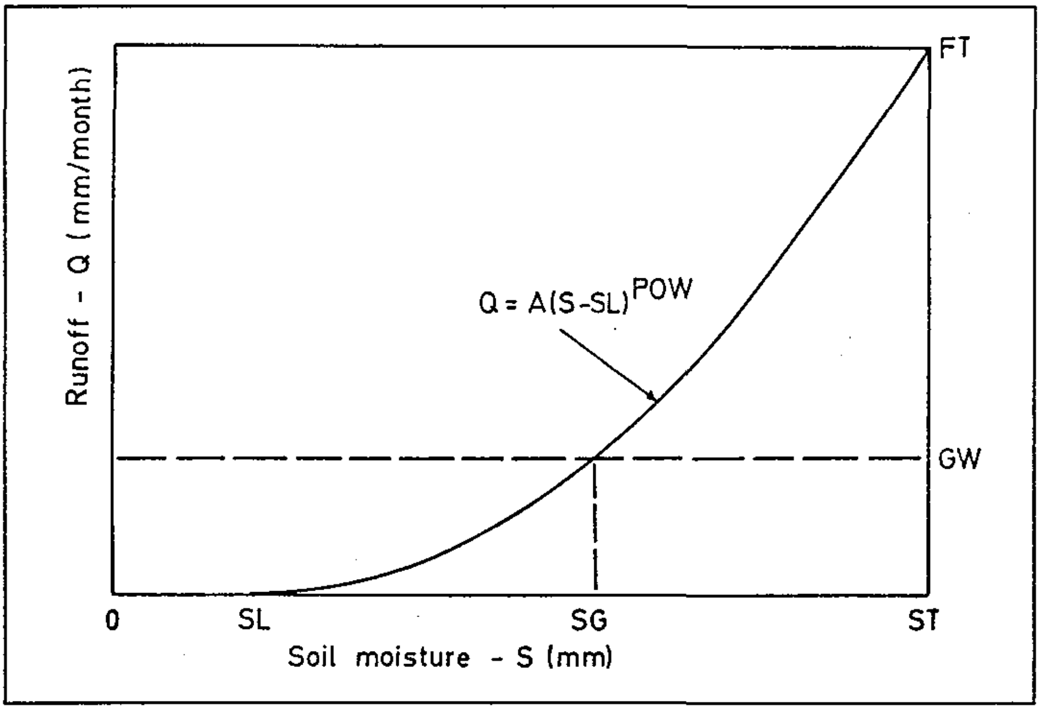

Figure 3.6 Soil water - runoff relationship (Pitman, 1973)

3.2.2.6 *Time delay of runoff*

Since the simulation model is a lumped model, i.e. the response of the whole catchment is characterized by the processes taking place at a representative location, the components of model runoff have to be lagged to indicate the runoff at the catchment outlet. The runoff for any given month computed according to the processes described may be regarded as instantaneous runoff
which must be subjected to time delay and attenuation as it moves laterally through the catchment. This is achieved by application of the Muskingum equation with the weighting factor, x, set to zero for reservoir storage-type attenuation. The equation is of the following

form :

$$O_2 - O_1 = C_1(I_1 - O_1) + C_2(I_2 - I_1) \qquad \text{Eq. 3.16}$$

in which :

$$C_1 = dt/(K + [0.5*dt]) \qquad \text{Eq. 3.17}$$

and

$$C_2 = 0.5*C_1 \qquad \text{Eq. 3.18}$$

in which : O = monthly runoff total at catchment outlet (m^3),
I = instantaneous monthly runoff (m^3),
dt = routing period, and
K = lag of runoff (months).

The subscripts 1 and 2 to I and O refer to the previous and current day's runoff respectively. In the model, allowance is made to lag two components of runoff by assigning different K values. All runoff from soil water that is equal to or less than the quantity GW is assigned a K value equal to GL and the remaining runoff is assigned a somewhat shorter lag with K = TL where TL $\ll$ GL.

3.2.2.7 *Daily rainfall*

The Pitman monthly runoff model includes a provision for daily, as opposed to monthly, rainfall input. Instead of using four time steps to represent the non-uniformity of rainfall input as was done with monthly rainfall, smaller time steps, corresponding to the number of days in the respective months, are used to represent the cumulative mass curve of rainfall. This approach leads to a decrease in the accumulated computational errors, and an increase in the execution time, of the program. Thus the use of daily rainfall has, on one hand, the advantage of greater accuracy of runoff simulation, but on the other hand, increases the rainfall input requirements. The output from the model is presented as monthly flows.

3.2.3 Simulation Tests

3.2.3.1 *Requirements of the model*

One of the basic requirements of the model was that it should represent the hydrologic regimes of a wide variety of catchments with an acceptable degree of accuracy. This criterion is especially important if the model is to be applied satisfactorily to catchments in southern Africa where there is a wide range of hydrologic regimes with extreme variance (<100mm to >3000mm) in the seasonal and regional distribution of rainfall as well as a large regional variance (1200mm to 3000mm) of mean annual potential evaporation. These wide ranges of climatic factors, together with variations in topographical features, in turn give rise to a considerable variety of vegetal cover. Pitman tested and calibrated the model using catchments displaying many different hydrologic regimes and used

a) long-term average yield of the catchment,
b) seasonal distribution of flow, and
c) reliability of runoff

as criteria for establishing the effectiveness of the model.

3.2.3.2 *Standardization of input*

3.2.3.2.1 Precipitation

The main input data to the runoff simulation model takes the form of an historic sequence of monthly averaged catchment rainfalls. A representative monthly rainfall total for a selected catchment is obtained by expressing the total at each catchment gauge as a percentage of Mean Annual Precipitation (MAP), averaging out the monthly percentile values to yield the corresponding catchment value in terms of the catchment MAP and then applying the catchment MAP to convert the average percentile value to an average depth.

3.2.3.2.2 Potential evapotranspiration

Lake evaporation, which may be estimated from Symons evaporation pan records, is considered to be a good estimate of potential evaporation. Using results from Kriel (1963) and Barker and Whitmore (1965), Pitman (1973) calculated and used pan to lake evaporation conversion factors of 0.8 for the period July - October and unity for the period November - June. Mean monthly Symons pan evaporation maps are given in Appendix B.

3.2.3.2.3 Catchment parameters

In realising the aim of the model, i.e. simplicity, Pitman (1973) conducted a parameter sensitivity analysis on selected gauged catchments and then generalized the results of the analysis using quantitative plots and regionalized maps to facilitate the selection of parameter values for use on ungauged catchments.

Table 3.1 gives the recommended values of the model parameters, or shows where these values, may be found (see Appendix A).

The best fit parameter values for selected southern African catchments using model calibrations by Pitman (1973) are given in Appendix C.

3.3 The Catchment Phosphorus Export Model (PEM)

3.3.1 Introduction

The rates and magnitudes of discharges of P, and indeed most pollutants (ie. a substance observed in nonbeneficial quantities or concentrations), from non-point sources do not relate easily to source characteristics or source-related parameters. Evaluation of the severity of non-point source pollution is hampered by the lack of tools to quantify pollutant loads, and scanty and imprecise data on the interrelationships between control measures and pollutant loads are a deterrent to formulation of control or regulatory strategies (McElroy *et al.*, 1976). In short the estimation of non-point source derived pollution is an approximate science at the present stage of development in southern Africa.

Table 3.1 Proposed parameters for ungauged areas (Pitman, 1973)

Model Parameter	Climatic Zone (see Fig. A1)		
	Humid	Semi-arid	Arid
POW	see Fig. A2	see Fig. A2	not used
SL	0	0	0
ST	see Fig. A3	see Fig. A3	see Fig. A3
FT	see Fig. A4	see Fig. A4	not used
GW, GL	not used unless recorded flow data indicate otherwise		not used
AI	generally zero, but may be estimated from suitable maps		
ZMIN	not used	see Fig. A5	see Fig. A5
ZMAX	not used	see Fig. A6	see Fig. A6
PI	1.5 mm for all areas except those covered by forest where typical values are 4 - 5 mm		
TL	generally 0.5 but see Fig. A2 for exceptions		
R	see Fig. A2	see Fig. A2	see Fig. A2

The PEM has been developed to assist in water quality management decisions by allowing the simulation of P load emissions from non-point sources and discharge of the P into surface waterways. In this respect a source is defined as a land area devoted reasonably exclusively to a specific use, which therefore can be treated as a unit with respect to land use practices and potential for P discharges. A load is defined as the quantity of P discharged to surface waters from the source per unit time. All the sources within an area of interest can be summed up to obtain the load of P discharges to surface waters from all identified sources.

Essentially three categories of data are needed. The first category is the information which describes the areal characteristics of a source : its location within southern Africa, its size and its basic land uses. A second category of data is that which is characteristic of a source or area, independently of land use. This includes data describing soil characteristics and properties, topographic features of the land, rainfall and runoff, and drainage densities. The third category of data is a description of how the source is used, such as tillage methods and conservation practices.

In the formulation of the PEM, emphasis was given to the functions and simulation procedures which were generally useful from the standpoint of the depth, quality and quantity of available data or information. For this reason, the functions are, generally, relatively simple and basic concepts, as opposed to theoretically orientated descriptions of physical, chemical, mechanical and biological processes.

The PEM has been developed for the simulation of Total Phosphorus (TP) monthly loads from a non-point source dominated catchment. The determination of available phosphorus in the soil is difficult. Most reported data fail to distinguish between soluble P, adsorbed or particulate P, and organic P in sediment runoff. Total Phosphorus is a somewhat meaningless parameter, since soluble orthophosphate is the predominant form that is readily available for uptake by aquatic organisms. Other forms of P in sediment can, however, act as a source or sink for subsequent release of P in available form (McElroy *et al.*, 1976). Despite the limitations of the TP parameter mentioned above, and considering the limited recorded orthophosphate values available, it was felt that the use of TP as a basis for the development of the PEM was justified. South African water quality managers, used to relating the trophic state of water bodies to the recorded TP values, should find use for the simulated TP values.

3.3.2 Model Structure

3.3.2.1 *Introduction*

The Phosphorus Export Model (PEM) was developed to simulate P accumulation and wash-off from predominantly non-point source dominated catchments. The model accepts as input recorded or model simulated monthly runoff volumes and appropriate catchment and process parameters. The PEM was originally envisaged as a sub-routine of the Pitman monthly runoff simulation model which would act as the 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.

The monthly runoff volumes input to the 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. P is carried almost entirely on sediment (McElroy *et al.*, 1976). Logan (1982) estimated that more than 75% of the P in surface generated runoff from agricultural land is in the particulate form adsorbed to soil particles and only a minor fraction of the P in surface runoff is in a soluble form. The P load washed off the catchment surface depends, therefore, on the monthly runoff volume as well as on sediment loss. The operation of the PEM is shown in Figure 3.7.

3.3.2.2 *Estimation of the groundwater flow component*

If the Pitman model, updated for this project, is used, a computer file of monthly groundwater and surface flow components can be obtained from the Pitman model for input to the PEM. If however another model is used to generate monthly runoff volumes, or recorded volumes are used, the monthly runoff must be separated into the groundwater and surface flow components. A sub-routine to accomplish this task is included in the PEM.

The assumption is made that streamflow below GGMAX (the maximum possible groundwater flow, in million m^3/month, during the current month) is groundwater flow (Herold, 1980). Thus :

$$QS_i = Q_i - GGMAX \quad (\text{for } Q_i > GGMAX) \qquad \text{Eq. 3.19}$$

or

$$QS_i = 0 \quad (\text{for } Q_i \leq GGMAX) \qquad \text{Eq. 3.20}$$

Therefore : $QG_i = Q_i - QS_i$ Eq. 3.21

in which : QS_i = surface runoff during month i (million m^3/month),
Q_i = total streamflow during month i (million m^3/month), and
QG_i = groundwater contribution during month i (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). Therefore :

$$GGMAX_i = (DECAY*GGMAX_{i-1}) + (PG/100*QS_{i-1}) \quad \text{Eq. 3.22}$$

in which : DECAY = groundwater decay factor ($0 < DECAY < 1$),
PG = groundwater growth factor (%), and
subscripts i and i-1 refer to the current and preceding months.

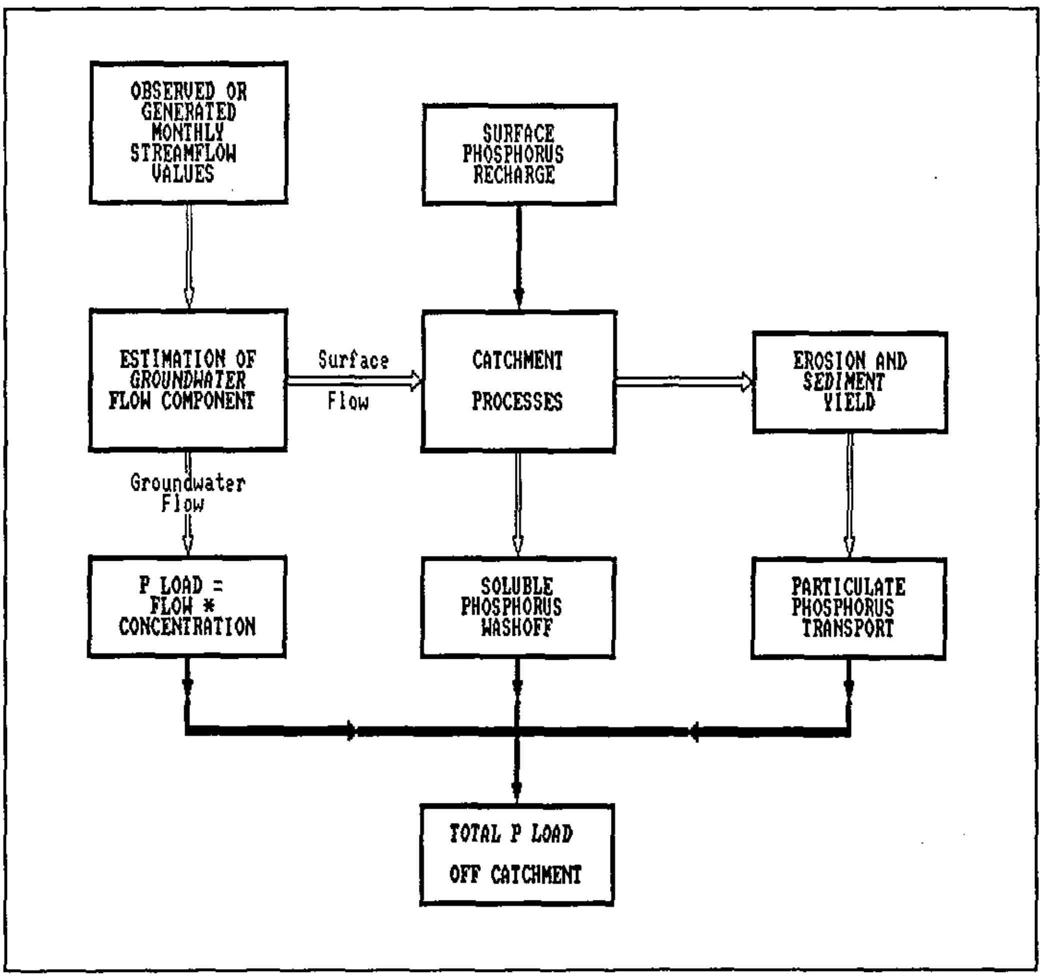

Figure 3.7 Operation of the PEM

3.3.2.3 *Groundwater P concentration*

Subsurface drainage contains virtually no particulate P because of the filtering action of the water percolating through the soil horizons (Cooke, 1988). Furthermore, the subsurface drainage contains a small concentration of P only, derived from dissolution and desorption processes within the soil. These two processes are relatively slow (Logan, 1982).

As the P load derived from groundwater drainage has been found to be negligible when compared to that derived from surface processes, the load derived from subsurface drainage has been ignored in the development of the PEM. The user can however input a value for groundwater P concentration and loads will be calculated from the product of groundwater flow and P concentration.

3.3.2.4 *Surface P balance*

P is assumed to accumulate on the catchment surfaces by a multitude of processes, the more important of which include :

a) atmospheric deposition,
b) urban,agricultural and forestry additions, and
c) in situ weathering.

Precipitation contains significant quantities of numerous substances, including phosphorus. That fraction of precipitation-borne P which does not fall on stream surfaces or does not discharge to streams via overland runoff becomes a part of the continually changing inventory of P in the soil and becomes relatively immobile in the surface layers of soil. The surface-sorbed P becomes a non-point pollutant when it is discharged to streams on eroded sediment (McElroy *et al.*, 1976). Atmospheric deposition of P at Midmar Dam, Natal was estimated to be 0.348 kg P ha^{-1} yr^{-1} (Hemens, Simpson and Warwick, 1977), while 0.6 kg ha^{-1} yr^{-1} was reported by Simpson and Kemp (1982) and Bosman and Kempster (1985) for different areas of southern Africa. For the USA values of 1.02, 0.4, 0.27, 0.11 and 0.8 kg ha^{-1} yr^{-1} were obtained (Kleusener, 1972 ; Armstrong and Schindler, 1971 ; Barica and Armstrong, 1971 ; Singer and Rust, 1975 ; Sonzogni and Lee, 1974).

McElroy *et al.* (1976) state that phosphorus losses from well managed forested soils are usually low. For USA data Duffy *et al.* (1978) reported 0.088 kg ha^{-1} yr^{-1} for a pine forest while other researchers reported values of 0.047, 0.02, 0.07, 0.2 kg ha^{-1} yr^{-1} (Taylor, Edwards and Simpson, 1971 ; Ryden, Syers and Harris, 1973 ; Sanderford, 1975). For deciduous forests in the USA, Singer and Rust (1975) reported total P losses of 0.03 kg ha^{-1} yr^{-1} while Ryden *et al.* (1973) reported values in the range 0.02 to 0.68 kg ha^{-1} yr^{-1}.

Urban additions of P are not well researched but P values in the range 0.39 to 2.3 g day^{-1} $person^{-1}$ were reported by Hemens *et al.* (1977) for southern Africa and 0.11 to 0.31 g m^{-2} yr^{-1} by Uttormark, Chapin and Green (1974) for the USA.

Agricultural additions of P range widely in value with values of between 0.02 to 3.0 g P m^{-2} yr^{-1} in surface runoff being reported by Uttormark *et al.* (1974) for the USA. For feedlots, Sharpley *et al.* (1984) reported 8100 μg P per g of manure.

Phosphorus occurs naturally in soil from weathering of primary phosphorus-bearing minerals in the parent material. Thus non-point P loads can arise from land which has not been disturbed by man's activities. Such loads, referred to as background loads, represent natural non-point emissions and can have a significant affect upon surface water quality. In general, a clear cut distinction between loads arising from background sources and loads arising from man's land-use practices is virtually impossible to achieve, either philosophically or technically (McElroy *et al.*, 1976). The concept of natural background is both quite important and difficult to describe in universally accepted terms. The importance attributed to natural background comes from the following :

a) background is often thought to represent the ideal environmental quality and thus to represent the goal for which water quality managers should strive to achieve, and
b) background accordingly is often thought to be a fundamental criterion for assessing the reasonableness of control measures and for evaluating the cost of control in relation to the benefits (McElroy *et al.*, 1976).

The rate of P accumulation can be expected to increase annually due to 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 population or industrialised area or some other index of catchment, or neighbouring, development that is likely to affect P accumulation on catchment surfaces (Herold, 1980). The rate at which P accumulates is assumed to be proportional to the growth index, POP.

Therefore, during year, i, the P storage recharge rate, R_i (t/km^2/month), is given by :

$$R_i = AREA*R_0*(POP_i/POP_0) \qquad \text{Eq. 3.23}$$

in which : AREA = catchment area (km^2),
R_0 = P recharge rate at start of simulation (tons/km^2/month),
POP_i = growth index for year i, and
POP_0 = growth index for starting year.

P stored on the catchment surface is assumed to be depleted, in its soluble form, at a rate proportional to surface runoff intensity :

$$SL_i = L_{i-1}\{1 - e^{(-SPAR*QSi*\Delta t)}\} \qquad \text{Eq. 3.24}$$

in which : SL_i = soluble P load washed off catchment surface during time Δt (tons/km^2),
L_{i-1} = P load on catchment surface at start of time step Δt (tons/km^2),
SPAR = soluble P wash-off parameter (m^{-3} * 10^{-6}), and
Δt = time step (= 1 month).

In addition particulate P, adsorped onto soil particle surfaces, is depleted at a rate proportional to the sediment yield of the catchment :

$$PL_i = L_{i-1}\{1 - e^{(-PPAR*Sed*\Delta t)}\} \qquad \text{Eq. 3.25}$$

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

The algorithm for the calculation of the sediment yield, Sed, is given in the following section.

The mass balance equation for P stored on the catchment surface is :

$$L_i = L_{i-1} + R_i - SL_i - PL_i \qquad \text{Eq. 3.26}$$

in which subscripts i and i-1 refer to the current and previous months respectively.

3.3.2.5 *Streamflow P concentration*

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

$$C_P = (SL_i + PL_i)/(QS_i + QG_i) \qquad \text{Eq. 3.27}$$

in which : C_P = P concentration of the streamflow at the catchment outlet (mg/l).

3.3.2.6 *Sediment yield*

Soil erosion in southern Africa is a serious problem due to one or a combination of :

a) arid climatic conditions,
b) intense thunderstorm activity with inherent high rainfall erosivity,
c) shallow erodible soils, and
d) limited vegetation cover and poor conservation management techniques.

It has been estimated that the average annual sediment load carried by southern African rivers is approximately 100 - 150 million tons (Rooseboom, 1975). There is as yet no simple procedure for predicting the sediment production from a catchment. Complex deterministic models representing erosion processes and sediment transport:deposition functions do exist, but remain of limited practical use owing to the requirements for input parameters which are unobtainable other than from a research catchment (Schmidt, 1989).

Simple empirical methods do, however, meet the requirements for simulating sediment loads in the absence of gauged data. The Universal Soil Loss Equation, USLE (Wischmeier and Smith, 1978), is the method that has received the greatest recognition worldwide, has seen most application and is the foundation for many other empirical equations. The USLE provides for an estimate of the long term average annual soil loss due to sheet and rill erosion. It thus excludes the soil loss due to concentrated flow and gulley formation and requires the inclusion of a separate term to represent the delivery ratio which accounts for the portion of eroded soil which leaves the catchment (Schmidt, 1989).

An advantage in the use of the USLE equation is that components of the equation have been researched extensively, also for southern African conditions. Smithen (1981), for example, investigated the areal distribution of rainfall erosivity and Smithen and Schulze (1982) presented equations to assist in its prediction at locations in southern Africa where recorded rainfall data are not available. The State Directorate of Agricultural Engineering and Water Supply in South Africa have evaluated in the past, and continue to evaluate, the erodibility of southern African soils and the effects of conservation practices and crop cover conditions on soil loss (Crosby, Smithen and McPhee, 1981 ; McPhee *et al.*, 1983). The South African Sugar Association's Experiment Station (Platford, 1982) and the Natal Parks Board (Venter, 1988) have undertaken research to improve the application of the USLE as a decision tool in sugarcane farming and in game management respectively.

In the PEM, sediment yield is calculated as :

$$Sed = Erosion*Reg*Dratio \qquad \text{Eq. 3.28}$$

in which : Erosion = USLE gross catchment erosion (tons),
Reg = regional annual EI_{30} distribution fraction for current month, and
Dratio = sediment delivery ratio.

The gross erosion is calculated using the USLE developed by Wischmeier and Smith (1978) and described in Appendix D.

$$Erosion = (R*K*LS*C*P)_i * Uarea_i * 100.0 \qquad \text{Eq. 3.29}$$

in which : 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 = land-use section (i) area (km^2),
i = one of 20 land-use or otherwise delineated areas, and
100.0 = conversion factor for ha to km^2.

Eroded soil materials often move only a short distance before a decrease in runoff velocity causes their deposition. The ratio of sediment delivered at a given location in the stream system to the gross erosion from the drainage area above that location is the sediment delivery ratio for that drainage area (Crosby *et al.*, 1981). As catchment area increases the usual trend is towards decreasing drainage density and subsequently an increase in the distance over which soil particles must be transported to the receiving water channel. P load in streams, therefore, is inversely related to catchment area (Prairie and Kalff, 1986) and directly related to drainage density. Furthermore, it is logical to assume that P load is directly related to runoff intensity. The following equation for the sediment delivery ratio is thus proposed :

$$Dratio = (Qs*Dd) / 100.0 \qquad \text{Eq. 3.30}$$

Measurements of drainage density, Dd (kms), can be made from a topographic map with a planimeter and chartometer or a digitiser. Care must be taken to include all perennial rivers to their upper reaches.

As mentioned previously, the factor Erosion in Equation 3.28 is the USLE estimate of long term average annual soil loss from a catchment. As the PEM is a monthly model, the average annual soil loss must be disaggregated into monthly values. Two methods were combined in order to satisfy this requirement.

The first method utilises Figure 3.8 (after Smithen, 1981) which shows the monthly distribution of EI_{30} values for four southern African regions. The plots show, for each month and region, the percentage of the annual EI_{30} contributed during that specific month. The factor, Reg, in Equation 3.28 is thus set to the percentage fraction for the relevant region for the current month in the calculations.

The second method (Görgens, 1991) ensures that the annual soil 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 exist.

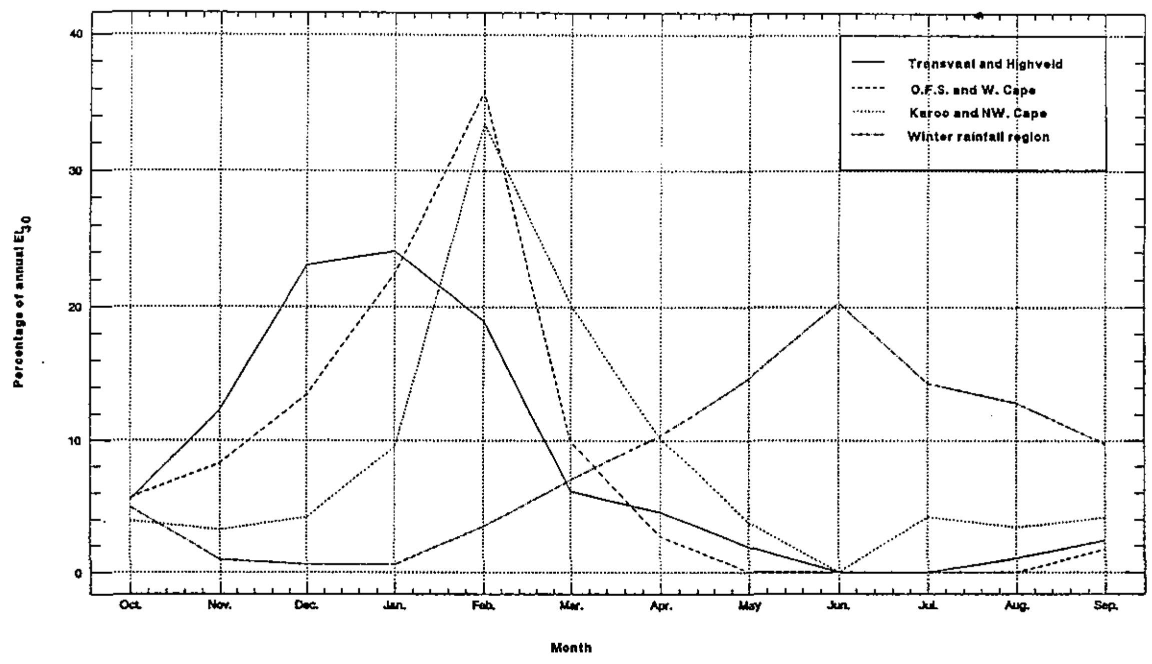

Figure 3.8 Typical EI_{30} distribution curves for the indicated regions (after Smithen, 1981)

4. DATA

Much time, effort and finance is spent annually worldwide in collection, checking, capture and storage of hydrological and meteorological data. This data is ultimately utilised for decision making concerning hydraulic structures, roads, culverts and a multitude of other engineering projects. Economic decisions also depend upon accurate knowledge of the environment and historic measurements of environmental processes. Much research is occupied with the development of environmental models to extend the data base to ungauged areas and to fill gaps in a data record.

The plethora of observed data records has, particularly in recent years, provided valuable insight into the processes governing the environment. The data base is, however, not without problems. Faulty or broken gauges and operator or transcriber errors have ensured that the user of observed data should be aware of the errors that do exist in many of South Africa's data bases.

The PEM has been developed for use with data or information on record and accessible to the user. Where data on record is inadequate or non-existent, field sampling and laboratory analysis is suggested. The user should obtain and use the best data they can find. This is usually data which have been measured or developed local to the area of interest.

The quality of the hydrometeorological data obtained from the national gauging networks of the Department of Environment Affairs and the Weather Bureau of the Department of Transport is highly variable, both spatially and temporally. Specifically in the semi-arid parts of the country, the quality of the data is not satisfactory for in-depth modelling research (Görgens and Hughes, 1982). A common problem in these areas is non-stationarity of streamflow records due to changing land-use and other human interference with the flow regime (Görgens, 1983).

A number of organisations exist, from whom data may be obtained. The onus, however, rests with the user of the data to check that the data is error free.

4.1 Data Sources

Data used for this project was obtained from a number of organisations in South Africa. Monthly rainfall values and MAP values were obtained from the Computing Centre for Water Research and the South African Weather Bureau, monthly streamflow values, P concentration values and catchment delineations were obtained from the Department of Water Affairs and evaporation values were obtained from the Soil and Irrigation Research Institute. Land use information was obtained from the Department of Agriculture and the Department of Agricultural Engineering, University of Natal.

4.2 Data Handling Methodologies

Data handling refers to the process by which the raw data is checked for errors and abnormalies before being input to the relevant programs.

4.2.1 Precipitation

The main input data to the Pitman runoff simulation model takes the form of an historic sequence of monthly averaged catchment rainfalls expressed as a percentage of catchment MAP. Monthly rainfalls supplied by the SAWB often contain months for which a problem occurred with the recording raingauge during some months. The CCWR has available, software which may be used to patch these missing values using a technique developed by Zucchini and Adamson (1984).

4.2.2 Evaporation

Monthly Symons pan evaporation values presented no problems as values follow a seasonal trend with very little daily variation in evaporation for each month. The measuring equipment is very basic and not prone to major problems.

4.2.3 Catchment Streamflow

Monthly streamflow records supplied by the DWA are generally good but do contain periods for which flow was not recorded due to gauge problems. Missing flows are somewhat easier to handle than are missing rainfall values due to the less variable nature of daily streamflow and the fact that concurrent flows are usually dependent. The method adopted for patching missing flow records was very simplistic in that the product of mean daily flow and the number of missing days for each problem month was added to the monthly total for those months with missing daily flows.

4.2.4 Phosphorus

It is impractical to measure the Total Phosphorus (TP) loads in a river continuously. Therefore it must be estimated from continuously recorded discharge data and TP concentration data obtained from grab samples taken at regular or irregular intervals (Grobler and Rossouw, 1988). Several methods are available for estimating TP loads from such data (Bodo and Unny, 1983 ; Walker, 1987 ; Bath, 1989). The most appropriate method to use depends, however, 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).

Phosphorus concentrations and daily flows were obtained from the DWA as TP, sampled at approximately weekly intervals at the outflows of the selected catchments. As the time resolution of the PEM is monthly, monthly P loads are required in order to calibrate the PEM. A method was thus required in which weekly grab samples could be converted to monthly loads. Due to highly variable fluctuations in P concentration, especially during the high flow periods, the most obvious solution of multiplying the average monthly concentration by the monthly flow does not constitute sound statistical practice.

It was found that the most suitable model for estimating monthly TP loads in rivers characterized by highly variable flows was the flux:discharge regression model developed by Walker (1987). The computer program, FLUX, developed by Walker (1987) is an interactive program for estimating loadings or mass discharges passing an outflow monitoring station over a given period. These estimates can be used in formulating reservoir nutrient balances over annual or seasonal averaging periods appropriate for application of empirical eutrophication models. The function of the program is to interpret water quality and flow information derived from intermittent grab or event sampling to estimate mean or total loading over the complete flow record between two dates.

Since the appropriate loading calculation method depends partially upon the concentration-flow-seasonal dynamics which are characteristic of a given station and component and upon the sampling program design, five alternative calculation methods are provided. An option to stratify the samples into groups based upon flow and/or date is also included. In many cases, stratifying the sample increases accuracy and reduces potential biases in loading estimates. The variances of the estimated mean loadings are calculated to provide relative indications of error. A variety of graphical and statistical diagnostics are included to assist the user in evaluating data adequacy and in selecting the most appropriate calculation method and stratification scheme for each loading estimate (Walker, 1987).

The conversion of grab sample P concentration to loads using FLUX followed the same course as that described by Grobler and Rossouw (1988). It was found that the load:discharge regression model methods 4 and 5 were the most appropriate in that they provided load estimates with the lowest variance and the least bias. To assess the validity of the selected load:discharge regression model, a linear regression equation was fitted to the simulated and observed load data for the sampled discharge record. Three statistical criteria were used to assess the correspondence between the two sets of values. The R^2 value was used as a measure of goodness-of-fit with R^2 approaching unity indicating a good fit. The slope and intercept of the regression were used as measures of one-to-one correspondence with a slope of unity indicating perfect correspondence and an intercept of zero indicating no bias between the simulated and observed values.

A fixed time interval sampling strategy applied to event response rivers, despite large numbers of samples being taken, typically results in small sample sizes, high discharges being sampled with less frequency. This introduces strong bias in load estimates due to the higher frequency of sampled low flows. Little can be done about sample sizes that are too small or the low frequency of sampled high flows, but to continue monitoring and modifying the sampling strategy to increase the sample size and to obtain samples in the high flow part of the flow population (Grobler and Rossouw, 1988). The effects of bias in the sample, however, can be partly corrected by stratification of the population so that each stratum becomes a more homogeneous population. The discharge records were thus stratified into a maximum of five strata. Stratum bounds were determined on a trial-and-error basis while using the criteria described above to test the correspondence between simulated and observed loads.

The FLUX program requires two data sets, one listing the instantaneous flow (m^3/s) and TP concentration (mg/l) for each sample, and the second listing the date and instantaneous flow (m^3/s) for the entire period for which samples were taken. The first data set is used to develop the load:discharge regression equations, whilst the second data set is used to estimate the TP load corresponding to each of the recorded discharges using the selected load:discharge regression model (Grobler and Rossouw, 1988). For all months with no missing recorded discharges, the daily discharges and loads were used to calculate the monthly flows (thousand m^3/month) and TP loads (kg/month). These were, in turn, used to calibrate the PEM.

At present the ownership and funding rights to FLUX belong to the US Army Corps of Engineers. The author of FLUX, Dr. W.W. Walker is attempting to transfer these rights to an organisation such as the North American Lake Management Society in order to remove the current restrictions on the use of FLUX. If this endeavour is successful, then FLUX will be made available in South Africa. FLUX, however, is merely a composite software package which facilitates calculation of water quality variable loads and statistics from grab samples. The process of stratification of P concentration and flow data followed by application of regression analysis on each stratum as used for this study, can be accomplished using most statistical software already available.

5. SIMULATION TESTS AND RESULTS

5.1 Catchment Selection

The PEM was developed for use on non-point source dominated southern African catchments. As the separation of observed P loads into non-point and point loads is not feasible, an important requirement for the selection of catchments to test the PEM was that they should be non-point source dominated with regard to P export.

Grobler and Rossouw (1988) were faced with the same catchment requirements for their research into stochastic models for estimating P export from non-point source, sensitive catchments. Their work comprises a part of the suite of models making up the REMDSS model, to which this research will also contribute.

As a result the same catchments selected by Grobler and Rossouw (1988) were used for this study. Grobler and Rossouw (1988) explain the selection of the catchments as...'for each sensitive drainage basin...', shown in Figure 5.1, '...separate lists of all flow gauging stations and all stations for which water quality data were, or are, being collected were obtained from the Department of Water Affairs (Directorate of Hydrology). From these lists gauging stations were identified for which both discharge and TP concentration data were available and consequently which could potentially be used for estimating the parameters for the TP export model. This list of potentially suitable catchments was systematically worked through to eliminate those catchments for which TP export were significantly influenced by point sources. To identify catchments in which point sources had a significant influence, information provided by the Department of Water Affairs (Directorate of Pollution Control) and records of TP concentrations at the gauging stations for the catchments were used. Once one or more catchments in a drainage basin suitable for estimating the parameters of the non-point source derived TP export model had been identified it had to be determined how representative the catchments are of the drainage basin as a whole. Several sources of information were used for this purpose e.g. site visits, the maximum sediment yield map for South Africa (Rooseboom, 1978), geological, geographical and demographic information and discussion with people knowledgeable about the regions involved'.

The selected catchments are given in Table 5.1, however not all of them could be used. Catchment R2H009 did not have TP data records of sufficient quality to include in the study, while catchments U2H006 and U2H011 only had one year (namely 1985) for which both flow and TP records were concurrent. An additional catchment, G1H020, not used by Grobler and Rossouw (1988) but used in a later study (Bath, 1989) was included as a representative of the Cape winter rainfall region.

5.2 Objective Functions

Objective functions are statistically derived measures of how well the model simulates the observed data. The following four criteria were used to measure this goodness-of-fit between simulated and observed monthly P loads :

a) Mean,
b) Standard deviation,

c) Sum of squared residuals,
d) Coefficient of determination, r^2 and
e) Visual fit.

In the case of the first two functions listed above the objective would be to obtain values for the simulated data that were as close as possible to that of the observed data. The functions, mean and standard deviation, do however have severe disadvantages in that they represent the values for the total data set. Thus the severity of simulated values far higher than observed values for a specific year may well be reduced by the simulated values being far lower than the observed values in a subsequent year. This should be kept in mind and visual fitting should be used to check for this occurrence. The sum of squared residuals is the sum of the squared differences between observed and simulated monthly P loads and should be kept to a minimum. For the coefficient of determination the value of r^2 should be as close to unity as possible. This remains, perhaps, the simplest but most frequently used method of model calibration, especially in non-research applications.

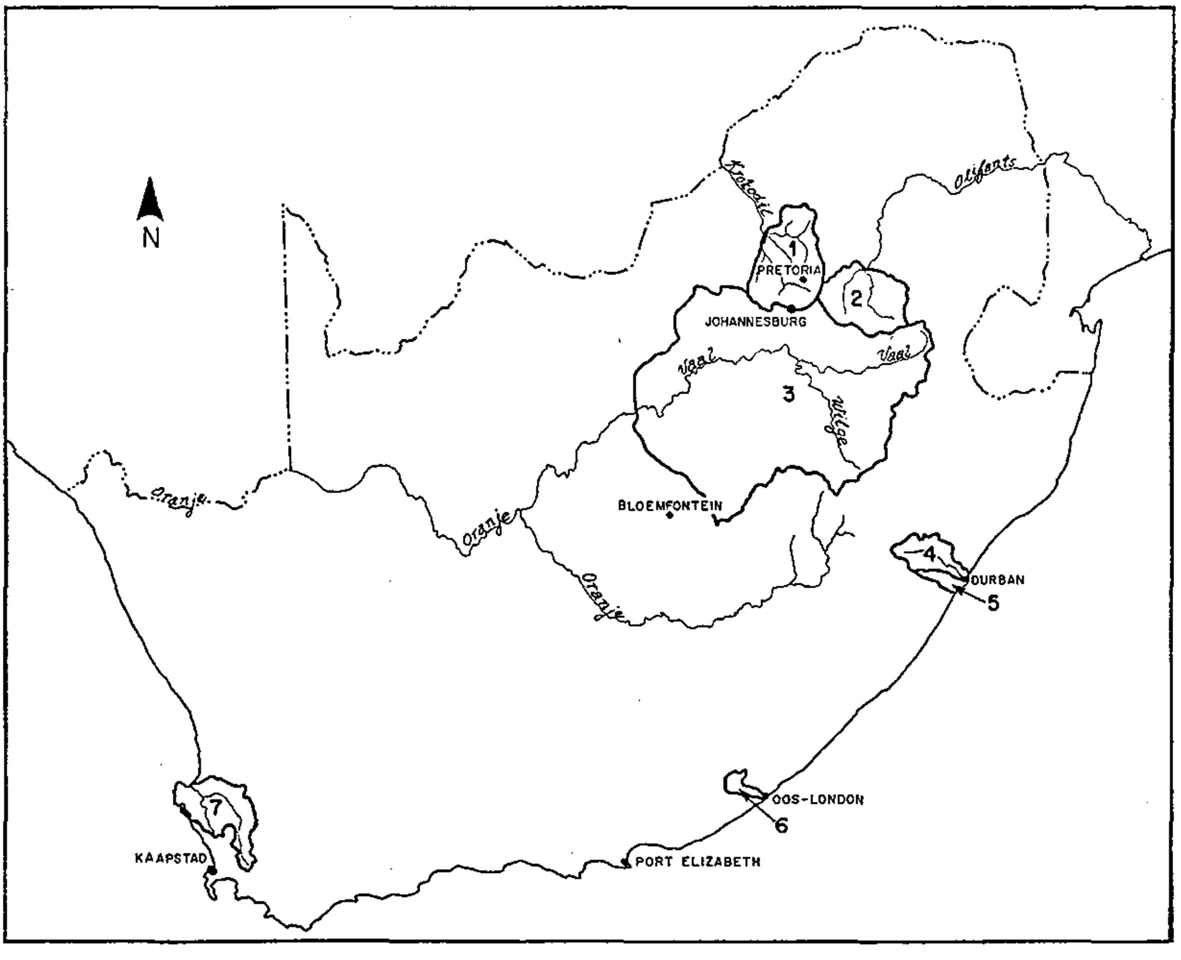

Figure 5.1 Map of southern Africa showing sensitive drainage basins for which decisions about the implementation of a 1 mg P/l standard have to be reviewed (Grobler and Rossouw, 1988)

Table 5.1 Non-point source dominated catchments representing the sensitive drainage basins in southern Africa

DWA No.	Position	Rainfall	Flow	TP
A2H013	Magalies River at Scheerpoort	10/69-9/89	10/69-9/89	10/80-9/89
B1H005	Olifants River at Wolwekrans	72-89	72-89	86-89
C1H006	Blesbokspruit at Rietvlei	69-89	69-89	85-89
C1H007	Vaal River at Uitspanning	72-89	72-89	85-89
C4H004	Vet River at Nooitgedacht	69-89	69-89	85-3/89
G1H020	Berg River at Noorder Paarl	/	66-90	83-86
R2H006	Mgqakwebe River at Msenge Ridge	57-89	57-89	82-86
R2H009	Mgqokweni River at Ngqokweni location	79-89	79-89	/
U2H006	Karkloof River at Shafton	69-85	69-85	85-8/88
U2H011	Mzunduze River at Henley Dam	69-85	69-85	85-7/88
U2H012	Sterk River at Groothoek	69-89	69-89	85-12/88
U2H013	Umgeni River at Petrusstroom	69-89	69-89	85-7/88

5.3 Model Calibration

The procedure by which parameter values are determined for a specific catchment is known as the calibration of a 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, P loads, etc. If only one "average" set of parameters is specified for the entire catchment, the model concerned is known as a lumped-parameter model whereas, the expression of the spatial variability common to all catchments in the form of a different set of parameters for different segments of the catchment is known as a distributed-parameter approach (Görgens, 1983).

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

a) Model parameters can be inferred from measurable catchment characteristics. This is termed an *a priori* approach by 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).

b) Model parameters can be inferred 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 hydrologic 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. The term objective function is used to describe any specific fitting criterion employed in the parameter estimation process (Görgens, 1983). Obviously, the nature of the objective function used will dictate the outcome of the calibration process (Diskin and Simon, 1977). Consequently, a purely curve fitting approach to parameter estimation is usually accompanied by uncertainty as to whether or not the inferred 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 (Ibbitt 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 impressions of the correspondence between the simulated and observed time series (Pitman, 1976).

c) Model parameters can be inferred 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 will 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 time and facilities 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 then further "hardened" by subsequent curve-fitting calibration methods (Manley, 1978 ; Body and Goodspeed, 1979). The practising hydrologist is, however, often left with little choice but to accept the inevitability of a certain amount of "curve-fitting" when using hydrologically based models in an applied or operational situation (Görgens, 1983).

Manual calibration procedures have a number of disadvantages. Firstly this approach can be costly in man-hours. Secondly, the manual approach necessitates an intimate understanding of the workings of a model for rapid convergence on an optimal set of parameters. Thirdly, calibration by goodness-of-fit criteria is general subjective. Rational use of automatic optimization procedures can facilitate minimization of these problems. Automatic optimization procedures are discussed in depth by Görgens (1983) and an excerpt from that report is given as Appendix E.

5.3.1 Parameter Selection

Once the observed monthly streamflow and P load files had been set up, the first-approximation parameter values were tentatively chosen based on information gleaned from topographical maps, soil maps, vegetation maps and the USLE documentation given in Appendix D. Although observed streamflow data were used for manual calibration in this study, streamflow data was simulated for each catchment using the Pitman (1973) monthly model in order to ascertain to what extent groundwater flow was produced in the test catchments. The results of these simulations showed that the catchment U2H013 was the only one for which groundwater flow consideration was relevant. According, the parameters QGMax, Pg and Decay which are used to separate total flow into groundwater and surface flows, were set to zero for all catchments except U2H013. For the purposes of this study, the PEM was used as a lumped-parameter model in which only one homogenous USLE reaction segment is defined. In cases where air photographs or a catchment land use study information are available, the PEM can be used as a distributed-parameter model with up to twenty defined USLE land-use segments within the catchment. The USLE parameters were estimated from the relevant Figures and Tables given in Appendix D. The parameters Spar and Ppar are the "wildcards" of the model controlling the rate of soluble and particulate P loss. They have no readily apparent physical meaning. These two parameters were set initially to unity and then optimized during calibration of the model.

5.3.2 Parameter Adjustments

Due to the complexity and specialist knowledge needed to operate and understand the automatic parameter optimizing techniques presented in Appendix E, manual optimization was used to calibrate the catchment parameters in this study. Manual calibration is deemed the most likely approach by a potential conceptual model user in a non-research environment, because of the computer costs associated with automatic optimization (Görgens, 1983). Goodness-of-fit as measured by the objective functions as well as visual scrutiny of results were the only methods employed in calibration. A sensitivity analysis of the parameters in given in section 5.5.

5.3.3 Calibration Period

Görgens (1983) noted that a primary uncertainty associated with the use of lumped-parameter conceptual models is the effect of choice of calibration data sample on reliability of the model parameter estimates. It follows that the shorter the period of observed data used for model calibration the less likely the calibration sample will contain a broad enough range of events to ensure activation of all reaction paths in a model or to reveal particular model deficiencies such as, for example, inability to model occurrences during extreme events. Parameters obtained from such a sample are subject to uncertainty as to how they relate to "true" parameters for the catchment under consideration. There is a distinct danger that estimated parameters may be mere artifacts not only of unreliable fitting procedure but also of an unrepresentative calibration period (Görgens, 1983).

To solve the dilemma of adequacy of observed data record length the split-record approach can be used. In this procedure, the model is calibrated on one part of the record and verified on an independent part of the record. This presupposes that the modeller has available a record of adequate length.

Despite the uncertainty associated with the use of short calibration records, there was little choice in the matter for the calibration of the PEM. Measured Total Phosphorus record lengths available for the test catchments, and indeed elsewhere in southern Africa, are short. The record lengths used, range from three to nine years of observed data.

5.3.4 Parameter Transfer

Simulation of quantity and quality of runoff from ungauged catchments is a major challenge facing modellers. Models for which parameter values can be estimated for the catchment under consideration constitute a valuable approach to this problem. In this situation parameter values can be estimated by three different techniques, conditions permitting :

a) Parameter values can be inferred by measurable catchment characteristics but presupposes a model that is physically-based to a high degree. These models are, for practical purposes, usually too advanced for conventional use (Görgens, 1983).

b) Parameter values can be based on regionalized trends. However published information of such trends usually omits information on the degree of uncertainty involved in applying such regionalized parameters. Consequently no confidence limits can be placed on model estimates (Görgens, 1983).

c) Parameters can be estimated by calibrating the model on one or more catchments that are thought to be physically similar to the ungauged one and then assigning those variables to the ungauged catchment (Görgens, 1983).

Very little has been reported in hydrological and limnological literature on the magnitude of errors involved in the general feasibility of parameter transfer from gauged to ungauged catchments. Intuitively it may be expected that the parameter sets of models that are structurally more complex should display a higher level of transferability than those of simple models, based on the assumption that the more complex models simulate physical processes more accurately. Similarly, models requiring a finer time resolution of input data may be expected to support greater transferability because they incorporate higher levels of input information. To the model user, who is considering a parameter transfer application of the model, the issue of adequate levels of structural and input data complexity can be important. The user may feel satisfied with the performance of a simple model in a gauged catchment, but may be hesitant to risk such a model in a parameter transfer operation. The costs and time involved in turning to a more complex model may, however, be unacceptable (Görgens, 1983).

The parameter transferability of the PEM has not been tested, but considering the great number of factors affecting P loss from a catchment, initial P storage within catchments and P loading onto the catchment surface, parameter transfer, at the present stage of deterministic P export modelling, is not recommended.

5.4 Simulation Results

In this section the observed flow, observed P, and calibrated parameter values for each selected catchment as well as the simulation results and statistics of performance are given. Although the original idea was to "piggy-back" the PEM on the Pitman Monthly Runoff Model, it was decided to develop the PEM as a stand-alone model which could use either observed flow records or flow records simulated by any of a number of rainfall-runoff models in use in South Africa today.

The procedure adopted by Grobler and Rossouw (1988) to calculate monthly P loads from DWA concentration and instantaneous flow data, obtained from intermittent (mostly weekly) grab samples and flow stage recorders, was used in this study to obtain monthly observed P load data against which the goodness-of-fit of the PEM could be judged.

5.4.1 Catchment A2H013

The input values are presented in Tables 5.2 to 5.4 and the results are given in Table 5.5.

Land use in catchment A2H013 is mainly agricultural with a small residential area. The major crop is cereal. The average slope of the catchment was measured from a topographical map as being approximately 5% and the slope length was set to 300m. An estimated average EI_{30} value of 200.0 was obtained from Figure D1. Although information on soil and land use distribution over the catchment was of poor quality and too coarse, Rooseboom's (1978) sediment map for southern Africa was used during model calibration to ensure that the sediment loss from the catchment was of the correct magnitude. Accordingly, the parameters for soil erodibility, land cover and land management were given values based on the assumption that the predominant land cover in the catchment was veld.

The total length of perennial rivers in the catchment was measured from a topographic map as 70.0 km. As no data exists for catchment P stores or replenishment rates, these two values had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} $month^{-1}$.

As reported in the Grobler and Rossouw (1988) report, the discharge data were stratified before fitting the flux:discharge regression models to the sampled data. The bias towards sampling low discharges more frequently than high discharges as a result of employing fixed interval sampling strategy as shown by Grobler and Rossouw (1988) was not apparent as shown in Table 5.6. The 86% of the samples flows compared to 88.2% of the recorded flows falling in the first stratum compared favourably as did the 2.8% of the sampled discharges compared to 2.2% of recorded discharges falling in the fifth stratum as shown in Table 5.5. The discrepancies between the stratification reported by Grobler and Rossouw (1988) and this scheme can be explained by the fact that a shorter data record, which included a period during which southern Africa experienced a major drought, was used by Grobler and Rossouw (1988). Although the period of data used in this study also included the drought period, the longer record decreases the effect of the drought on data representiveness.

The benefits of stratifying the discharge data were shown by Grobler and Rossouw (1988) in that the differences between the means of the unstratified sampled and recorded discharges were highly significant, whereas the differences between the means of the sampled and recorded discharges in each stratum were not significant. The discharge data was accordingly stratified before being used for fitting the flux:discharge regression models. Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. The high R-squared and low mean squared error values (as measures of goodness-of-fit), slope close to unity and intercept close to zero (as measures of one-to-one correspondence) showed that the correspondence between observed and regression model estimated P loads was good. Regression model 4 REG-1 was chosen over 5 REG-2 and the monthly P loads so produced are listed in Table 5.3.

The catchment map is given as Figure 5.2 and the plot of simulated against observed P loads is shown in Figure 5.3.

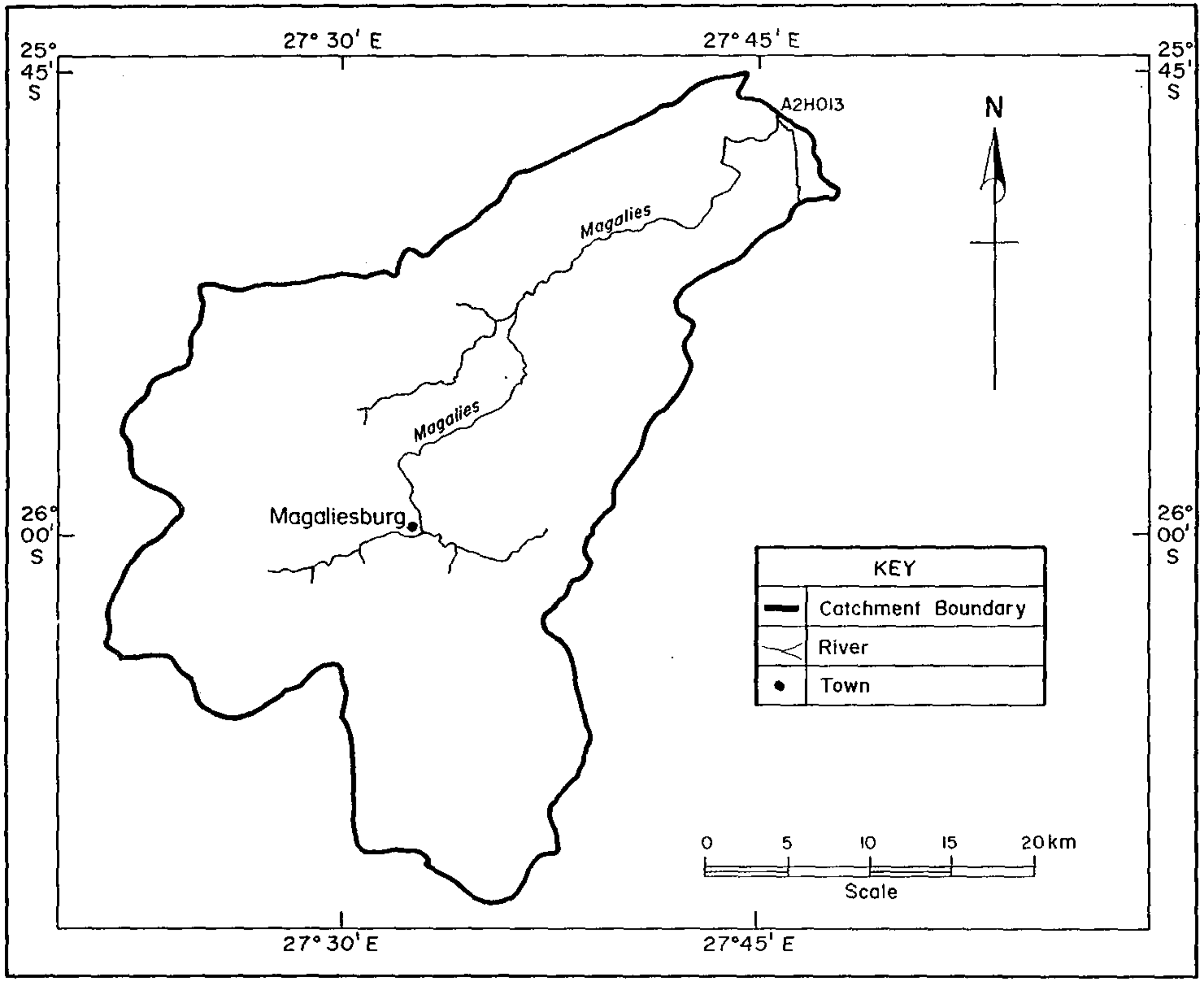

Figure 5.2 Catchment A2H013 in the Crocodile River basin

Table 5.2 Monthly observed flow values (million m^3) for catchment A2H013

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1980	1.62	2.62	5.90	4.86	6.95	10.96	3.41	3.46	3.29	3.13	2.74	2.11
1981	2.68	1.07	2.63	4.73	1.98	1.32	1.48	1.16	1.11	1.41	1.13	0.42
1982	0.42	0.64	0.85	1.26	0.08	0.06	0.20	0.07	0.27	0.15	0.18	0.06
1983	0.15	1.45	1.49	1.69	0.06	0.10	0.06	0.14	0.09	0.16	0.09	0.05
1984	0.11	0.05	0.17	5.35	0.65	0.44	0.15	0.24	0.19	0.15	0.13	0.07
1985	0.09	0.61	0.07	0.02	0.03	0.03	0.05	0.03	0.05	0.05	0.05	0.05
1986	0.08	0.19	0.62	1.26	0.56	1.94	0.51	0.30	0.10	0.10	0.15	1.58
1987	0.65	0.52	1.07	0.27	0.51	3.70	0.88	0.44	0.24	0.28	0.21	0.23
1988	0.16	0.09	0.52	0.48	6.30	1.20	0.38	0.97	1.34	0.79	0.51	0.17

Table 5.3 Monthly observed TP values (ton) for catchment A2H013

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1980	0.1620	0.3213	0.8563	0.6820	1.0487	1.6553	0.4657	0.4497	0.4290	0.3408	0.2844	0.2242
1981	0.3360	0.0942	0.3126	0.6639	0.2240	0.1179	0.1493	0.0948	0.0958	0.1417	0.0812	0.0163
1982	0.0249	0.0456	0.0772	0.1075	0.0043	0.0033	0.0112	0.0037	0.0158	0.0086	0.0099	0.0034
1983	0.0081	0.1604	0.1374	0.1991	0.0036	0.0054	0.0035	0.0080	0.0048	0.0088	0.0050	0.0030
1984	0.0062	0.0030	0.0093	0.9212	0.0377	0.0257	0.0084	0.0135	0.0105	0.0084	0.0070	0.0038
1985	0.0056	0.0752	0.0039	0.0014	0.0016	0.0015	0.0030	0.0017	0.0027	0.0027	0.0027	0.0028
1986	0.0045	0.0131	0.0542	0.0965	0.0657	0.2486	0.0289	0.0169	0.0057	0.0056	0.0081	0.2133
1987	0.0446	0.0338	0.0731	0.0152	0.0537	0.4583	0.0535	0.0243	0.0133	0.0158	0.0118	0.0130
1988	0.0090	0.0050	0.0464	0.0288	0.9161	0.1054	0.0220	0.0648	0.1032	0.0440	0.0285	0.0094

Table 5.4 Parameters used in the PEM to simulate P loads for A2H013

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
1171.0	0.0	0.0	0.0	100.0	1980	1988	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	0.80	4.70

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
1171.0	200.0	0.30	300.0	5.0	0.30	0.30	70.0	0.60	0.003

Table 5.5 Results for catchment A2H013

Phosphorus export from catchment A2H013 for the period 10/1980 to 9/1989

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) (-0.001 indicates missing value)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1980	1.6200	2.6200	5.9000	4.8600	6.9500	10.9600	3.4100	3.4600	3.2900	3.1300	2.7400	2.1100	4.2542
	0.1004	0.1557	0.2432	0.2522	0.2115	0.1073	0.0949	0.0737	0.0581	0.0583	0.0676	0.0791	0.1252
	0.1627	0.4078	1.4348	1.2256	1.4699	1.1759	0.3236	0.2550	0.1911	0.1826	0.1853	0.1670	0.5984
	0.1620	0.3213	0.8563	0.6820	1.0487	1.6553	0.4657	0.4497	0.4290	0.3408	0.2844	0.2242	0.5766
1981	2.6800	1.0700	2.6300	4.7300	1.9800	1.3200	1.4800	1.1600	1.1100	1.4100	1.1300	0.4200	1.7600
	0.0783	0.1024	0.1406	0.1448	0.1273	0.0822	0.0770	0.0679	0.0612	0.0615	0.0657	0.0709	0.0900
	0.2098	0.1096	0.3699	0.6850	0.2521	0.1085	0.1139	0.0788	0.0680	0.0867	0.0743	0.0298	0.1822
	0.3360	0.0942	0.3126	0.6639	0.2240	0.1179	0.1493	0.0948	0.0958	0.1417	0.0812	0.0163	0.1940
1982	0.4200	0.6400	0.8500	1.2600	0.0800	0.0600	0.2000	0.0700	0.2700	0.1500	0.1800	0.0600	0.3533
	0.0664	0.0717	0.0800	0.0811	0.0777	0.0683	0.0675	0.0658	0.0646	0.0648	0.0660	0.0673	0.0701
	0.0279	0.0459	0.0680	0.1022	0.0062	0.0041	0.0135	0.0046	0.0174	0.0097	0.0119	0.0040	0.0263
	0.0249	0.0456	0.0772	0.1075	0.0043	0.0033	0.0112	0.0037	0.0158	0.0086	0.0099	0.0034	0.0263
1983	0.1500	1.4500	1.4900	1.6900	0.0600	0.1000	0.0600	0.1400	0.0900	0.1600	0.0900	0.0500	0.4608
	0.0713	0.0785	0.0898	0.0912	0.0863	0.0734	0.0721	0.0696	0.0679	0.0682	0.0696	0.0713	0.0758
	0.0107	0.1138	0.1338	0.1541	0.0052	0.0073	0.0043	0.0097	0.0061	0.0109	0.0063	0.0036	0.0388
	0.0081	0.1604	0.1374	0.1991	0.0036	0.0054	0.0035	0.0080	0.0048	0.0088	0.0050	0.0030	0.0456
1984	0.1100	0.0500	0.1700	5.3500	0.6500	0.4400	0.1500	0.2400	0.1900	0.1500	0.1300	0.0700	0.6417
	0.0772	0.0876	0.1040	0.1059	0.0986	0.0796	0.0776	0.0739	0.0712	0.0715	0.0734	0.0758	0.0830
	0.0085	0.0044	0.0177	0.5668	0.0641	0.0350	0.0116	0.0177	0.0135	0.0107	0.0095	0.0053	0.0637
	0.0062	0.0030	0.0093	0.9212	0.0377	0.0257	0.0084	0.0135	0.0105	0.0084	0.0070	0.0038	0.0879
1985	0.0900	0.6100	0.0700	0.0200	0.0300	0.0300	0.0500	0.0300	0.0500	0.0500	0.0500	0.0500	0.0942
	0.0736	0.0754	0.0782	0.0787	0.0778	0.0752	0.0751	0.0748	0.0746	0.0749	0.0754	0.0760	0.0758
	0.0066	0.0460	0.0055	0.0016	0.0023	0.0023	0.0038	0.0022	0.0037	0.0037	0.0038	0.0038	0.0071
	0.0056	0.0752	0.0039	0.0014	0.0016	0.0015	0.0030	0.0017	0.0027	0.0027	0.0027	0.0028	0.0087
1986	0.0800	0.1900	0.6200	1.2600	0.5600	1.9400	0.5100	0.3000	0.1000	0.1000	0.1500	1.5800	0.6158
	0.0843	0.0952	0.1125	0.1145	0.1068	0.0868	0.0846	0.0807	0.0779	0.0782	0.0802	0.0827	0.0904
	0.0067	0.0181	0.0697	0.1442	0.0598	0.1684	0.0432	0.0242	0.0078	0.0078	0.0120	0.1306	0.0577
	0.0045	0.0131	0.0542	0.0965	0.0657	0.2486	0.0289	0.0169	0.0057	0.0056	0.0081	0.2133	0.0634
1987	0.6500	0.5200	1.0700	0.2700	0.5100	3.7000	0.8800	0.4400	0.2400	0.2800	0.2100	0.2300	0.7500
	0.0899	0.1038	0.1256	0.1280	0.1182	0.0927	0.0899	0.0848	0.0812	0.0815	0.0840	0.0870	0.0972
	0.0584	0.0540	0.1344	0.0346	0.0603	0.3431	0.0791	0.0373	0.0195	0.0228	0.0176	0.0200	0.0734
	0.0446	0.0338	0.0731	0.0152	0.0537	0.4583	0.0535	0.0243	0.0133	0.0158	0.0118	0.0130	0.0675
1988	0.1600	0.0900	0.5200	0.4800	6.3000	1.2000	0.3800	0.9700	1.3400	0.7900	0.5100	0.1700	1.0758
	0.0986	0.1192	0.1516	0.1552	0.1403	0.1021	0.0977	0.0900	0.0845	0.0847	0.0883	0.0927	0.1087
	0.0158	0.0107	0.0788	0.0745	0.8842	0.1225	0.0371	0.0873	0.1132	0.0669	0.0450	0.0158	0.1293
	0.0090	0.0050	0.0464	0.0288	0.9161	0.1054	0.0220	0.0648	0.1032	0.0440	0.0285	0.0094	0.1152

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	1.11	1.74	108
Average monthly PO4 (mg/l)	0.09	0.03	108

Total modelled surface runoff = 120.07 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 702.60 (ton)
Final catchment surface P storage = 1067.88 (ton)
Total surface P recharge = 379.40 (ton)
Total surface soluble P washoff = 7.84 (ton)
Total surface particulate P washoff = 6.29 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.12 (mg/l)

Total soil eroded from catchment = 8136.67 (t/[km*km]/yr)
Total sediment delivered to streams = 151.78 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 1.3972
Coef. of Determination = 0.8038

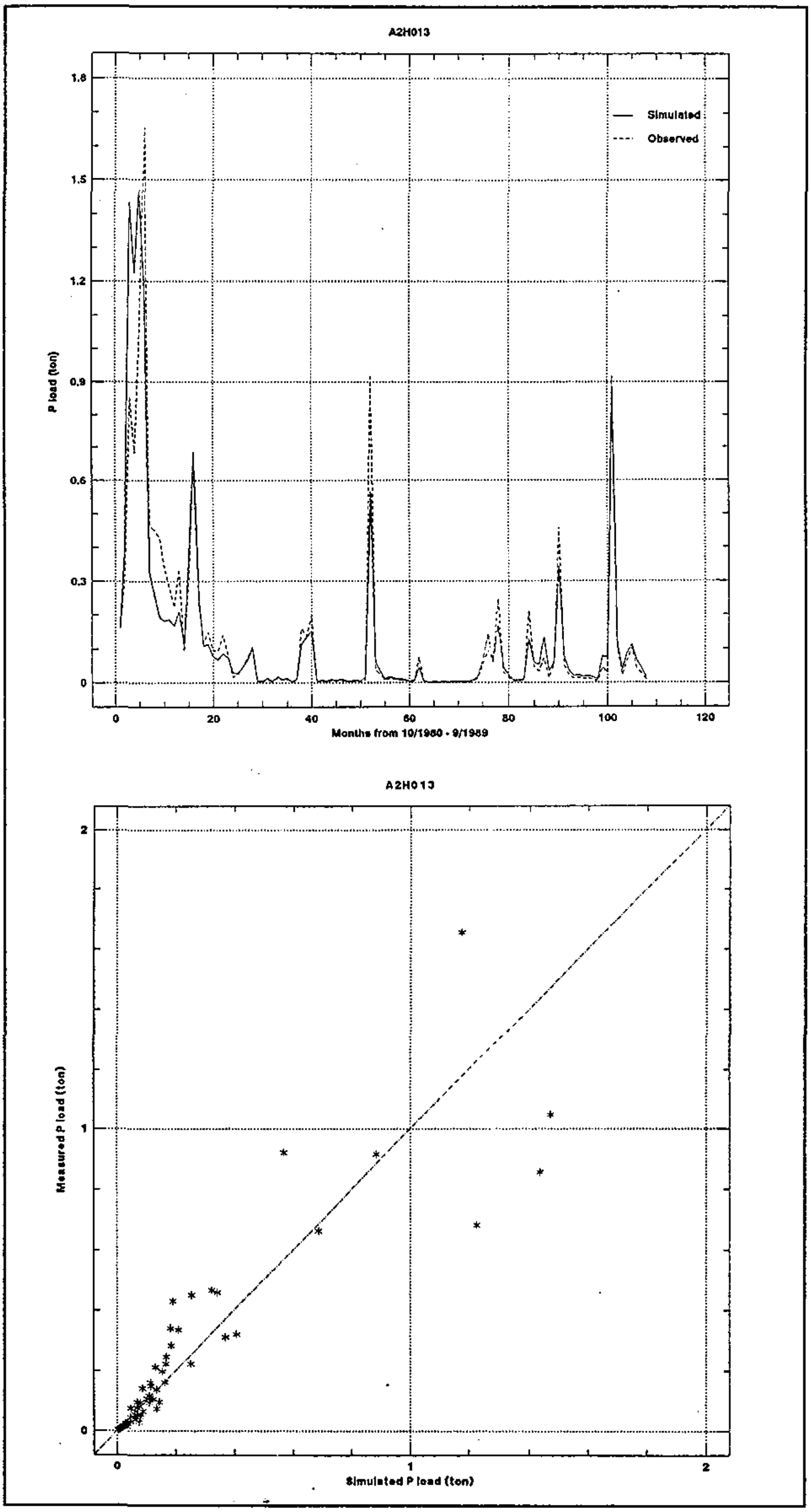

Figure 5.3 Observed versus simulated P loads for A2H013

Table 5.7 Monthly observed flow values (million m^3) for catchment B1H005

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1986	0.01	7.24	19.81	16.08	2.90	19.32	1.73	0.13	0.03	0.00	0.00	4.07
1987	17.44	75.08	55.95	14.96	1.14	3.96	1.38	0.25	0.13	0.11	0.02	0.15
1988	13.39	0.52	14.44	8.63	7.01	3.45	0.20	0.07	0.31	0.11	0.08	0.00

Table 5.8 Monthly observed TP values (ton) for catchment B1H005

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1986	0.0004	0.8439	4.4467	1.8826	0.3407	5.6933	0.2033	0.0087	0.0010	0.0000	0.0000	0.4718
1987	4.2978	39.1998	23.2312	1.7509	0.1350	0.4672	0.1605	0.0214	0.0103	0.0079	0.0006	0.0001
1988	7.1909	0.0572	4.8294	2.9567	0.8173	0.4027	0.0185	0.0043	0.0319	0.0087	0.0060	0.0001

Table 5.9 Parameters used in the PEM to simulate P loads for B1H005

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
3256.0	0.0	0.0	0.0	100.0	1986	1988	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	0.80	5.00

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
3256.0	250.0	0.25	300.0	1.5	0.25	0.30	621.0	0.60	0.003

Table 5.10 Results for catchment B1H005

Phosphorus export from catchment B1H005 for the period 10/1986 to 9/1989

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) { -0.001 indicates missing value }

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1986	0.0100	7.2400	19.8100	16.0800	2.9000	19.3200	1.7300	0.1300	0.0300	0.0000	0.0000	4.0700	5.9433
	0.1940	0.2413	0.3158	0.3234	0.2892	0.2016	0.1915	0.1741	0.1615	0.0000	0.0000	0.1810	0.1895
	0.0019	1.7473	6.2559	5.2002	0.8388	3.8954	0.3313	0.0226	0.0048	0.0000	0.0000	0.7365	1.5863
	0.0004	0.8439	4.4467	1.8826	0.3407	5.6933	0.2033	0.0087	0.0010	0.0000	0.0000	0.4718	1.1577
1987	17.4400	75.0800	55.9500	14.9600	1.1400	3.9600	1.3800	0.2500	0.1300	0.1100	0.0200	0.1500	14.2142
	0.2582	0.3109	0.5286	0.5665	0.4817	0.2666	0.2412	0.1975	0.1654	0.1661	0.1856	0.2098	0.2982
	4.5027	23.3452	29.5736	8.4745	0.5491	1.0556	0.3329	0.0494	0.0215	0.0183	0.0037	0.0315	5.6632
	4.2978	39.1998	23.2312	1.7509	0.1350	0.4672	0.1605	0.0214	0.0103	0.0079	0.0006	0.0111	5.7745
1988	13.3900	0.5200	14.4400	8.6300	7.0100	3.4500	0.2000	0.0700	0.3100	0.1100	0.0800	0.0000	4.0175
	0.1955	0.2300	0.2844	0.2903	0.2657	0.2022	0.1952	0.1828	0.1738	0.1745	0.1809	0.0000	0.1979
	2.6181	0.1196	4.1061	2.5049	1.8629	0.6976	0.0390	0.0128	0.0539	0.0192	0.0145	0.0000	1.0040
	7.1909	0.0572	4.8294	2.9567	0.8173	0.4027	0.0185	0.0043	0.0319	0.0087	0.0060	0.0001	1.3603

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	8.06	15.68	36
Average monthly PO4 (mg/l)	0.23	0.10	33

Total modelled surface runoff	=	290.10 (million m**3)
Total modelled groundwaterflow	=	0.00 (million m**3)
Initial catchment P storage	=	1953.60 (ton)
Final catchment surface P storage	=	2206.21 (ton)
Total surface P recharge	=	351.65 (ton)
Total surface soluble P washoff	=	47.46 (ton)
Total surface particulate P washoff	=	51.58 (ton)
Total P leaving groundwater	=	0.00 (ton)
Flow weighted average P	=	0.34 (mg/l)
Total soil eroded from catchment	=	454.22 (t/[km*km]/yr)
Total sediment delivered to streams	=	155.45 (t/[km*km]/yr)

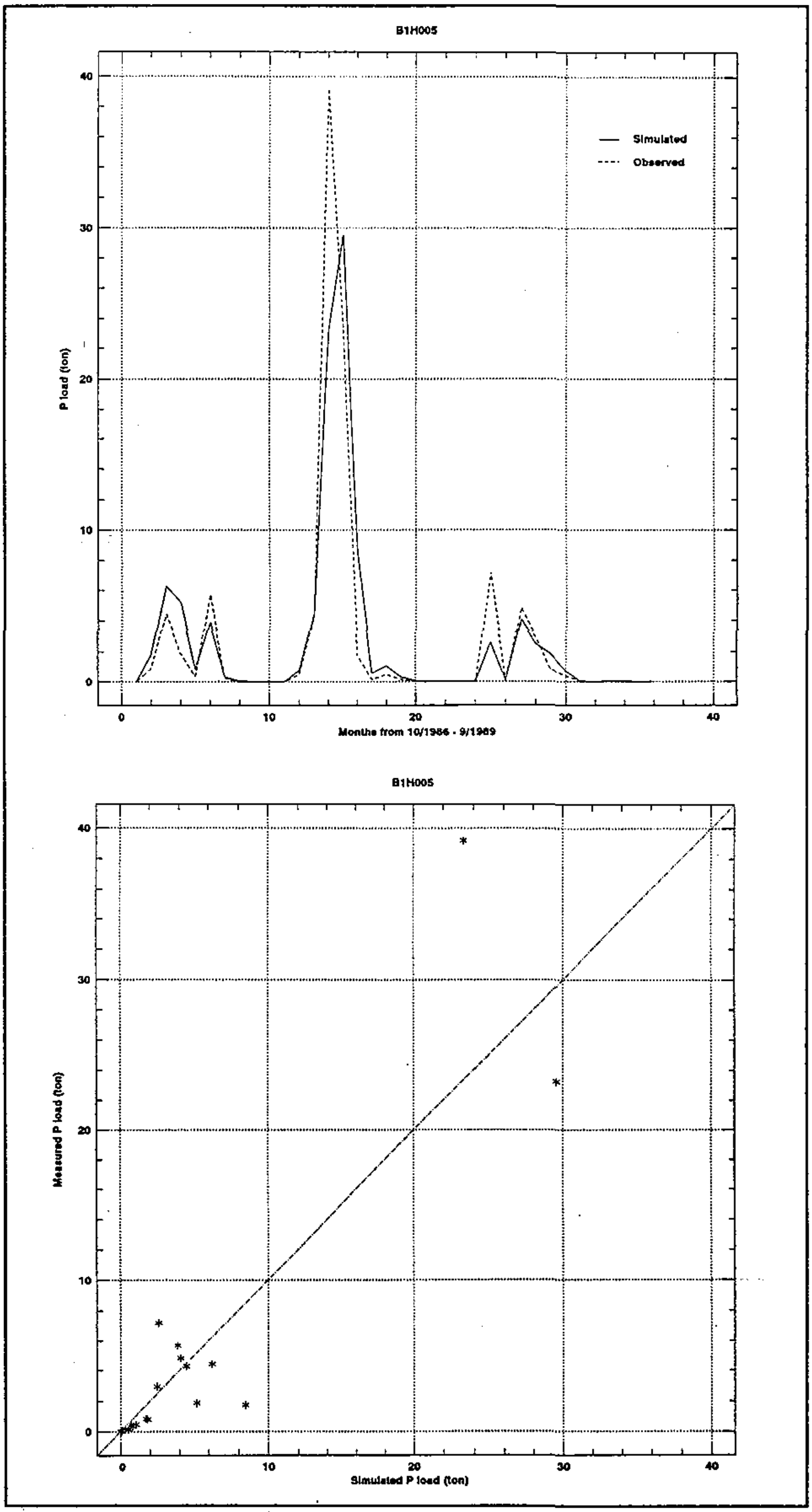

Figure 5.5 Observed versus simulated P loads at B1H005

Table 5.11 Stratification scheme for monthly P load estimation at B1H005

Gauging station : B1H005	Olifants River at Wolwekrans	
Stratum	Sampled flows	Recorded flows
1	8 (7.1%)	476 (32.6%)
2	37 (32.7%)	357 (24.5%)
3	43 (38.1%)	411 (28.1%)
4	21 (18.6%)	179 (12.3%)
5	4 (3.5%)	37 (2.5%)
Total	113	1460

Catchment area : 3256 km^2
Basin area : 1263 km^2 (Bronkhorstspruit)
12285 km^2 (Loskop Dam)
Latitude : 26°00′ 30″ Longitude : 29°15′ 15″
Sample record length : 22/01/1986 - 07/12/1989
Discharge record length : 01/01/1986 - 31/12/1989

5.4.3 Catchment C1H006

The input values are presented in Tables 5.12 to 5.14 and the results are given in Table 5.15.

Land use in catchment C1H006 is mainly agricultural cereal production. The average slope of the catchment was measured as approximately 1.5% and the slope length was set to 300m. An estimated average EI_{30} value of 250.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 176.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} month^{-1}.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data. The bias towards sampling high discharges more frequently than low discharges is shown in Table 5.16 where only 7.8% of the sampled discharges fall into the first stratum compared to 23.0% of the recorded discharges. The probable reason for this, as given by Grobler and Rossouw (1988), is that, like the Olifants River, the rivers in the upper Vaal River basin dry up for more than 50% of the time and during those times the rivers could not be sampled. The other strata display fairly equal numbers of sampled and recorded discharges. Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 4 REG-1 was chosen over 5 REG-2 and the monthly P loads so produced are listed in Table 5.13. The catchment map is given as Figure 5.6 and the plot of simulated against observed P loads is shown in Figure 5.7.

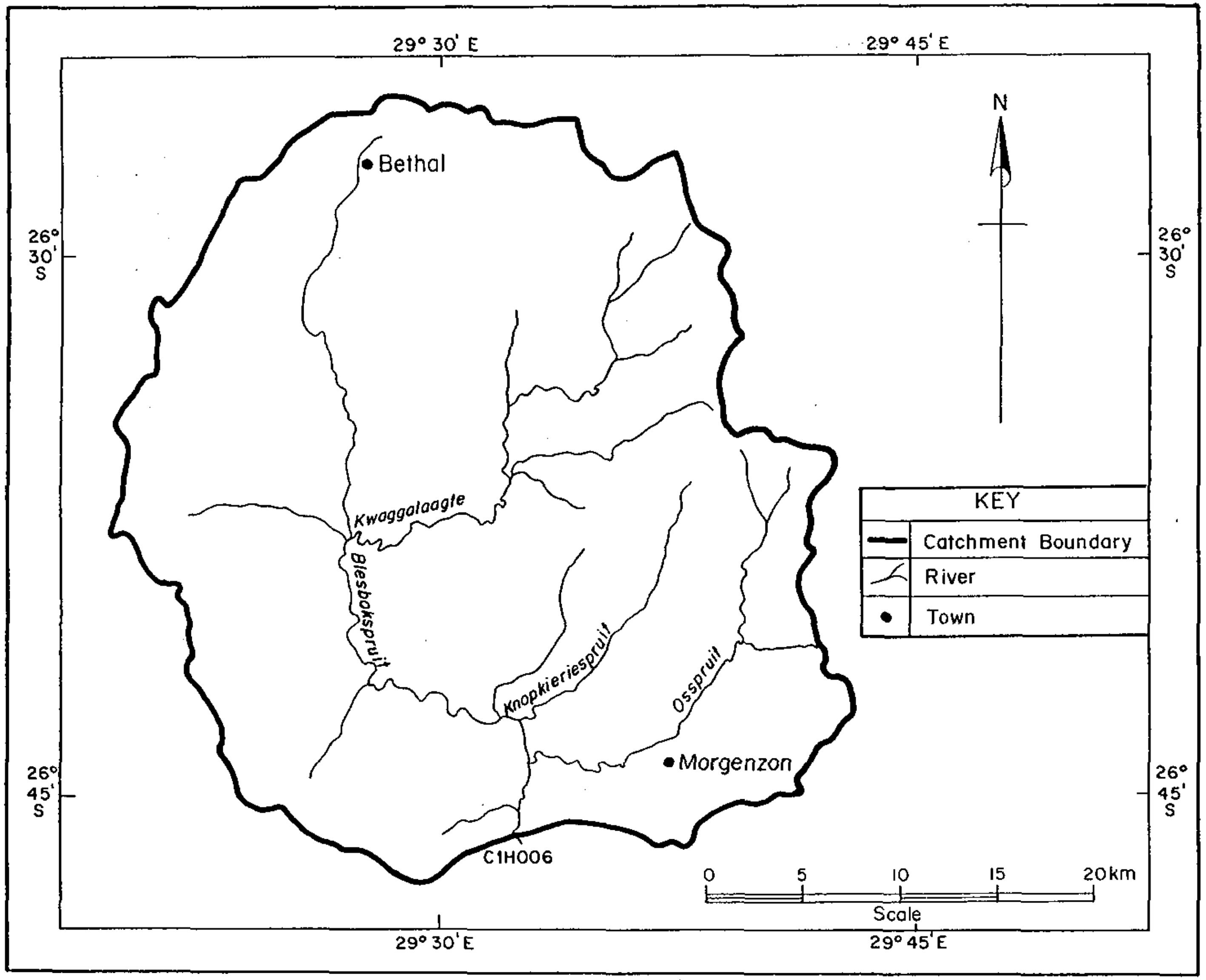

Figure 5.6 Catchment C1H006 in the upper Vaal River basin

Table 5.12 Monthly observed flow values (million m^3) for catchment C1H006

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.00	11.26	1.83	1.69	2.50	0.15	0.03	0.01	0.02	0.09	0.01	0.00
1986	0.00	0.92	1.26	4.41	0.63	5.36	0.30	0.01	0.16	0.03	0.06	14.41
1987	22.33	88.95	104.15	3.79	0.15	1.09	0.15	0.07	0.12	0.20	0.10	0.17
1988	18.83	0.35	15.96	15.68	6.02	1.31	0.13	0.15	0.41	0.13	0.17	0.03

Table 5.13 Monthly observed TP values (ton) for catchment C1H006

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.0000	4.8126	0.6493	0.5895	0.9039	0.0216	0.0045	0.0018	0.0031	0.0130	0.0014	0.0000
1986	0.0000	0.3342	0.3064	1.6134	0.1454	1.9563	0.0575	0.0015	0.0000	0.0050	0.0087	6.2191
1987	9.4353	38.4483	45.0385	1.3908	0.0218	0.3105	0.0210	0.0105	0.0174	0.0285	0.0143	0.0248
1988	8.0745	0.0579	6.5788	6.5804	2.4490	0.4522	0.0181	0.0221	0.0827	0.0187	0.0248	0.0042

Table 5.14 Parameters used in the PEM to simulate P loads for C1H006

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
1094.0	0.0	0.0	0.0	100.0	1985	1988	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	2.60	13.50

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
1094.0	250.0	0.40	300.0	1.5	0.40	0.40	176.0	0.60	0.003

Table 5.15 Results for catchment C1H006

Phosphorus export from catchment C1H006 for the period 10/1985 to 9/1989

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) { -0.001 indicates missing value }

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1985	0.0000	11.2600	1.8300	1.6900	2.5000	0.1500	0.0300	0.0100	0.0200	0.0900	0.0100	0.0000	1.4658
	0.0000	0.1933	0.2127	0.2154	0.2073	0.1854	0.1835	0.1796	0.1770	0.1779	0.1807	0.0000	0.1594
	0.0000	2.1763	0.3893	0.3641	0.5183	0.0278	0.0055	0.0018	0.0035	0.0160	0.0018	0.0000	0.2920
	0.0000	4.8126	0.6493	0.5895	0.9039	0.0216	0.0045	0.0018	0.0031	0.0130	0.0014	0.0000	0.5834
1986	0.0000	0.9200	1.2600	4.4100	0.6300	5.3600	0.3000	0.0100	0.1600	0.0300	0.0600	14.4100	2.2958
	0.0000	0.2169	0.2491	0.2531	0.2390	0.2021	0.1983	0.1914	0.1865	0.1873	0.1914	0.1960	0.1926
	0.0000	0.1995	0.3139	1.1161	0.1506	1.0833	0.0595	0.0019	0.0298	0.0056	0.0115	2.8242	0.4830
	0.0000	0.3342	0.3064	1.6134	0.1454	1.9563	0.0575	0.0015	0.0000	0.0050	0.0087	6.2191	0.8873
1987	22.3300	88.9500	104.1500	3.7900	0.1500	1.0900	0.1500	0.0700	0.1200	0.2000	0.1000	0.1700	18.4392
	0.3219	0.3910	0.4879	0.6846	0.5763	0.3010	0.2685	0.2124	0.1711	0.1719	0.1967	0.2275	0.3342
	7.1880	34.7764	50.8123	2.5947	0.0865	0.3281	0.0403	0.0149	0.0205	0.0344	0.0197	0.0387	7.9962
	9.4353	38.4483	45.0385	1.3908	0.0218	0.3105	0.0210	0.0105	0.0174	0.0285	0.0143	0.0248	7.8968
1988	18.8300	0.3500	15.9600	15.6800	6.0200	1.3100	0.1300	0.1500	0.4100	0.1300	0.1700	0.0300	4.9308
	0.2069	0.2479	0.3131	0.3184	0.2875	0.2113	0.2029	0.1879	0.1771	0.1779	0.1854	0.1946	0.2259
	3.8967	0.0868	4.9971	4.9927	1.7307	0.2768	0.0264	0.0282	0.0726	0.0231	0.0315	0.0058	1.3474
	8.0745	0.0579	6.5788	6.5804	2.4490	0.4522	0.0181	0.0221	0.0827	0.0187	0.0248	0.0042	2.0303

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	6.78	19.76	48
Average monthly PO4 (mg/l)	0.23	0.11	45

Total modelled surface runoff = 325.58 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 656.40 (ton)
Final catchment surface P storage = 692.51 (ton)
Total surface P recharge = 157.54 (ton)
Total surface soluble P washoff = 58.70 (ton)
Total surface particulate P washoff = 62.72 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.37 (mg/l)

Total soil eroded from catchment = 2067.21 (t/[km*km]/yr)
Total sediment delivered to streams = 617.74 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 96.1195
Coef. of Determination = 0.9720

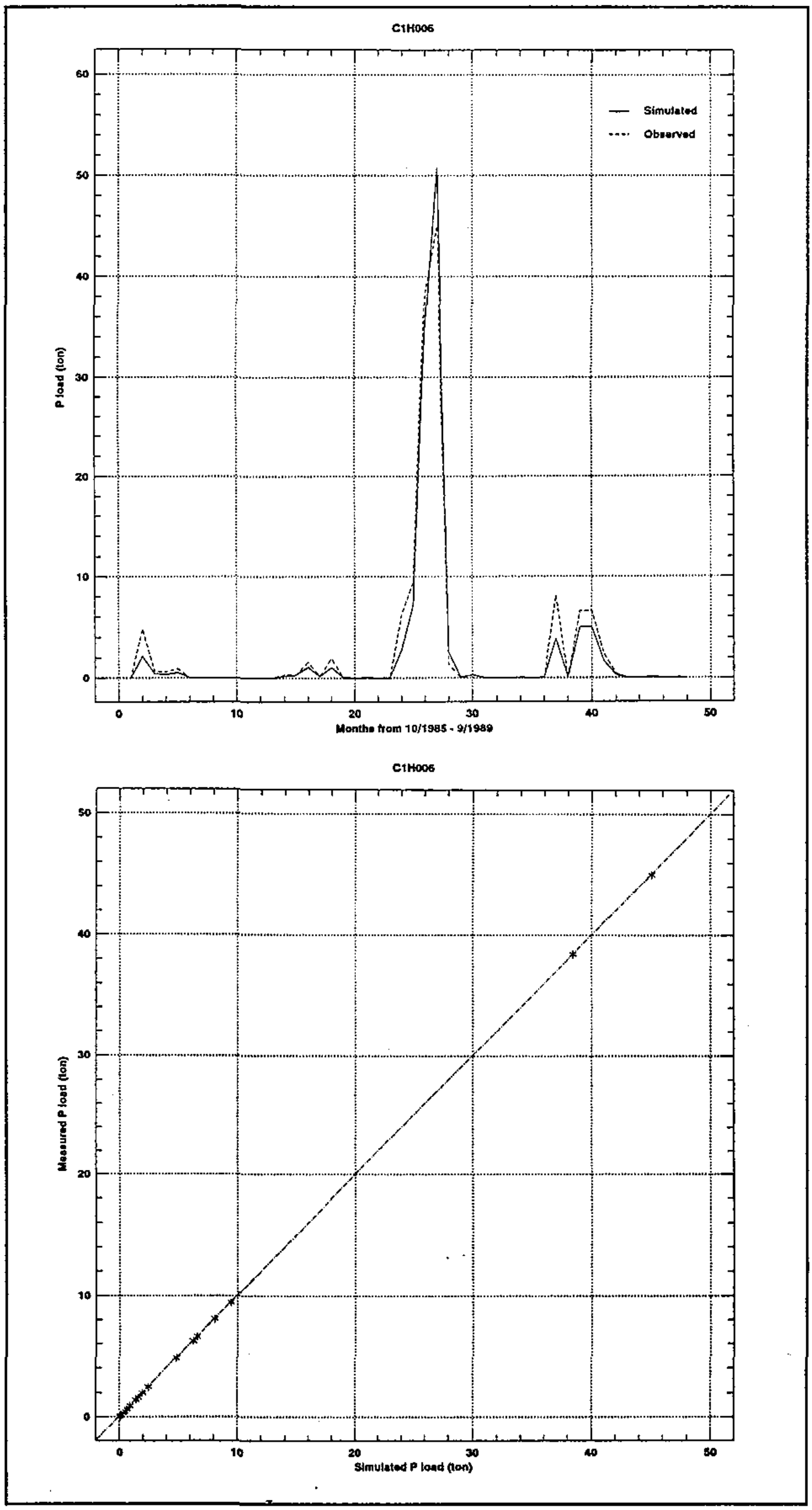

Figure 5.7 Observed versus simulated P loads for C1H006

Table 5.16 Stratification scheme for monthly P load estimation at C1H006

Gauging station : C1H006	Blesbokspruit at Rietvlei	
Stratum	Sampled flows	Recorded flows
1	18 (7.8%)	419 (23.0%)
2	143 (61.9%)	929 (51.0%)
3	40 (17.3%)	235 (13.0%)
4	11 (4.8%)	104 (5.7%)
5	19 (8.2%)	133 (7.3%)
Total	113	1460

Catchment area : 1094 km^2
Basin area : 7924 km^2 (Grootdraai)
38505 km^2 (Vaal)
Latitude : 26°46′ 30″ Longitude : 29°32′ 30″
Sample record length : 16/04/1985 - 21/12/1989
Discharge record length : 01/01/1985 - 31/12/1989

5.4.4 Catchment C1H007

The input values are presented in Tables 5.17 to 5.19 and the results are given in Table 5.20.

Land use in catchment C1H007 is mainly agricultural cereal production. The average slope of the catchment was measured as approximately 1.5% and the slope length was set to 300m. An estimated average EI_{30} value of 250.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 659.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} $month^{-1}$.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data as shown in Table 5.21. The bias towards sampling high discharges more frequently than low discharges as shown in previous cases was not apparent for this catchment with all the strata displaying fairly equal numbers of sampled and recorded discharges.

Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 4 REG-1 was chosen over 5 REG-2 and the monthly P loads so produced are listed in Table 5.18.

The catchment map is given as Figure 5.8 and the plot of simulated against observed P loads is shown in Figure 5.9.

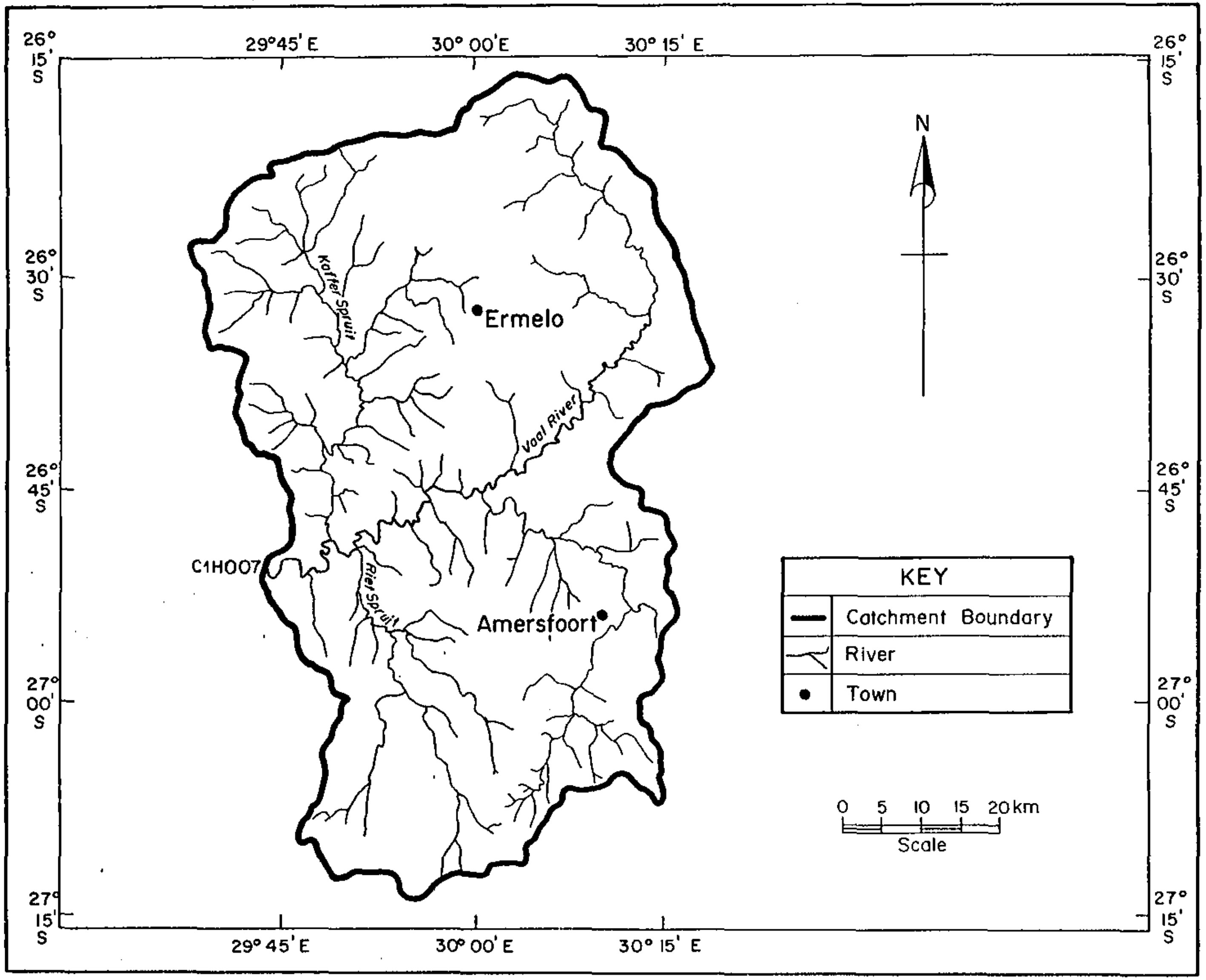

Figure 5.8 Catchment C1H007 in the upper Vaal River basin

Table 5.17 Monthly observed flow values (million m^3) for catchment C1H007

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	11.96	15.67	22.44	14.91	29.04	12.67	13.34	2.40	0.39	0.47	0.38	0.34
1986	0.89	1.33	2.76	4.37	1.74	5.96	0.11	0.10	0.49	0.81	0.03	9.62
1987	62.98	273.99	70.40	13.01	0.87	2.75	0.12	0.00	0.00	0.02	0.00	0.02
1988	29.78	0.50	16.16	6.89	4.25	1.16	0.00	0.02	0.36	0.02	0.00	0.00

Table 5.18 Monthly observed TP values (ton) for catchment C1H007

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	1.6722	2.4481	4.0825	2.0842	5.5257	1.8154	1.8643	0.4428	0.0330	0.0402	0.0319	0.0286
1986	0.1061	0.1354	0.3783	0.6730	0.2173	0.9514	0.0094	0.0086	0.0414	0.0692	0.0023	1.9483
1987	12.6237	48.4180	14.1232	2.2699	0.0741	0.3497	0.0099	0.0000	0.0003	0.0019	0.0000	0.0017
1988	5.9915	0.0430	3.0623	1.0124	0.6509	0.1423	0.0000	0.0017	0.0307	0.0019	0.0005	0.0000

Table 5.19 Parameters used in the PEM to simulate P loads for C1H007

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
4686.0	0.0	0.0	0.0	100.0	1985	1988	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	0.30	1.30

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
4686.0	250.0	0.30	300.0	1.5	0.30	0.30	659.0	0.60	0.003

Table 5.20 Results for catchment C1H007

Phosphorus export from catchment C1H007 for the period 10/1985 to 9/1989

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) (-0.001 indicates missing value)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1985	11.9600	15.6700	22.4400	14.9100	29.0400	12.6700	13.3400	2.4000	0.3900	0.4700	0.3800	0.3400	10.3342
	0.1085	0.1387	0.1865	0.1917	0.1698	0.1134	0.1069	0.0956	0.0874	0.0878	0.0931	0.0997	0.1233
	1.2977	2.1740	4.1853	2.8579	4.9319	1.4363	1.4261	0.2295	0.0341	0.0413	0.0354	0.0339	1.5569
	1.6722	2.4481	4.0825	2.0842	5.5257	1.8154	1.8643	0.4428	0.0330	0.0402	0.0319	0.0286	1.6724
1986	0.8900	1.3300	2.7600	4.3700	1.7400	5.9600	0.1100	0.1000	0.4900	0.8100	0.0300	9.6200	2.3508
	0.0948	0.1024	0.1142	0.1158	0.1109	0.0977	0.0964	0.0940	0.0924	0.0928	0.0944	0.0963	0.1002
	0.0844	0.1362	0.3151	0.5059	0.1929	0.5820	0.0106	0.0094	0.0453	0.0752	0.0028	0.9262	0.2405
	0.1061	0.1354	0.3783	0.6730	0.2173	0.9514	0.0094	0.0086	0.0414	0.0692	0.0023	1.9483	0.3784
1987	62.9800	237.9900	70.4000	13.0100	0.8700	2.7500	0.1200	0.0000	0.0000	0.0200	0.0000	0.0200	32.3467
	0.1773	0.1494	0.4394	0.4535	0.3783	0.1860	0.1632	0.0000	0.0000	0.0953	0.0000	0.1337	0.1813
	11.1643	35.5655	30.9360	5.9001	0.3291	0.5115	0.0196	0.0000	0.0000	0.0019	0.0000	0.0027	7.0359
	12.6237	48.4180	14.1232	2.2699	0.0741	0.3497	0.0099	0.0000	0.0003	0.0019	0.0000	0.0017	6.4894
1988	29.7800	0.5000	16.1600	6.8900	4.2500	1.1600	0.0000	0.0200	0.3600	0.0200	0.0000	0.0000	4.9283
	0.1096	0.1262	0.1524	0.1554	0.1437	0.1132	0.0000	0.1040	0.0997	0.1001	0.0000	0.0000	0.0920
	3.2628	0.0631	2.4624	1.0706	0.6108	0.1314	0.0000	0.0021	0.0359	0.0020	0.0000	0.0000	0.6368
	5.9915	0.0430	3.0623	1.0124	0.6509	0.1423	0.0000	0.0017	0.0307	0.0019	0.0005	0.0000	0.9114

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	12.49	36.30	48
Average monthly PO4 (mg/l)	0.12	0.09	42

Total modelled surface runoff = 599.52 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 2811.60 (ton)
Final catchment surface P storage = 3372.74 (ton)
Total surface P recharge = 674.78 (ton)
Total surface soluble P washoff = 55.32 (ton)
Total surface particulate P washoff = 58.32 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.19 (mg/l)

Total soil eroded from catchment = 872.10 (t/[km*km]/yr)
Total sediment delivered to streams = 311.06 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 473.8411
Coef. of Determination = 0.8149

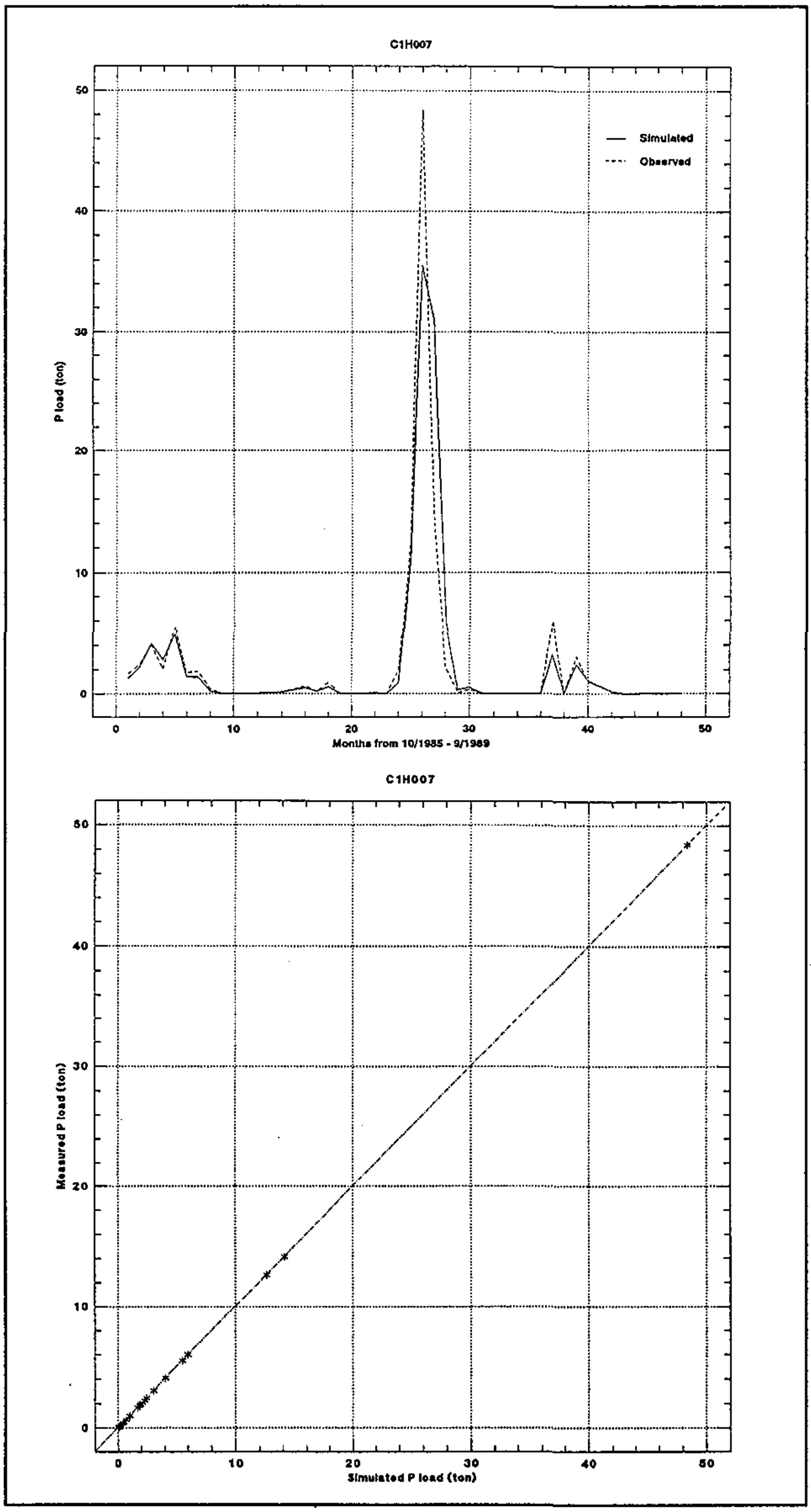

Figure 5.9 Observed versus simulated P loads for C1H007

Table 5.21 Stratification scheme for monthly P load estimation at C1H007

Gauging station : C1H007	Vaal River at Uitspanning	
Stratum	Sampled flows	Recorded flows
1	111 (67.7%)	1101 (60.6%)
2	33 (20.1%)	554 (30.4%)
3	14 (8.5%)	110 (6.1%)
4	6 (3.7%)	52 (2.9%)
Total	164	1817

Catchment area : 4686 km^2
Basin area : 7924 km^2 (Grootdraai)
38505 km^2 (Vaal)
Latitude : 26°50′ 30″ Longitude : 29°43′ 15″
Sample record length : 16/04/1985 - 19/12/1989
Discharge record length : 01/01/1985 - 31/12/1989

5.4.5 Catchment C4H004

The input values are presented in Tables 5.22 to 5.24 and the results are given in Table 5.25.

Land use in catchment C4H004 is mainly agricultural cereal production. The average slope of the catchment was measured as approximately 1.5% and the slope length was set to 300m. An estimated average EI_{30} value of 150.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 322.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} $month^{-1}$.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data as shown in Table 5.26. There was a slight bias towards sampling high discharges more frequently than low discharges as shown by the percentages in the first stratum but the rest of the strata display fairly equal numbers of sampled and recorded discharges.

Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 4 REG-1 was chosen over 5 REG-2 and the monthly P loads so produced are listed in Table 5.23.

The catchment map is given as Figure 5.10 and the plot of simulated against observed P loads is shown in Figure 5.11.

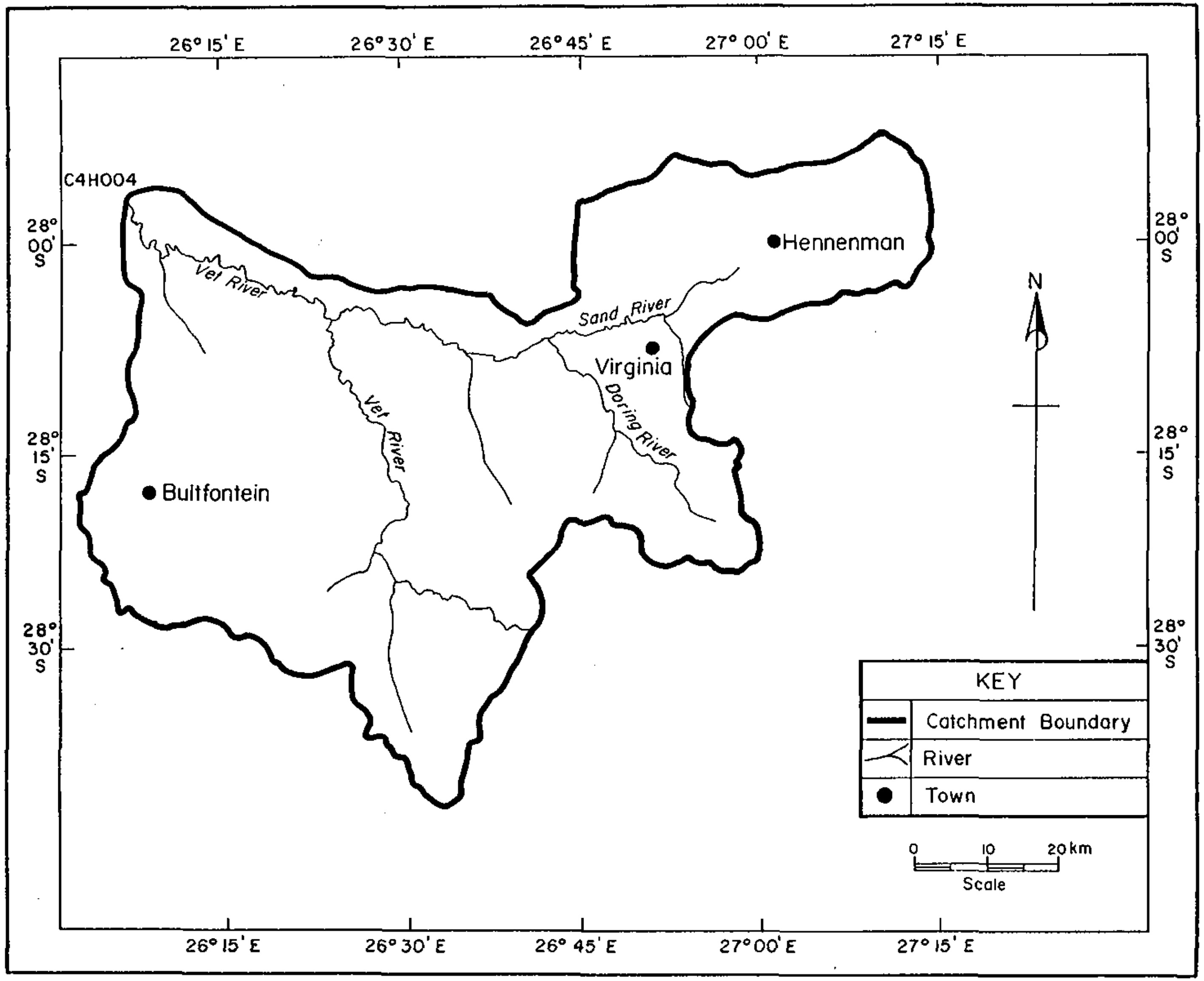

Figure 5.10 Catchment C4H004 in the lower Vaal River drainage basin

Table 5.22 Monthly observed flow values (million m^3) for catchment C4H004

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.57	14.91	0.54	4.24	1.66	0.99	6.70	0.62	0.50	0.67	0.63	0.71
1986	0.75	91.36	1.08	0.48	2.25	2.42	0.70	0.68	0.38	0.46	0.62	18.84
1987	12.22	10.45	3.79	0.79	13.97	53.85	26.79	3.98	3.01	2.50	2.05	2.68
1988	6.19	8.81	0.86	59.46	51.08	22.97	13.97	3.48	1.78	1.45	1.67	2.68

Table 5.23 Monthly observed TP values (ton) for catchment C4H004

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.1372	4.4155	0.1275	1.0123	0.3155	0.2106	1.8272	0.1518	0.1227	0.1489	0.1561	0.1685
1986	0.1725	5.6836	0.2209	0.1514	0.4790	0.4309	0.1616	0.1688	0.1232	0.1142	0.1538	5.6484
1987	3.3352	4.0363	0.6951	0.1885	4.1522	25.9047	18.8400	1.1718	0.5073	0.4226	0.3451	-0.001
1988	-0.001	-0.001	0.4503	18.1340	15.5566	8.8492	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001

Table 5.24 Parameters used in the PEM to simulate P loads for C4H004

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
7738.0	0.0	0.0	0.0	100.0	1985	1988	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	0.56	0.12

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
7738.0	150.0	0.90	300.0	1.5	0.90	0.90	322.0	0.60	0.003

Table 5.25 Results for catchment C4H004

Phosphorus export from catchment C4H004 for the period 10/1985 to 9/1989

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) (-0.001 indicates missing value)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1985	0.5700	14.9100	0.5400	4.2400	1.6600	0.9900	6.7000	0.6200	0.5000	0.6700	0.6300	0.7100	2.7283
	0.2632	0.2675	0.2738	0.2756	0.2745	0.2697	0.2702	0.2702	0.2706	0.2719	0.2737	0.2756	0.2714
	0.1500	3.9891	0.1478	1.1684	0.4556	0.2670	1.8105	0.1675	0.1353	0.1822	0.1724	0.1957	0.7368
	0.1372	4.4155	0.1275	1.0123	0.3155	0.2106	1.8272	0.1518	0.1227	0.1489	0.1561	0.1685	0.7328
1986	0.7500	19.3600	1.0800	0.4800	2.2500	2.4200	0.7000	0.6800	0.3800	0.4600	0.6200	18.8400	4.0017
	0.2797	0.2858	0.2947	0.2968	0.2944	0.2863	0.2865	0.2858	0.2857	0.2870	0.2891	0.2913	0.2886
	0.2098	5.5322	0.3183	0.1425	0.6625	0.6929	0.2005	0.1944	0.1086	0.1320	0.1792	5.4872	1.1550
	0.1725	5.6836	0.2209	0.1514	0.4790	0.4309	0.1616	0.1688	0.1232	0.1142	0.1538	5.6484	1.1257
1987	12.2200	10.4500	3.7900	0.7900	13.9700	53.8500	26.7900	3.9800	3.0100	2.5000	2.0500	2.6800	11.3400
	0.3023	0.3180	0.3425	0.3462	0.3365	0.3093	0.3064	0.3017	0.2987	0.3000	0.3037	0.3079	0.3144
	3.6936	3.3234	1.2981	0.2735	4.7004	16.6532	8.2097	1.2009	0.8992	0.7500	0.6225	0.8252	3.5375
	3.3352	4.0363	0.6951	0.1885	4.1522	25.9047	18.8400	1.1718	0.5073	0.4226	0.3451	-0.0010	4.9665
1988	6.1900	8.8100	0.8600	59.4600	51.0800	22.9700	13.9700	3.4800	1.7800	1.4500	1.6700	2.6800	14.5333
	0.3195	0.3403	0.3728	0.3768	0.3621	0.3253	0.3218	0.3153	0.3109	0.3121	0.3166	0.3219	0.3329
	1.9779	2.9985	0.3206	22.4022	18.4955	7.4722	4.4951	1.0971	0.5533	0.4526	0.5287	0.8626	5.1380
	-0.0010	-0.0010	0.4503	18.1340	15.5566	8.8492	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	3.5818

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	8.15	13.83	48
Average monthly PO4 (mg/l)	0.30	0.03	48

Total modelled surface runoff = 391.24 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 4642.80 (ton)
Final catchment surface P storage = 5630.26 (ton)
Total surface P recharge = 1114.27 (ton)
Total surface soluble P washoff = 116.03 (ton)
Total surface particulate P washoff = 10.78 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.32 (mg/l)

Total soil eroded from catchment = 14128.05 (t/[km*km]/yr)
Total sediment delivered to streams = 214.55 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 265.9600
Coef. of Determination = 0.8211

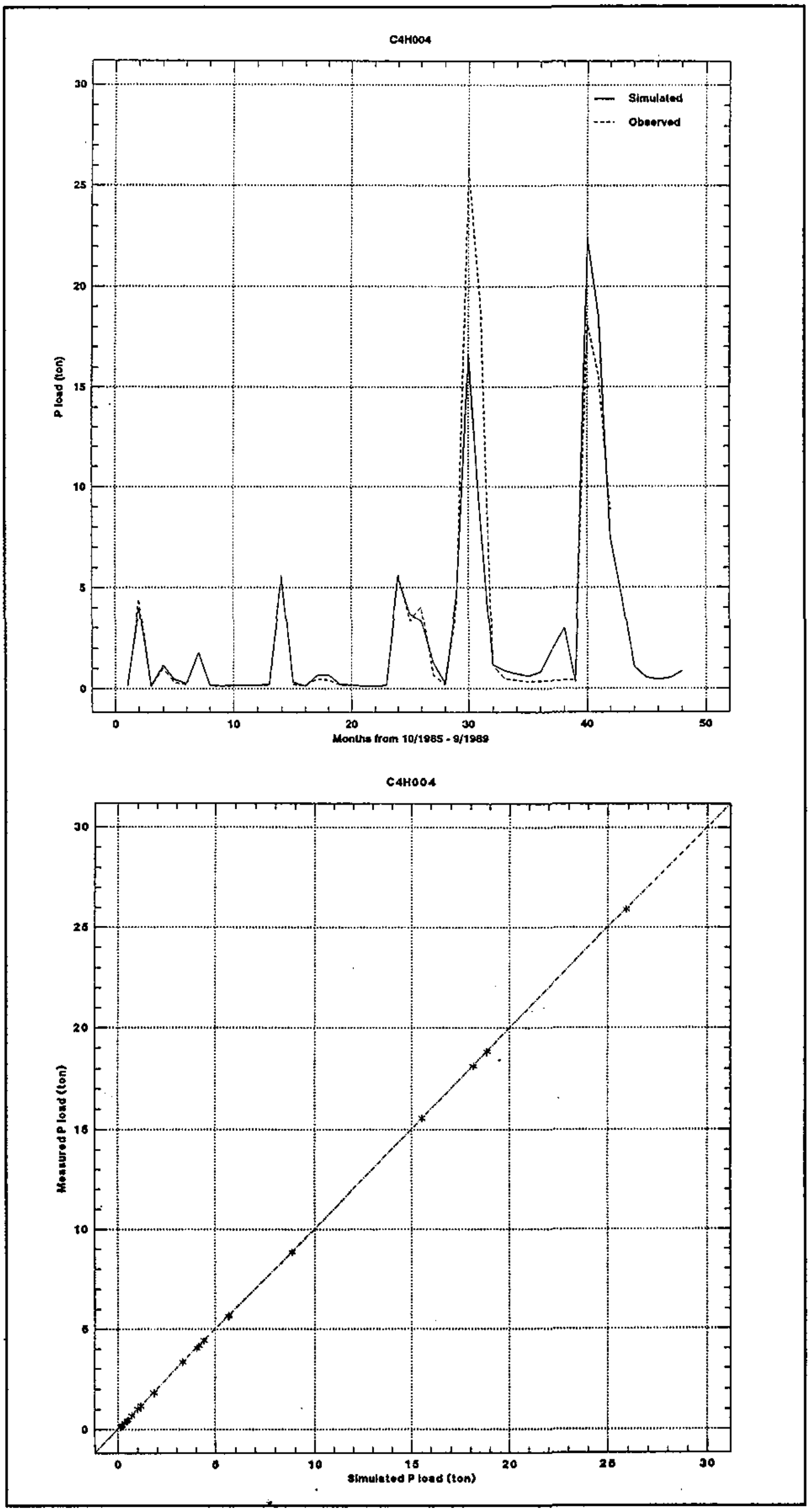

Figure 5.11 Observed versus simulated P loads for C4H004

Table 5.26 Stratification scheme for monthly P load estimation at C4H004

Gauging station : C4H004	Vet River at Hoopstad	
Stratum	Sampled flows	Recorded flows
1	63 (43.8%)	729 (53.2%)
2	24 (16.7%)	169 (12.3%)
3	38 (26.4%)	307 (22.4%)
4	10 (6.9%)	82 (6.0%)
5	9 (6.2%)	84 (6.1%)
Total	144	1371

Catchment area : 7738 km^2
Basin area : 69374 km^2 (Bloemhof below barrage)
Latitude : 27°56′ 15″ Longitude : 26°07′ 30″
Sample record length : 12/04/1985 - 29/03/1989
Discharge record length : 01/01/1985 - 31/12/1989

5.4.6 Catchment G1H020

The input values are presented in Tables 5.27 to 5.29 and the results are given in Table 5.30.

The major land use in catchment G1H020 is agricultural grape production. The average slope of the catchment was measured as approximately 7.0% and the slope length was set to 300m. An estimated average EI_{30} value of 100.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 196.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} $month^{-1}$.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data. There appears to be no bias towards sampling either high or low discharges as shown in Table 5.31.

Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 4 REG-1 was chosen over 5 REG-2 and the monthly P loads so produced are listed in Table 5.28.

The catchment map is given as Figure 5.12 and the plot of simulated against observed P loads is shown in Figure 5.13.

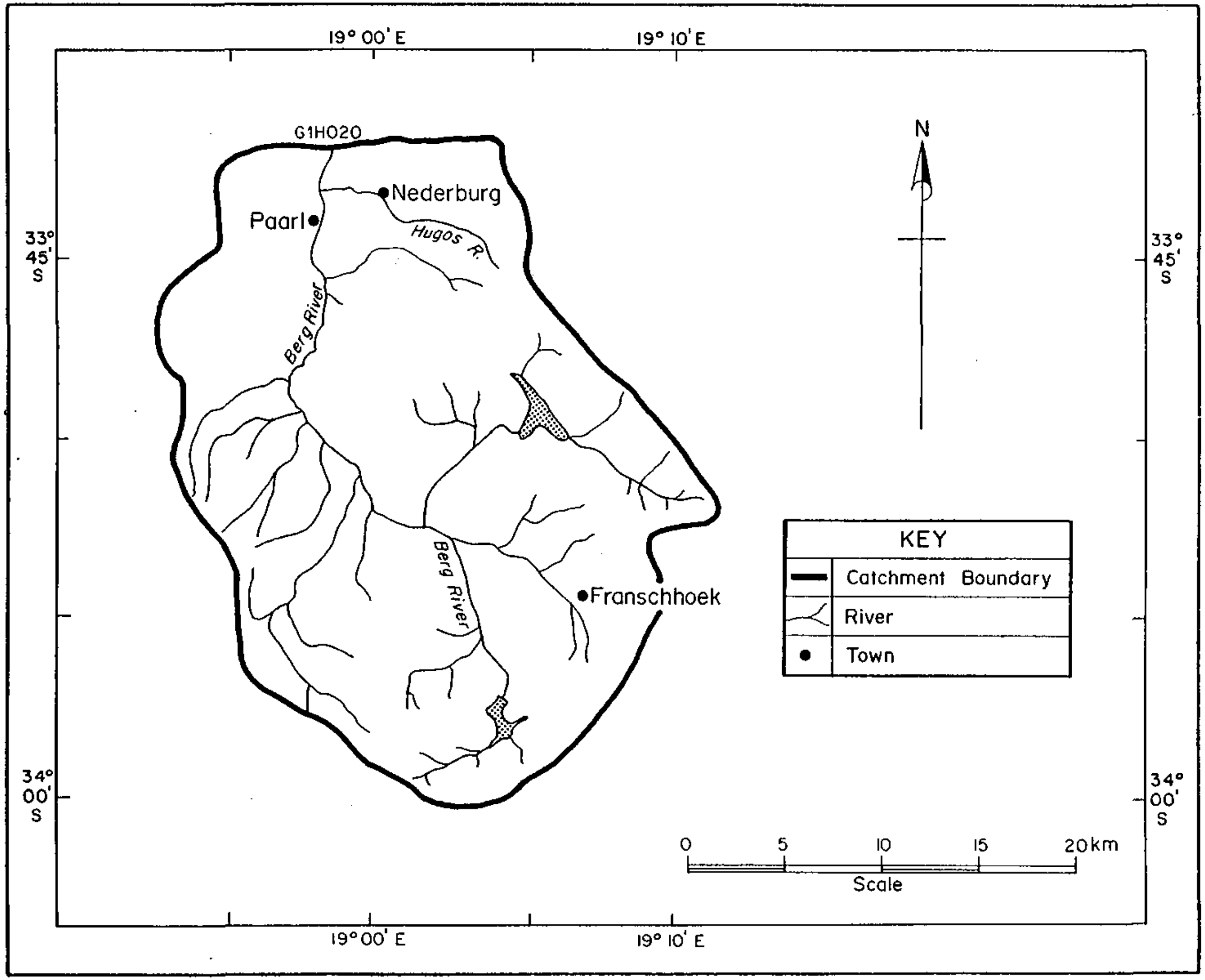

Figure 5.12 Catchment G1H020 in the Berg River drainage basin

Table 5.27 Monthly observed flow values (million m^3) for catchment G1H020

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1983	17.03	3.70	3.63	4.45	2.33	2.57	2.57	71.75	18.94	73.48	45.51	69.08
1984	43.43	4.43	15.20	6.72	5.77	21.89	12.93	17.25	76.94	82.02	80.81	27.51
1985	12.98	5.80	6.83	5.46	5.84	5.07	12.44	22.67	65.74	101.70	111.01	63.16

Table 5.28 Monthly observed TP values (ton) for catchment G1H020

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1983	0.6558	0.1185	0.1195	0.1480	0.0745	0.0821	0.0906	3.3743	0.5459	3.6570	2.5980	4.7558
1984	3.1611	1.1468	0.7749	0.2374	0.2166	1.4052	0.6494	1.0814	3.5278	3.4867	4.4238	1.3544
1985	0.4996	0.2020	0.2266	0.1772	0.1922	0.1781	0.7545	1.4302	4.7917	6.8861	5.8633	3.0

Table 5.29 Parameters used in the PEM to simulate P loads for G1H020

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
65.1	0.0	0.0	0.0	100.0	1983	1985	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	4	0.0	1.10	75.00

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
65.1	100.0	0.40	300.0	7.0	0.30	0.30	196.0	4.00	0.003

Table 5.30 Results for catchment G1H020

Phosphorus export from catchment G1H020 for the period 10/1983 to 9/1986

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) { -0.001 indicates missing value }

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1983	17.0300	3.7000	3.6300	4.4500	2.3300	2.5700	2.5700	71.7500	18.9400	73.4800	45.5100	69.0800	26.2533
	0.0574	0.0542	0.0452	0.0421	0.1320	0.2361	0.3352	0.0485	0.1319	0.0464	0.0542	0.0404	0.1020
	0.9774	0.2005	0.1639	0.1874	0.3076	0.6068	0.8615	3.4778	2.4991	3.4131	2.4665	2.7884	1.4958
	0.6558	0.1185	0.1195	0.1480	0.0745	0.0821	0.0906	3.3743	0.5459	3.6570	2.5980	4.7558	1.3517
1984	43.4300	4.4300	15.2000	6.7200	5.7700	21.8900	12.9300	17.2500	76.9400	82.0200	80.8100	27.5100	32.9083
	0.0402	0.0519	0.0314	0.0372	0.0965	0.0635	0.1184	0.1238	0.0560	0.0451	0.0427	0.0632	0.0642
	1.7443	0.2299	0.4772	0.2502	0.5569	1.3905	1.5312	2.1360	4.3057	3.6972	3.4499	1.7394	1.7923
	3.1611	0.1468	0.7749	0.2374	0.2166	1.4052	0.6494	1.0814	3.5278	3.4867	4.4238	1.3544	1.7055
1985	12.9800	5.8000	6.8300	5.4600	5.8400	5.0700	12.4400	22.6700	65.7400	101.7000	111.0100	63.1600	34.8917
	0.0683	0.0436	0.0349	0.0374	0.0924	0.1809	0.1185	0.0973	0.0585	0.0391	0.0357	0.0392	0.0705
	0.8860	0.2527	0.2383	0.2044	0.5397	0.9172	1.4740	2.2063	3.8461	3.9806	3.9686	2.4775	1.7493
	0.4996	0.2020	0.2266	0.1772	0.1922	0.1781	0.7545	1.4302	4.7917	6.8861	5.8633	3.0926	2.0245

	Mean	Std. Dev.	N
Monthly flow (mill. cubic m)	31.35	32.86	36
Average monthly PO4 (mg/l)	0.08	0.06	36

Total modelled surface runoff = 1128.64 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 260.40 (ton)
Final catchment surface P storage = 206.98 (ton)
Total surface P recharge = 7.03 (ton)
Total surface soluble P washoff = 28.94 (ton)
Total surface particulate P washoff = 31.51 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.05 (mg/l)

Total soil eroded from catchment = 2790.15 (ton/[km*km]/yr)
Total sediment delivered to streams = 2751.50 (ton/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 29.9097
Coef. of Determination = 0.7687

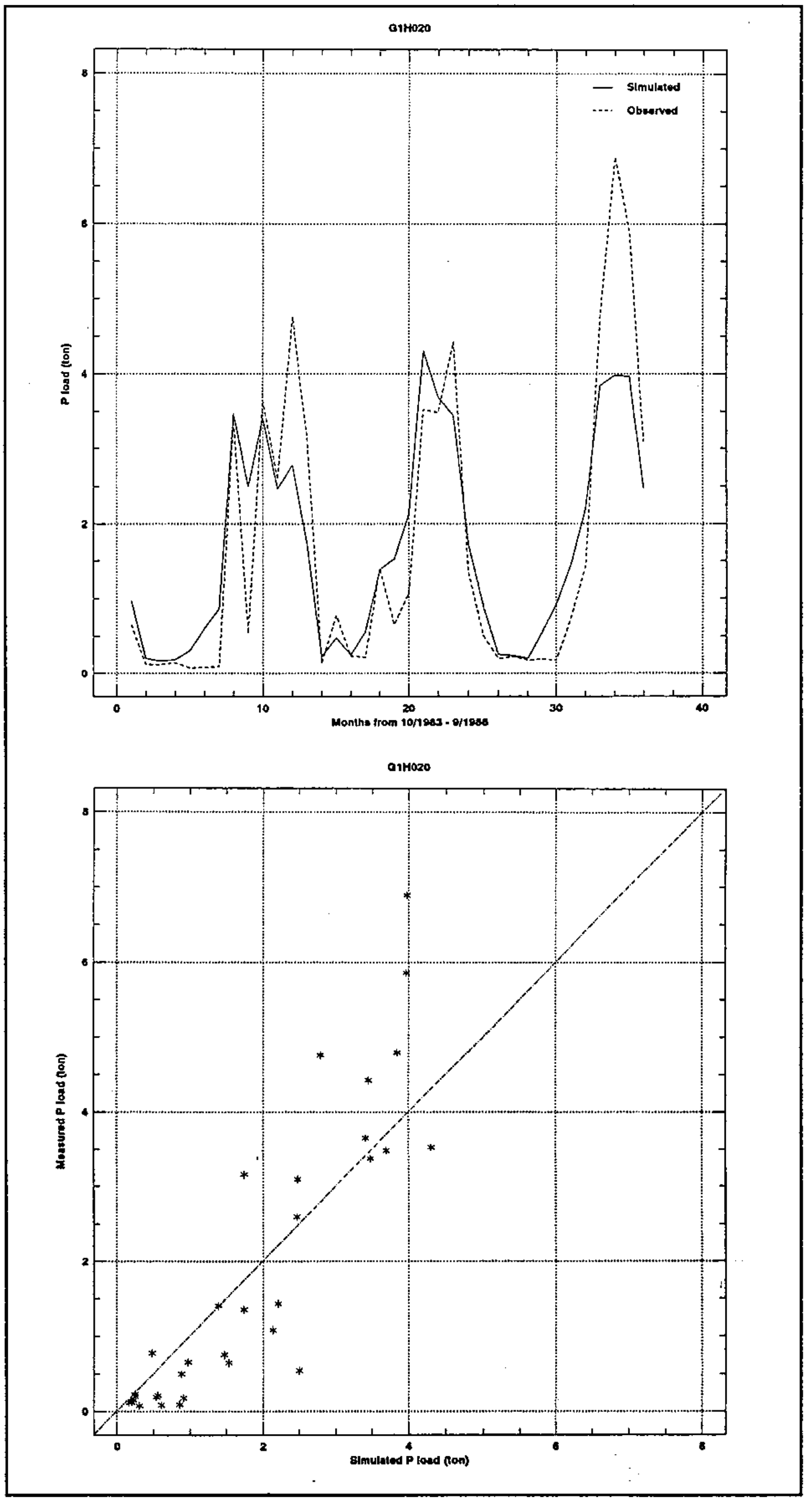

Figure 5.13 Observed versus simulated P loads for G1H020

Table 5.31 Stratification scheme for monthly P load estimation at G1H020

Gauging station : G1H020	Berg River at Noorder Paarl	
Stratum	Sampled flows	Recorded flows
1	39 (38.2%)	721 (50.4%)
2	32 (31.4%)	523 (36.6%)
3	27 (26.5%)	180 (12.6%)
4	4 (3.9%)	6 (0.4%)
Total	102	1430
Catchment area : 65.1 km^2 Latitude : 33°42′ 30″ Longitude : 18°58′ 30″ Sample record length : 28/11/1983 - 29/07/1986 Discharge record length : 01/01/1983 - 31/12/1986		

5.4.7 Catchment R2H006

The input values are presented in Tables 5.32 to 5.34 and the results are given in Table 5.35.

The average slope of catchment R2H006 was measured as approximately 3.0% and the slope length was set to 300m. An estimated average EI_{30} value of 200.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 40.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} $month^{-1}$.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data. There appears to be no bias towards sampling either high or low discharges as shown in Table 5.36.

Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 4 REG-1 was chosen over 5 REG-2 and the monthly P loads so produced are listed in Table 5.33.

The catchment map is given as Figure 5.14 and the plot of simulated against observed P loads is shown in Figure 5.15.

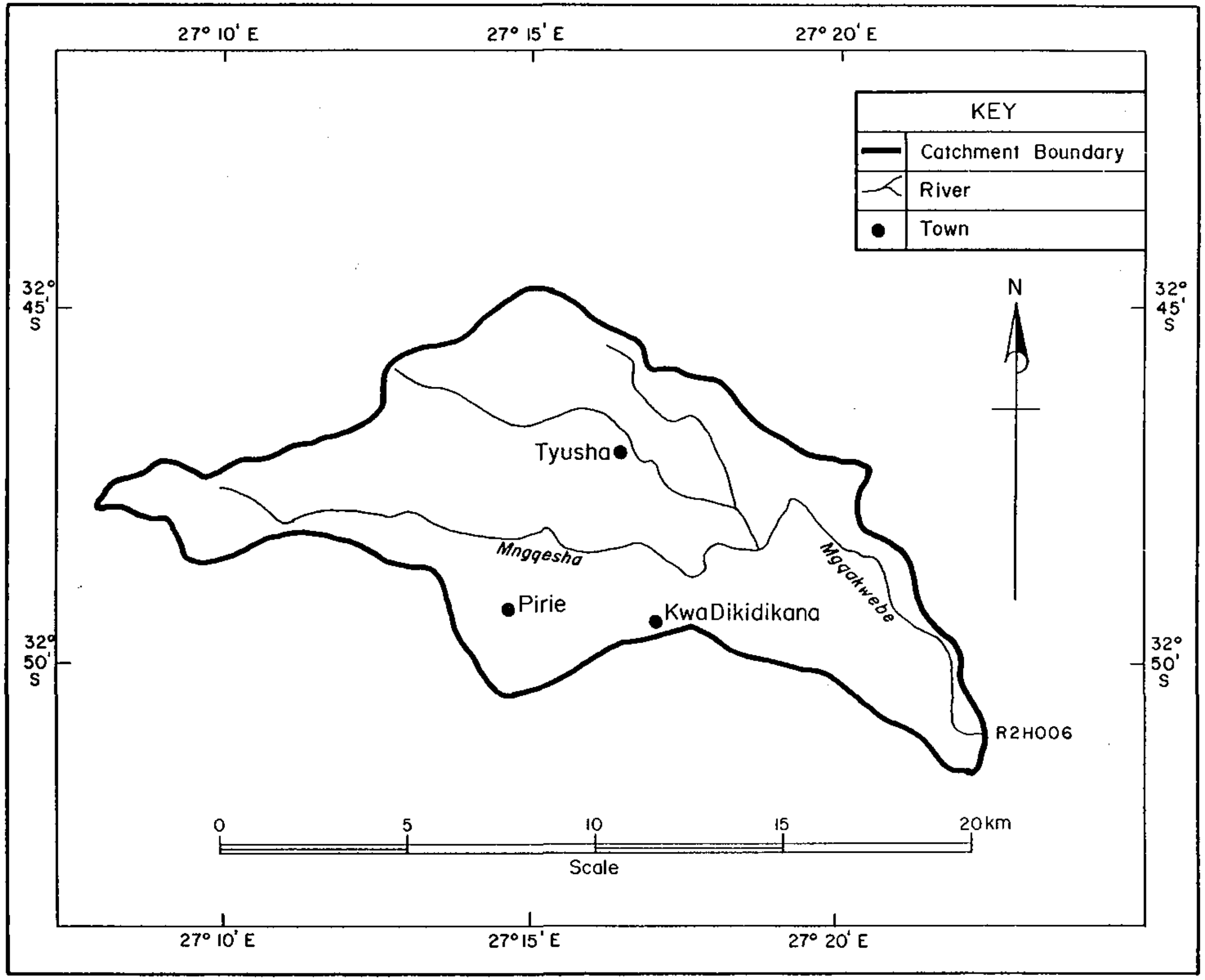

Figure 5.14 Catchment R2H006 in the Buffalo River drainage basin

Table 5.32 Monthly observed flow values (million m^3) for catchment R2H006

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1982	0.20	0.24	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.27	0.05	0.23
1983	0.70	1.83	0.68	0.98	0.33	1.41	0.92	0.17	0.12	0.10	0.08	0.06
1984	0.14	0.57	0.21	1.41	3.43	0.28	0.14	0.14	0.12	0.07	0.01	0.00
1985	0.92	5.91	5.02	1.99	0.58	1.28	0.53	0.28	0.15	0.11	0.14	0.30

Table 5.33 Monthly observed TP values (ton) for catchment R2H006

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1982	0.0090	0.0130	0.0007	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0512	0.0024	0.0121
1983	0.0397	0.3305	0.0372	0.0576	0.0180	0.2575	0.1855	0.0084	0.0053	0.0048	0.0037	0.0026
1984	0.0062	0.0655	0.0097	0.2153	0.7626	0.0127	0.0066	0.0064	0.0055	0.0030	0.0007	0.0000
1985	0.2180	1.5552	1.2197	0.3459	0.0269	0.2130	0.0265	0.0126	0.0067	0.0049	0.0071	0.0162

Table 5.34 Parameters used in the PEM to simulate P loads for R2H006

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
119.0	0.0	0.0	0.0	100.0	1982	1985	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	10.50	35.00

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
119.0	200.0	0.70	300.0	3.0	0.80	0.60	40.0	0.60	0.003

Table 5.35 Results for catchment R2H006

Phosphorus export from catchment R2H006 for the period 10/1982 to 9/1986

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. *P load leaving catchment in streamflow (t)*
4. Observed P load [when supplied by user] (t) (-0.001 indicates missing value)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1982	0.2000	0.2400	0.0200	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.2700	0.0500	0.2300	0.0850
	0.0778	0.0815	0.0872	0.0881	0.0000	0.0000	0.0000	0.0000	0.0000	0.0785	0.0794	0.0804	0.0477
	0.0156	0.0196	0.0017	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0212	0.0040	0.0185	0.0068
	0.0090	0.0130	0.0007	0.0005	0.0000	0.0000	0.0000	0.0000	0.0000	0.0512	0.0024	0.0121	0.0074
1983	0.7000	1.8300	0.6800	0.9800	0.3300	1.4100	0.9200	0.1700	0.1200	0.1000	0.0800	0.0600	0.6150
	0.1000	0.1257	0.1661	0.1705	0.1518	0.1038	0.0982	0.0886	0.0816	0.0820	0.0865	0.0921	0.1123
	0.0700	0.2300	0.1130	0.1671	0.0501	0.1464	0.0904	0.0151	0.0098	0.0082	0.0069	0.0055	0.0760
	0.0397	0.3305	0.0372	0.0576	0.0180	0.2575	0.1855	0.0084	0.0053	0.0048	0.0037	0.0026	0.0792
1984	0.1400	0.5700	0.2100	1.4100	3.4300	0.2800	0.1400	0.1400	0.1200	0.0700	0.0100	0.0000	0.5433
	0.1020	0.1258	0.1635	0.1676	0.1500	0.1053	0.1003	0.0915	0.0851	0.0855	0.0897	0.0000	0.1055
	0.0143	0.0717	0.0343	0.2363	0.5144	0.0295	0.0140	0.0128	0.0102	0.0060	0.0009	0.0000	0.0787
	0.0062	0.0655	0.0097	0.2153	0.7626	0.0127	0.0066	0.0064	0.0055	0.0030	0.0007	0.0000	0.0912
1985	0.9200	5.9100	5.0200	1.9900	0.5800	1.2800	0.5300	0.2800	0.1500	0.1100	0.1400	0.3000	1.4342
	0.1385	0.2026	0.3003	0.3065	0.2591	0.1412	0.1271	0.1031	0.0855	0.0859	0.0964	0.1095	0.1630
	0.1274	1.1971	1.5077	0.6099	0.1503	0.1807	0.0674	0.0289	0.0128	0.0095	0.0135	0.0328	0.3282
	0.2180	1.5552	1.2197	0.3459	0.0269	0.2130	0.0265	0.0126	0.0067	0.0049	0.0071	0.0162	0.3044

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	0.67	1.21	48
Average monthly PO4 (mg/l)	0.11	0.06	42

Total modelled surface runoff = 32.13 (million m**3)
Total modelled groundwaterflow = *0.00 (million m**3)*

Initial catchment P storage = 71.40 (ton)
Final catchment surface P storage = *82.66 (ton)*
Total surface P recharge = 17.14 (ton)
Total surface soluble P washoff = 2.70 (ton)
Total *surface particulate P washoff* = 3.18 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.18 (mg/l)

Total soil eroded from catchment = 15262.29 (t/[km*km]/yr)
Total sediment delivered to streams = 945.84 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 0.4231
Coef. of Determination = 0.9010

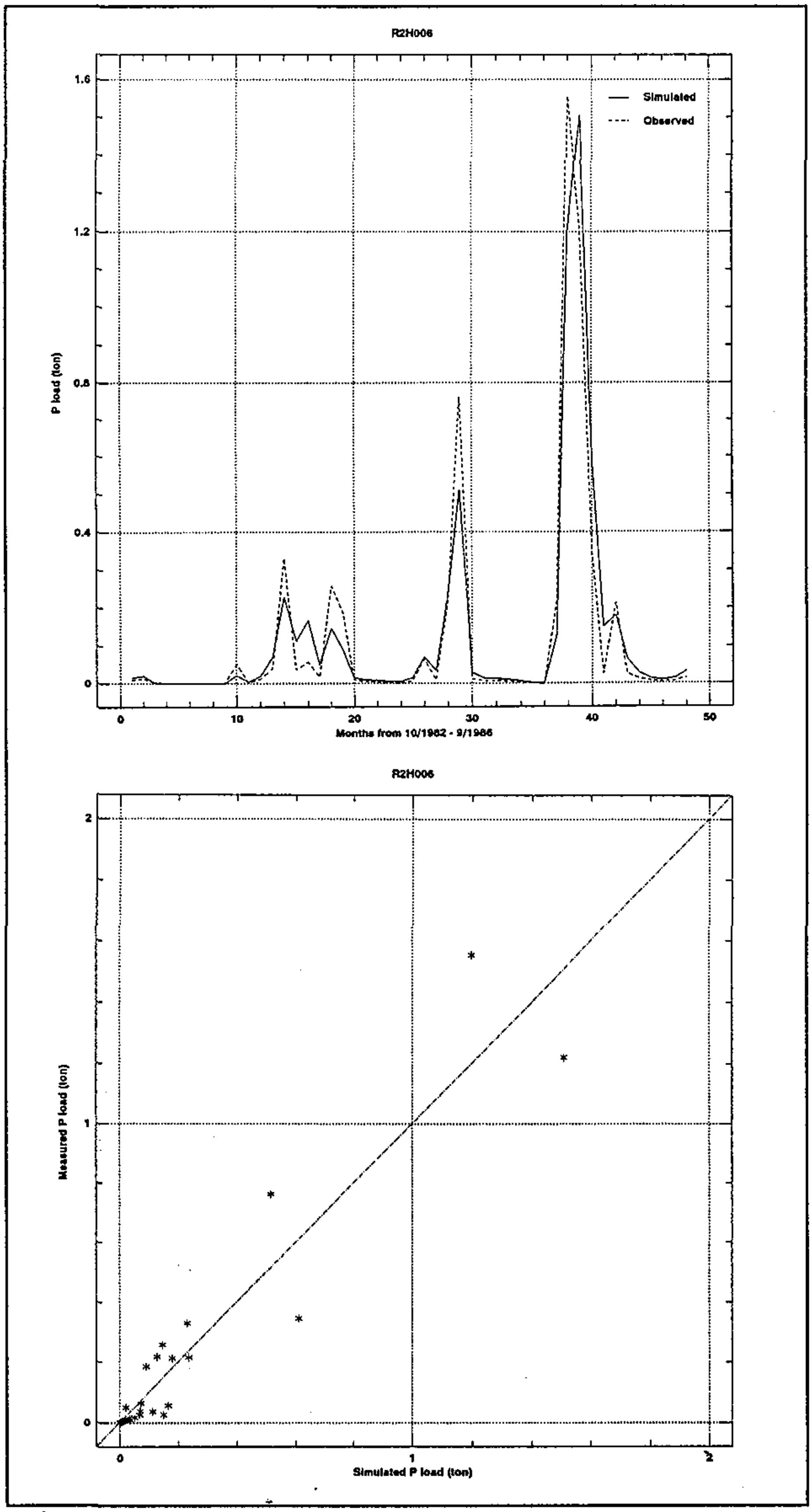

Figure 5.15 Observed versus simulated P loads for R2H006

Table 5.36 Stratification scheme for monthly P load estimation at R2H006

Gauging station : R2H006 Mgqakwebe River at Msenge Ridge		
Stratum	Sampled flows	Recorded flows
1 2 3	116 (87.2%) 13 (9.8%) 4 (3.0%)	1515 (87.5%) 163 (9.4%) 53 (3.1%)
Total	133	1731
Catchment area : 119 km² Basin area : 913 km² (Laing Dam) : 1176 km² (Bridledrift Dam) Latitude : 32°51′ 30″ Longitude : 27°22′ 30″ Sample record length : 06/01/1982 - 11/08/1986 Discharge record length : 01/01/1982 - 29/09/1986		

5.4.8 Catchment U2H012

The input values are presented in Tables 5.37 to 5.39 and the results are given in Table 5.40.

The land use in catchment U2H012 is mainly forestry and beef cattle production. The average slope of the catchment was measured as approximately 6.5% and the slope length was set to 300m. An estimated average EI_{30} value of 300.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 192.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} $month^{-1}$.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data. As shown in Table 5.41 there was a bias towards sampling low discharges. This was probably due to the good flow year round in most of Natal's rivers with no periods of zero flow as experienced in some of the catchments described earlier.

Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 5 REG-2 was chosen over 4 REG-1 and the monthly P loads so produced are listed in Table 5.38.

The catchment map is given as Figure 5.16 and the plot of simulated against observed P loads is shown in Figure 5.17.

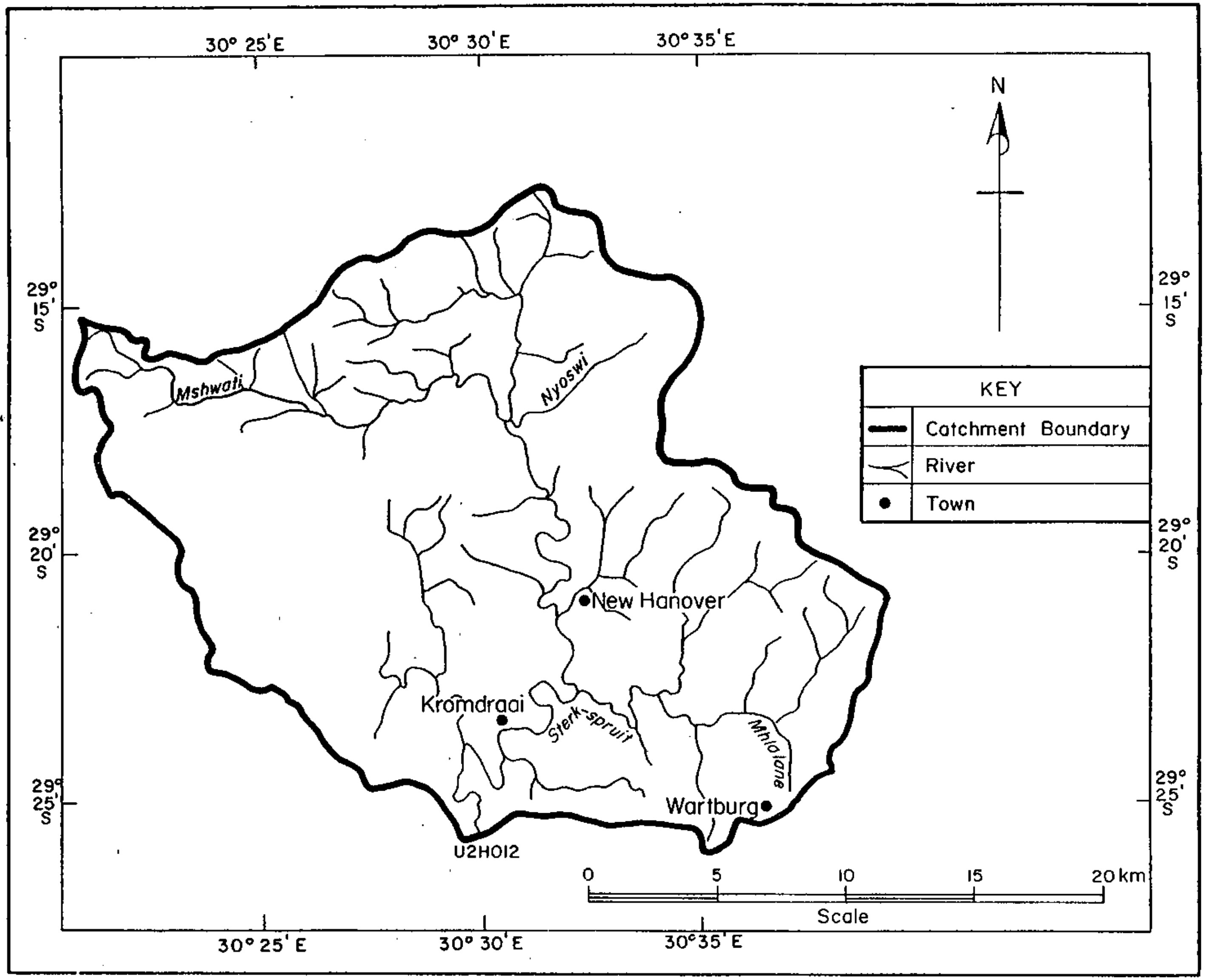

Figure 5.16 Catchment U2H012 in the Umgeni River drainage basin

Table 5.37 Monthly observed flow values (million m^3) for catchment U2H012

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.23	1.75	3.71	7.68	3.06	3.28	1.12	0.65	0.48	0.29	0.14	0.21
1986	0.47	1.10	4.57	11.01	9.27	24.54	1.70	3.04	1.37	1.52	3.80	9.47
1987	25.51	5.74	5.40	5.64	10.53	28.73	10.09	4.98	3.70	3.02	1.79	1.11
1988	0.82	2.51	15.93	11.74	11.96	10.79	3.61	1.90	1.42	1.26	0.61	0.33

Table 5.38 Monthly observed TP values (ton) for catchment U2H012

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.0112	0.1160	0.4217	0.8187	0.2131	0.2519	0.0954	0.0376	0.0217	0.0099	0.0048	0.0071
1986	0.0205	0.0741	0.2696	1.6799	1.6039	8.2541	1.1662	0.2160	0.1172	0.1083	0.2180	3.3979
1987	8.6919	1.0947	-0.001	2.4430	3.5438	13.1790	0.5047	0.3172	0.2483	0.2057	0.1249	0.0770
1988	0.0530	0.3055	4.6643	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001

Table 5.39 Parameters used in the PEM to simulate P loads for U2H012

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
438.0	0.0	0.0	0.0	100.0	1985	1988	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	5.60	30.00

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
438.0	300.0	0.17	300.0	7.0	0.15	0.15	192.0	0.60	0.003

Table 5.40 Results for catchment U2H012

Phosphorus export from catchment U2H012 for the period 10/1985 to 9/1989

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) { -0.001 indicates missing value }

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1985	0.2300	1.7500	3.7100	7.6800	3.0600	3.2800	1.1200	0.6500	0.4800	0.2900	0.1400	0.2100	1.8833
	0.1560	0.1673	0.1845	0.1864	0.1786	0.1590	0.1571	0.1536	0.1513	0.1520	0.1544	0.1573	0.1631
	0.0359	0.2927	0.6846	1.4315	0.5464	0.5214	0.1759	0.0999	0.0726	0.0441	0.0216	0.0330	0.3300
	0.0112	0.1160	0.4217	0.8187	0.2131	0.2519	0.0954	0.0379	0.0217	0.0099	0.0048	0.0071	0.1674
1986	0.4700	1.1000	4.5700	11.0100	9.2700	24.5400	1.7000	3.0400	1.3700	1.5200	3.8000	9.4700	5.9883
	0.1823	0.2181	0.2743	0.2791	0.2514	0.1819	0.1752	0.1624	0.1531	0.1537	0.1598	0.1668	0.1965
	0.0857	0.2399	1.2534	3.0733	2.3304	4.4650	0.2978	0.4937	0.2098	0.2337	0.6072	1.5800	1.2392
	0.0205	0.0741	0.2696	1.6799	1.6039	8.2541	1.1662	0.2160	0.1172	0.1083	0.2180	3.3979	1.4271
1987	25.5100	5.7400	5.4000	5.6400	10.5300	28.7300	10.0900	4.9800	3.7000	3.0200	1.7600	1.1100	8.8508
	0.1909	0.2446	0.3250	0.3321	0.2930	0.1859	0.1817	0.1624	0.1486	0.1491	0.1576	0.1681	0.2116
	4.8692	1.4041	1.7549	1.8728	3.0852	5.3398	1.8335	0.8087	0.5500	0.4503	0.2773	0.1866	1.8694
	8.6919	1.0947	-0.0010	2.4430	3.5438	13.1790	0.5047	0.3172	0.2483	0.2057	0.1249	0.0770	2.5358
1988	0.8200	2.5100	15.9300	11.7400	11.9600	10.7900	3.6100	1.9000	1.4200	1.2600	0.6100	0.3300	5.2400
	0.1750	0.2057	0.2530	0.2552	0.2315	0.1748	0.1680	0.1571	0.1493	0.1500	0.1553	0.1620	0.1864
	0.1435	0.5163	4.0305	2.9958	2.7684	1.8858	0.6064	0.2985	0.2120	0.1889	0.0948	0.0534	1.1495
	0.0530	0.3055	4.6643	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	0.4178

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	5.49	6.71	48
Average monthly PO4 (mg/l)	0.19	0.05	48

Total modelled surface runoff = 263.55 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 262.80 (ton)
Final catchment surface P storage = 270.82 (ton)
Total surface P recharge = 63.07 (ton)
Total surface soluble P washoff = 39.88 (ton)
Total surface particulate P washoff = 15.17 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.21 (mg/l)

Total soil eroded from catchment = 1185.81 (t/[km*km]/yr)
Total sediment delivered to streams = 425.37 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 126.0036
Coef. of Determination = 0.6023

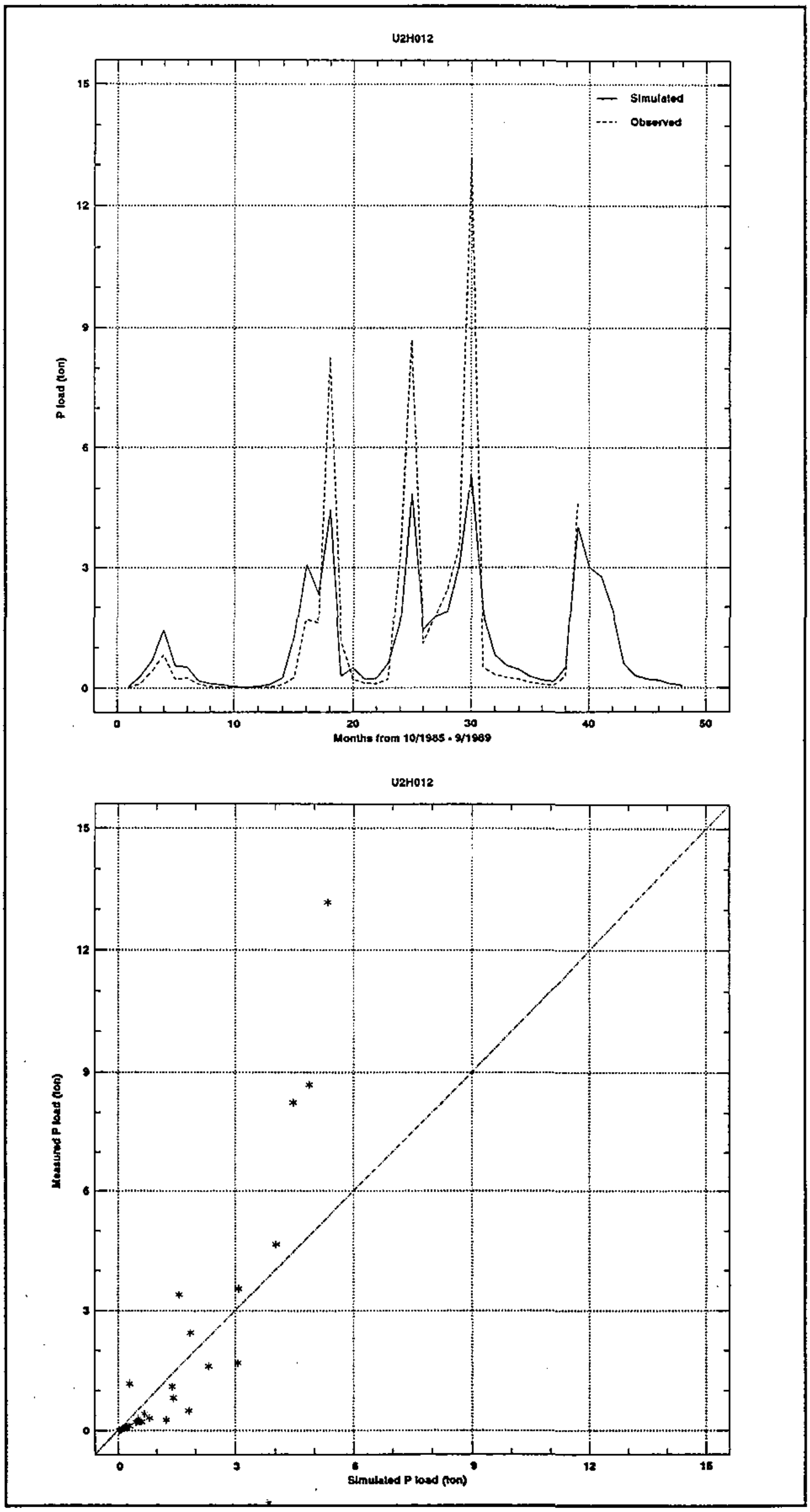

Figure 5.17 Observed versus simulated P loads for U2H012

Table 5.41 Stratification scheme for monthly P load estimation at U2H012

Gauging station : U2H012	Sterk River at Groothoek	
Stratum	Sampled flows	Recorded flows
1	15 (17.6%)	137 (10.3%)
2	17 (20.0%)	210 (15.8%)
3	23 (27.1%)	581 (43.6%)
4	24 (28.2%)	253 (19.0%)
5	6 (7.1%)	150 (11.3%)
Total	85	1331

Catchment area : 438 km^2
Basin area : 891 km^2 (Nagle)
Latitude : 29°26′ 15″ Longitude : 30°29′ 30″
Sample record length : 02/10/1985 - 11/05/1988
Discharge record length : 01/01/1985 - 31/12/1988

5.4.9 Catchment U2H013

The input values are presented in Tables 5.42 to 5.44 and the results are given in Table 5.45.

The land use in catchment U2H013 is mainly forestry and beef cattle production. The average slope of the catchment was measured as approximately 6.5% and the slope length was set to 300m. An estimated average EI_{30} value of 300.0 was obtained from Figure D1. As before the USLE soil and land cover parameters were estimated using Rooseboom's (1978) sediment map as a guide.

The total length of perennial rivers in the catchment was measured as 113.0 km. As before, initial P storage and replenishment rates had to be estimated. The initial catchment storage was set at 0.6 tons P km^{-1} and the replenishment rate was set at 0.003 tons km^{-2} month^{-1}.

As before the discharge data were stratified before fitting the flux:discharge regression models to the sampled data. As shown in Table 5.46 there was a slight bias towards sampling high discharges.

Flux estimates obtained by flux:discharge regression models 4 REG-1 and 5 REG-2 differed slightly with regard to the variance associated with flux estimates. Regression model 5 REG-2 was chosen over 4 REG-1 and the monthly P loads so produced are listed in Table 5.43.

The catchment map is given as Figure 5.18 and the plot of simulated against observed P loads is shown in Figure 5.19.

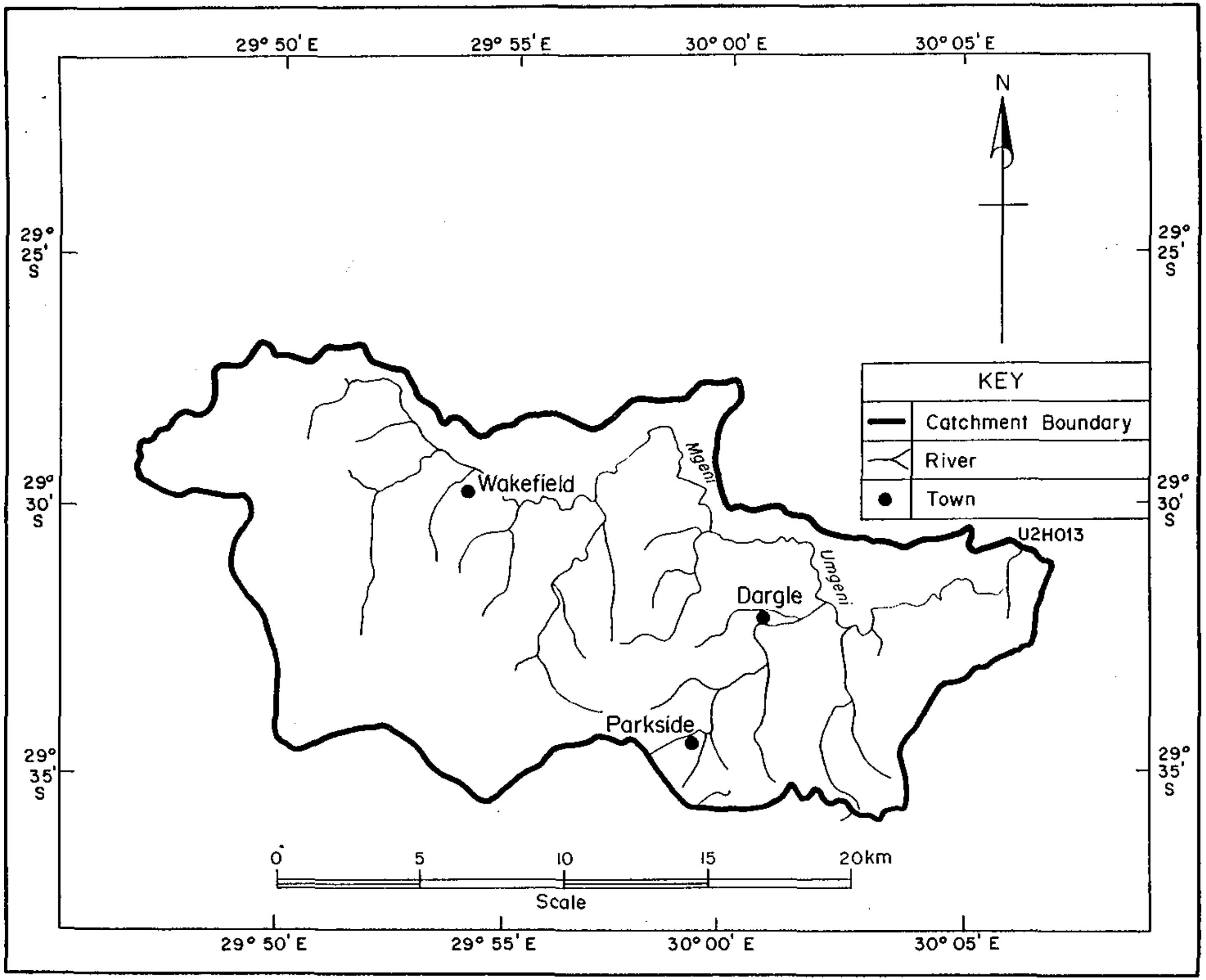

Figure 5.18 Catchment U2H013 in the Umgeni River drainage basin

Table 5.42 Monthly observed flow values (million m^3) for catchment U2H013

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	1.38	9.06	15.24	25.29	8.00	10.85	4.03	2.17	1.48	1.11	1.13	1.47
1986	1.99	6.51	9.50	8.36	4.16	11.86	6.53	2.46	1.67	1.54	3.54	16.35
1987	25.18	18.67	11.39	10.15	15.99	44.11	8.13	3.98	4.30	4.44	2.70	2.13

Table 5.43 Monthly observed TP values (ton) for catchment U2H013

Year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
1985	0.0542	0.6004	1.1992	2.0244	0.6209	0.8460	0.1416	0.0507	0.0344	0.0256	0.0375	0.0342
1986	0.0584	0.4884	0.7433	0.6666	0.1937	0.8407	0.4608	0.0579	0.0386	0.0356	0.2002	1.2717
1987	1.9974	1.4677	0.8580	0.7258	1.3269	3.7467	0.6063	0.1073	0.1745	0.2292	-0.001	-0.001

Table 5.44 Parameters used in the PEM to simulate P loads for U2H013

Area	QGMax	PG	Decay	Cgo	Iys	Iye	IGrow	Pit	Pobs
299.0	0.0	0.0	0.0	100.0	1985	1987	0	0	1

USLEdiv	Region	DRatio	Spar	Ppar
1	1	0.0	2.70	30.00

Uarea	EI_{30}	Erode	S-length	Slope	Cover	Support	Rivlen	StoreI	Ro
299.0	300.0	0.17	300.0	7.0	0.15	0.15	113.0	0.60	0.003

Table 5.45 Results for catchment U2H013

Phosphorus export from catchment U2H013 for the period 10/1985 to 9/1988

For each year the rows contain :
1. Observed flow (million m**3)
2. P Concentration (mg/l)
3. P load leaving catchment in streamflow (t)
4. Observed P load [when supplied by user] (t) (-0.001 indicates missing value)

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Average
1985	1.3800	9.0600	15.2400	25.2900	8.0000	10.8500	4.0300	2.1700	1.4800	1.1100	1.1300	1.4700	6.7675
	0.0564	0.0664	0.0820	0.0832	0.0755	0.0572	0.0551	0.0515	0.0490	0.0492	0.0510	0.0532	0.0608
	0.0779	0.6020	1.2497	2.1043	0.6042	0.6208	0.2221	0.1118	0.0725	0.0546	0.0576	0.0782	0.4880
	0.0542	0.6004	1.1992	2.0244	0.6209	0.8460	0.1416	0.0507	0.0344	0.0256	0.0375	0.0342	0.4724
1986	1.9900	6.5100	9.5000	8.3600	4.1600	11.8600	6.5300	2.4600	1.6700	1.5400	3.5400	16.3500	6.2058
	0.0573	0.0667	0.0815	0.0830	0.0761	0.0588	0.0567	0.0533	0.0509	0.0511	0.0528	0.0548	0.0619
	0.1140	0.4345	0.7743	0.6935	0.3167	0.6968	0.3704	0.1311	0.0849	0.0787	0.1869	0.8954	0.3981
	0.0584	0.4884	0.7433	0.6666	0.1937	0.8407	0.4608	0.0579	0.0386	0.0356	0.2002	1.2717	0.4213
1987	25.1800	18.6700	11.3900	10.1500	15.9900	44.1100	8.1300	3.9800	4.3000	4.4000	2.7000	2.1300	12.5942
	0.0669	0.0858	0.1157	0.1183	0.1038	0.0606	0.0628	0.0556	0.0505	0.0507	0.0539	0.0579	0.0735
	1.6843	1.6019	1.3176	1.2007	1.6595	2.6740	0.5102	0.2214	0.2170	0.2229	0.1455	0.1232	0.9648
	1.9974	1.4677	0.8580	0.7258	1.3269	3.7467	0.6063	0.1073	0.1745	0.2292	-0.0010	-0.0010	0.9365

	Mean	Std. Dev.	N
Monthly Flow (mill. cubic m)	8.52	8.94	36
Average monthly PO4 (mg/l)	0.07	0.02	36

Total modelled surface runoff = 306.81 (million m**3)
Total modelled groundwaterflow = 0.00 (million m**3)

Initial catchment P storage = 179.40 (ton)
Final catchment surface P storage = 189.48 (ton)
Total surface P recharge = 32.29 (ton)
Total surface soluble P washoff = 15.39 (ton)
Total surface particulate P washoff = 6.82 (ton)
Total P leaving groundwater = 0.00 (ton)
Flow weighted average P = 0.07 (mg/l)

Total soil eroded from catchment = 889.36 (t/[km*km]/yr)
Total sediment delivered to streams = 408.90 (t/[km*km]/yr)

Simulation Statistics : Sum of Error Squared = 2.1533
Coef. of Determination = 0.8982

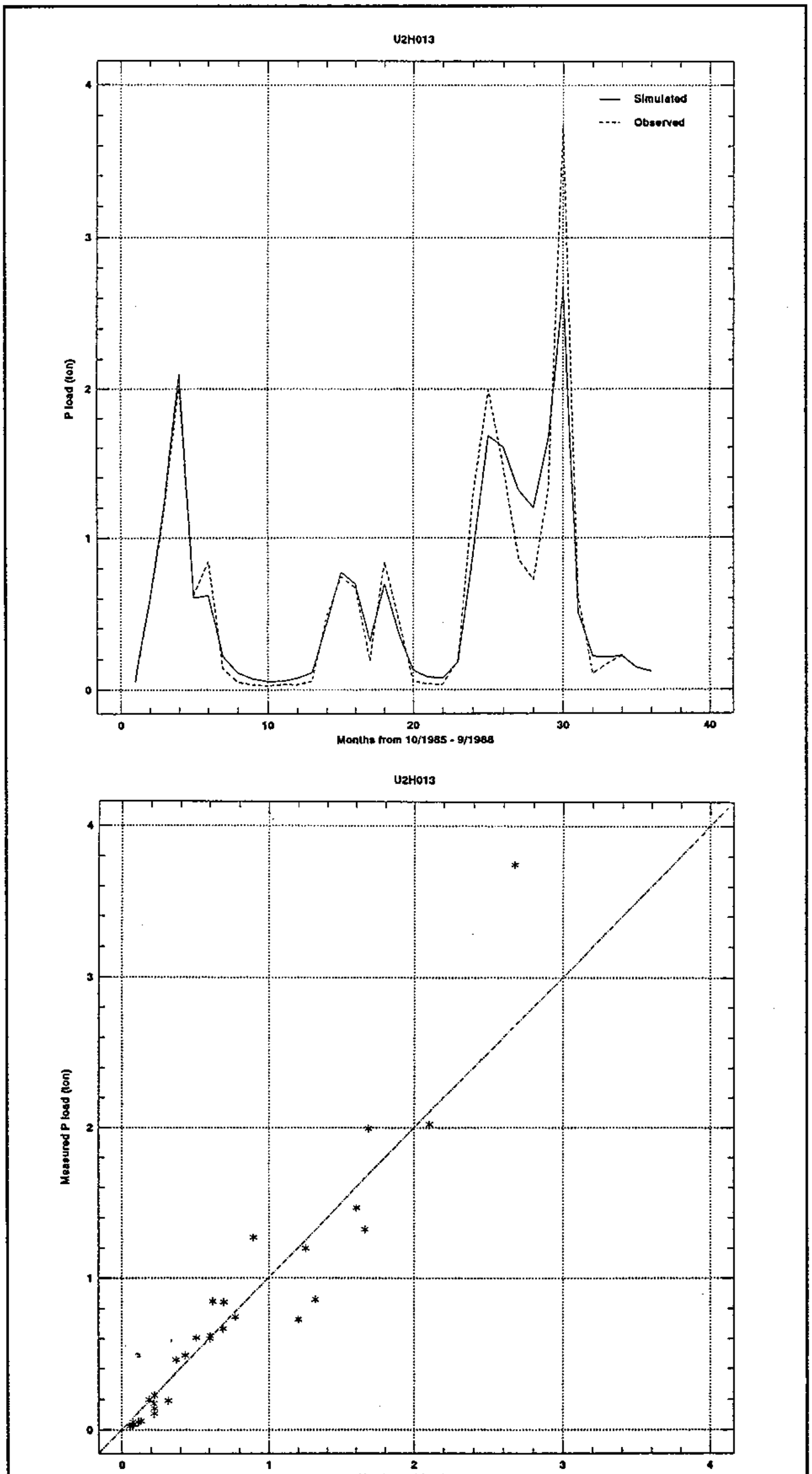

Figure 5.19 Observed versus simulated P loads for U2H013

Table 5.46 Stratification scheme for monthly P load estimation at U2H013

Gauging station : U2H013 Umgeni River at Petrusstroom		
Stratum	Sampled flows	Recorded flows
1	36 (29.0%)	484 (37.0%)
2	26 (21.0%)	227 (17.4%)
3	25 (20.2%)	267 (20.4%)
4	29 (23.3%)	249 (19.1%)
5	8 (6.5%)	80 (6.1%)
Total	124	1307
Catchment area : 299 km^2 Basin area : 928 km^2 (Midmar) Latitude : 29°30′ 45″ Longitude : 30°05′ 45″ Sample record length : 02/10/1985 - 23/06/1988 Discharge record length : 01/01/1985 - 31/07/1988		

5.5 Discussion of Simulation Results

Results for all but two of the test catchments gave coefficients of determination of above 80%. Of the other two catchments, G1H020 had a coefficient of 76.9% and U2H012 had a coefficient of 60.2%. The relatively poor coefficient for U2H012 is surprising in light of the fact that the fit between simulated and observed loads was good for the nearby catchment U2H013. The poor results for U2H012 could be a consequence of inaccuracies in the stratification of the observed flows when calculating values for observed load with the program FLUX.

Perusal of the one-to-one simulated against measured P load plots shows that in most cases the simulation is better at low flows than at high flows. This can be expected as the P load is directly related to the quantity of flow and is thus highly variable at times of high flow when the system is not in equilibrium. High flows, however, may present a major problem concerning the water quality of catchment outflow and subsequent inflow to a reservoir, not only in terms of the additional P load washed off the catchment but also due to resuspension of bottom sediments, and associated adsorbed P, in the transporting waterway. Future research in this field should address the problem of modelling, more exactly, P export from non-point source dominated catchments at high flows.

Pitman (1973) used a system of parameter regionalization which facilitated the selection of appropriate parameter values for input to the Pitman monthly rainfall/runoff model. No such regional pattern of parameters could be discerned for the PEM, however future inclusion of a wider range of test catchments may reveal a regional pattern, especially of the parameters Spar and Ppar. These two parameters, which control the rates of soluble and particulate losses off the catchment, have no physical meaning but appear to be major controlling factors in the calibration of the PEM.

5.6 Parameter Sensitivity

As the name implies parameter sensitivity is an exercise undertaken to determine how each parameter of a model effects the model results, or in other words, how sensitive the model is to parameter changes. For the PEM the parameters were adjusted to their optimum values based on estimates from *a priori* information and then manual calibration of the model for a catchment, in this case A2H013. The parameters were then altered by -50%, -10%, +10% and +50% around their "optimum" values and the program was rerun for each alteration. Percentage changes in model objective functions for each change in parameter are given below in Table 5.47.

Table 5.47 Percentage change in parameter and objective functions during parameter sensitivity analysis for the PEM

Area	Mean	St. dev.	Res.err.	CoD	Sed	Sol.	Part.
-50	- 50.0	- 50.0	+ 95.7	- 23.4	0.0	- 50.0	- 50.0
-10	- 10.0	- 10.0	- 9.1	+ 2.2	0.0	- 10.0	- 10.0
+10	+ 10.0	+ 10.0	+ 23.2	- 5.7	- 9.1	+ 10.0	+ 10.0
+50	+ 50.0	+ 50.0	+256.8	- 62.7	- 33.3	+ 50.0	+ 49.9
Spar							
-50	- 27.7	- 16.8	+ 42.4	- 10.8	0.0	- 49.9	+ 0.1
-10	- 5.5	- 3.5	+ 3.3	- 1.4	0.0	- 10.0	0.0
+10	+ 5.5	+ 3.5	- 0.7	- 0.4	0.0	+ 10.0	0.0
+50	+ 27.5	+ 17.6	+ 22.1	- 5.9	0.0	+ 49.7	- 0.1
Ppar, EI, Erode, Cover, Support and Rivlen							
-50	- 22.1	- 31.9	- 18.6	+ 4.5	0.0	+ 0.3	- 49.9
-10	- 4.4	- 6.5	- 15.3	+ 3.7	0.0	+ 0.1	- 10.0
+10	+ 4.4	+ 6.5	+ 21.0	- 5.1	0.0	- 0.1	+ 9.9
+50	+ 21.9	+ 32.8	+162.5	- 39.7	0.0	- 0.3	+ 49.7
Length							
-50	- 11.5	- 17.2	- 2.0	+ 0.4	- 29.3	+ 0.1	- 29.2
-10	- 2.0	- 3.0	- 3.5	+ 0.6	- 5.1	0.0	- 5.1
+10	+ 1.9	+ 2.9	+ 4.6	- 0.8	+ 4.9	0.0	+ 4.9
+50	+ 8.8	+ 13.5	+ 30.9	- 5.5	+ 22.5	- 0.1	+ 22.4

Table 5.47 Continued

StoreI	Mean	St. dev.	Res.err.	CoD	Sed	Sol.	Part.
-50	- 44.3	- 47.1	+ 71.9	- 17.6	0.0	- 42.6	- 46.4
-10	- 8.9	- 9.5	- 10.6	+ 2.6	0.0	- 8.5	- 9.3
+10	+ 8.9	+ 9.5	+ 23.0	- 5.6	0.0	+ 8.5	+ 9.3
+50	+ 44.3	+ 47.4	+239.9	- 58.6	0.0	+ 42.6	+ 46.4
Ro							
-50	- 5.7	- 2.5	+ 5.9	- 1.4	0.0	- 7.4	- 3.6
-10	- 1.2	- 0.5	+ 0.8	- 0.2	0.0	- 1.5	- 0.7
+10	+ 1.2	+ 0.6	- 0.6	+ 0.2	0.0	+ 1.5	+ 0.7
+50	+ 5.7	+ 2.8	- 0.9	+ 0.2	0.0	+ 7.4	+ 3.6
Slope							
-50	- 31.6	- 44.8	+ 17.8	- 4.3	- 71.4	+ 0.4	- 71.3
-10	- 14.1	- 20.6	- 28.5	+ 7.0	- 32.0	+ 0.2	- 32.0
+10	+ 5.5	+ 8.2	+ 27.2	- 6.6	+ 12.5	- 0.1	+ 12.4
+50	+ 30.6	+ 45.8	+265.6	- 64.8	+ 69.7	- 0.4	+ 69.2

6 STOCHASTIC MODELS

6.1 Introduction

Eutrophication is the excessive enrichment of water bodies with plant nutrients. The undesirable amounts of phytoplankton and/or macrophytes that occur as a consequence of eutrophication lead to many problems related to water quality, including increased water purification costs. Limiting water fertility is generally regarded to be the most desirable strategy for controlling the eutrophication of impoundments.

The first step taken to control eutrophication in South African water was the introduction of legislation, in 1980 and 1985, to limit phosphate concentrations in certain sensitive catchments. The need to assess the impact of phosphate limitation on the trophic status of South African impoundments, resulted in a report by Grobler and Silberbauer (1984), in which they analyzed the impact of the, then proposed, 1985 legislation for nineteen South African impoundments. They adopted the OECD eutrophication modelling approach (Jones and Lee, 1982; Reckhow and Chapra, 1983; Vollenweider, 1969,1975,1976; Vollenweider, Rast and Kerekes, 1980). The OECD modelling approach consists of the sequential application of :

a) a phosphate export model to simulate nutrient loads on impoundments,
b) an impoundment nutrient budget model for simulating nutrient concentrations in impoundments, and
c) a model which converts annual mean nutrient concentrations in impoundments to eutrophication-related water quality variables.

Grobler and Silberbauer (1984) defined water quality in terms of chlorophyll concentrations and they assumed that phosphate, alone, controlled the trophic response of impoundments. The research described in this chapter has been undertaken in order to address some of the research requirements they identified during their study. These requirements are discussed below.

Grobler and Silberbauer (1984) felt that the uncertainty associated with predictions needed to be quantified. They felt that the nutrient budget model used should be modified to accommodate the lack of complete mixing and the dynamic state of South African impoundments. In addition they suggested that water transparency was one of the variables which should be incorporated into the chlorophyll-phosphorus model.

In this study the uncertainty/inaccuracy associated with each of the models used by Grobler and Silberbauer (1984) has been quantified. Improved reservoir-specific models grew out of these evaluations. Finally, the reservoir eutrophication modelling procedure (REM) used by Grobler and Silberbauer (1984) has been compared to the newly developed reservoir specific eutrophication modelling procedure (RSEM), by applying both models in the context of phosphorus control for Hartbeespoort Dam.

Appendices K and L describe the methodology used in the study. Sections 6.3 to 6.6 describe the application of this methodology in the context of the various sub-models required in reservoir eutrophication modelling. In section 6.7 the REM and RSEM modelling procedures are applied in the context of a Monte Carlo simulation for Hartbeespoort Dam.

6.2 Data Base

In addition to the phosphorus export, phosphorus budget and chlorophyll models, Grobler and Silberbauer (1984) use the Pitman (1973) model to generate runoff data. Consequently this model has been evaluated as well. Table 6.1 lists those data sets which have been used to evaluate the Grobler and Silberbauer Reservoir Eutrophication Models (REM). In future these models will be referred to as the conventional models.

These data sets have also been used to produce improved reservoir-specific models. The improved reservoir-specific models (RSEM) will be referred to as the newly developed models. The final "uncertainty analysis" used to compare the conventional and newly developed model was performed using only one time series. In all other instances at least two data sets have been used to evaluate and improve each of the REM models. All data sets used, except for the cross-sectional (C/S) data set used to evaluate the chlorophyll model, are monthly time series.

The data used to evaluate the Pitman Runoff Model consisted of the observed and predicted values for nine rivers. The data for the first three rivers indicated in Table 6.1 were taken from Pitman (1973). In 1973 the methods of calibration used were somewhat primitive, so the predicted runoff values tended to be inaccurate. The data for the next six rivers were provided by Watertek (1991). Calibration methods similar to those used by Pitman (1973) were also used to obtain the predicted runoff values for these rivers.

The data used to test the phosphorus export model were supplied by Rossouw (1991). There is a problem in obtaining reliable data of this nature. Although flows (runoffs) are continuously measured and hence accurate, phosphorus concentrations are measured only periodically. Data are generally unavailable for flash floods. In the case of the two USA rivers indicated in Table 6.1, phosphorus concentrations were measured at four-hourly intervals. However, in the case of the South African rivers phosphorus concentrations were measured only once every two weeks.

Walker (1987) has tested numerous methods of estimating monthly phosphorus loads from continuous flows. One of his more successful methods which involves stratified regression was used in the compilation of the data used in this study. Grobler and Rossouw (1988) describe in detail how the phosphorus loads for the six South African rivers in Table 6.1 were obtained.

Finally, the data used to test the phosphorus budget and chlorophyll models, and to perform the uncertainty analysis for Hartbeespoort Dam were provided by Rossouw (1991).

Table 6.1 Data used in testing the stochastic models

Model	Data Set	No.Observations
Pitman Runoff Model ******************* Slang	V3H005	228 months
Elands	A2R007	336 months
Ongers	D6R002	300 months
Magalies	A2H013 1969-1985	204 months
Vaal	C1H007 1972-1985	168 months
Vet	C4H004 1969-1985	204 months
Umgeni	U2H013 1969-1985	204 months
Karkloof	U2H006 1969-1985	204 months
Sterk	U2H012 1969-1985	204 months
Phosphorus Export Model ************************ Tindall:USA		96 months
Maumee:USA		60 months
Magalies:SA	A2H013 1979-1987	92 months
Vaal:SA	C1H007 1979-1987	102 months
Vet:SA	C4H004 1979-1987	89 months
Umgeni:SA	U2H013 1979-1987	105 months
Karkloof:SA	U2H012 1979-1985	72 months
Sterk:SA	U2H006 1979-1985	72 months
Total P Budget Model ******************** Hartbeespoort	1980-1989	100 months
Witbank	1986-1989	35 months
Chlorophyll Model ***************** Hartbeespoort	1983-1990	79 months
Witbank	1986-1989	34 months
C/S SA Data set	41 SA Reservoirs	48 annual Obs.
Uncertainty Analysis ******************** Hartbeespoort	1983-1987	46 months

6.3 The Pitman Runoff Model

6.3.1 Introduction

Pitman (1973) has developed a hydrological model to simulate runoff. Using precipitation and potential evapotranspiration as input, the quantity of precipitation not absorbed by the soil is estimated. Total runoff is then determined by taking into account lagging in the various components. These predictions are used as the initial input to the conventional REM model.

In this section the Pitman model, calibrated for six catchments, is evaluated using the calibration techniques suggested by Pitman (1973). Next improvements in the calibration process are suggested. Many of the improvements suggested are commonly used by some South African hydrologists at this time (refer section 6.3.2), so this work, to some extent, is not new. Finally it is indicated how prediction errors may be modelled in terms of autocorrelation and distribution, allowing the Monte Carlo simulation of total runoff, compensating for the error characteristics of the predictions.

It is found that special handling is required for semi-arid and arid catchments. For such catchments zero runoffs are common.

6.3.2 Model Evaluation

The method used initially for the calibration of the Pitman model involves the matching of the mean of the log transformed runoffs, the standard deviations for the runoff values, untransformed, and the matching of seasonal distributions. These methods allow the cancellation of positive and negative errors and are incapable of detecting serial correlation in the errors. In this section, better evaluation methods, not all of them new, are proposed to redress these problems. These methods are discussed in detail and then the new evaluation methods are applied for six South African catchments. The section is concluded by introducing an improved calibration scheme, illustrating its use for the same six South African catchments.

In Figure 6.1 the errors from the Pitman model are plotted against their predicted (or simulated) values for the Umgeni river. This plot indicates that the errors are multiplicative in the sense that errors tend to be larger when predicted values are high. Meaningful residual analysis is much easier when errors are defined additively. Multiplicative errors can be converted to additive errors by logging the ratio of observed to predicted values. The residual error is defined as :

$$e_t = \ln y_t - \ln \hat{y}_t \qquad for\ t=1,2,\ldots,n \qquad \text{Eq. 6.1}$$

where y_t denotes the value of observed (or recorded) runoff for month t and $\hat{y}_t$ denotes the value of predicted (or simulated) runoff for month t.

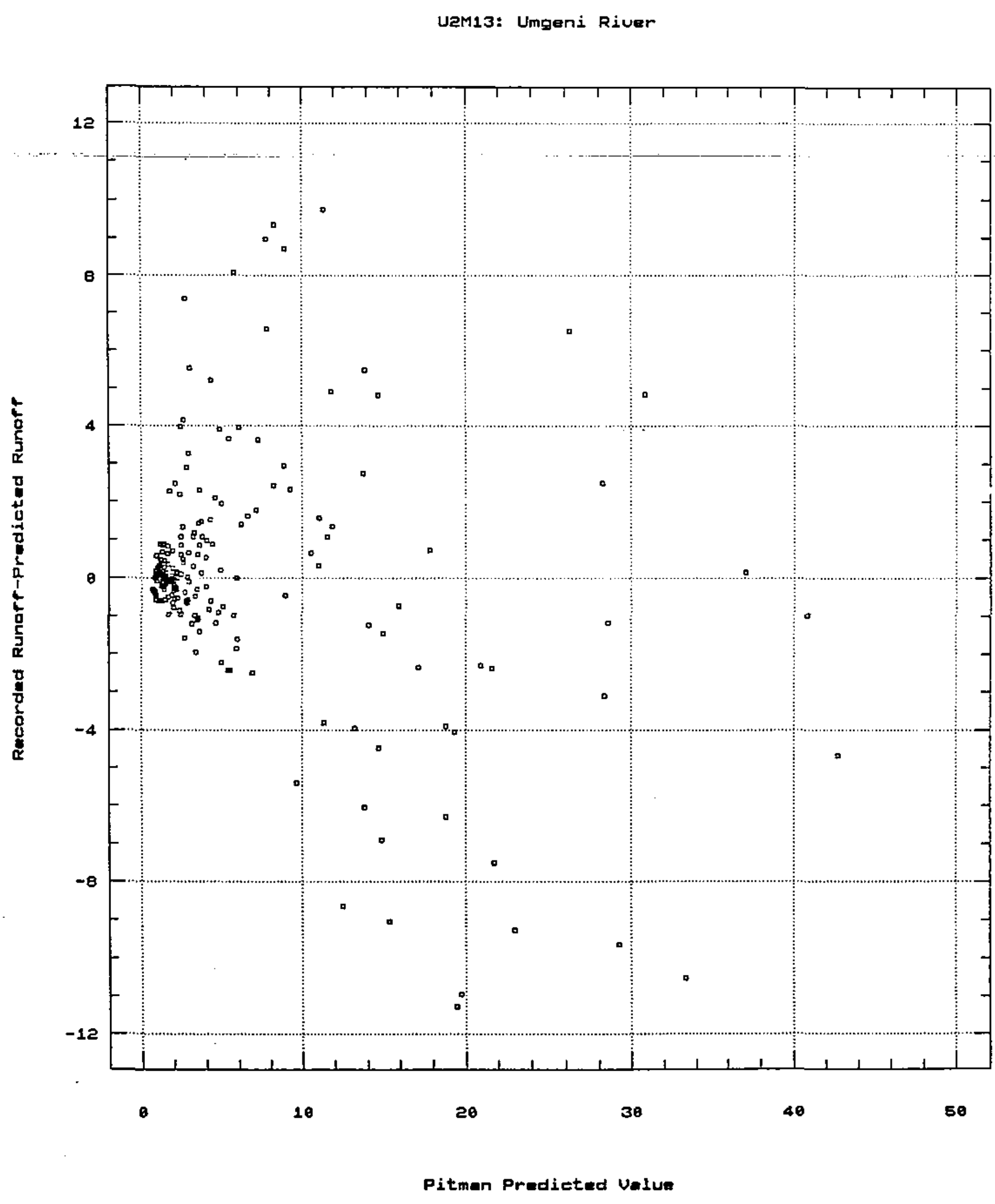

Figure 6.1 Fan-shaped runoff residual plot

These residuals should be used in the calibration of the Pitman model, together with the means and standard deviations for $\ln(y_t)$ and $\ln(\hat{y}_t)$. Note that in most cases the means and standard deviations of the unlogged data should not be used since these measures are distorted by flood runoffs. If flood flows are of importance in the model application, then the unlogged data should be used to ensure that the calibration is focused on the characteristics of interest to the particular study of concern (Görgens, 1991). For p modelling the flood flows are of dominant importance.

The e_t residuals should show a random pattern in relation to the Pitman predictions. If residual values are related to predicted values it means that the calibration can and must be improved. The best way of checking for such a relationship is to plot e_t against $\hat{y}_t$, and then test for the significance of any visible trends. If trends do exist it is generally an indication of a mismatch in the seasonal flow distribution.

The residuals obtained when fitting the trend line (a horizontal line when there is not trend) should show no serial correlation. The Pitman model makes provision for the lagged behaviour of runoff as a function of rainfall. If the residuals are serially correlated it means that the lagged parameter values used are inappropriate. The Durbin-Watson statistic is an appropriate method of checking for the significance of residual serial correlation at a lag of one. The Durbin-Watson statistic is calculated from the formula :

$$DW = \frac{\sum_{t=2}^{n} (e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2} \qquad \text{Eq. 6.2}$$

Appendix I provides critical values for the Durbin-Watson statistic. In this table, n represents the length of the series and p is equal to 1 or 2 respectively for a linear or quadratic $\{e_t:\hat{y}_t\}$ trend. A Durbin-Watson value of below d_L indicates that there is significant positive serial correlation in the errors and a value above $(4-d_L)$ indicates significant negative serial correlation. A value between d_L and d_U or between $(4-d_U)$ and $(4-d_L)$ is inconclusive, and a value between d_U and $(4-d_U)$ indicates that there is no serial correlation in the errors.

When either observed or predicted runoff values are recorded, correct to two decimal places, as zero, e_t is undefined because zero cannot be logged. When there are many such zero values it seems best to ignore these values when performing the residual analysis and re-calibration. If, instead, the zeros are replaced by a small value such as 0.005, calibration can be adversely affected. In the case of semi-arid or arid catchments where zero observed runoffs are common, they should not be ignored, but the study should focus on these low and zero flow periods (Görgens, 1991).

As an overall measure of model adequacy the Coefficient of Efficiency, referred to in this document as R-square (or R^2) and discussed in Appendix K3.4. is recommended. For independent errors this measure is defined as :

$$R^2 = 1 - \frac{\sum_{t=1}^{n} e_t^2}{\sum_{t=1}^{n} (\ln(y_t) - \overline{\ln(y)})^2} \qquad \text{Eq. 6.3}$$

When errors are serially correlated, the procedure described in Appendix K3.5 should be used to obtain a more accurate estimate for the R^2. The R-square is scale invariant and has a simple physical interpretation when positive. A positive R-square measures the proportion of variability in ln(runoff) explained by the current calibration of the Pitman model. Ideally the R-square should be as close to unity as possible. As indicated in Appendix K3.4 a negative R-square indicates gross miscalibration. This measure has the advantage that it does not allow positive errors to be cancelled by negative errors. Furthermore, since it relies on a squaring of errors the effect of grossly incorrect predictions on the R-square is magnified. It is desirable that grossly incorrect predictions should be penalised in this way because they greatly reduce the usefulness of the Pitman model in practical terms. For example, phosphorus predictions based on such runoff values would be totally misleading.

In summary :

a) It is suggested that when comparing means and standard deviations for observed and predicted runoffs, log-transformed runoff data should be used except in cases of flood flow importance.
b) If plots of e_t versus $\hat{y}_t$ show trend, this is an indication of an incorrect seasonal flow distribution.
c) If the errors obtained in b) are autocorrelated then the lag parameters in the Pitman model are incorrectly calibrated.
d) Runoff values of zero should be ignored when calibrating the model, except in cases of semi-arid and arid catchments where zero flows are common.
e) In order to assess the adequacy of the model fit the R^2 should be used.

These methods are now used to evaluate the Pitman model for six South African catchments, calibrated using the methods originally proposed by Pitman (1973). Table 6.2 suggests that this original calibration is sub-optimum.

In view of the apparent miscalibration indicated in Table 6.2, in Table 6.3 a scheme for recalibrating the Pitman model is suggested. The new calibration scheme is based on Pitman's calibration scheme and the above suggestions. The calibration parameters used in this table are:

ST	Maximum soil capacity parameter,
FT	Parameter for runoff from soil at full moisture capacity,
TL	Time lag between rainfall and runoff, and
GL & GW	Groundwater parameters.

Table 6.2 Efficiency of original calibration

Gauge	Logged Observed Runoff		Logged Predicted Runoff		R-square (%)	Durb. Wats. Value	TREND e_t v $\hat{y}_t$
	Mean	StdDev	Mean	StdDev			
U2H013	1.266	1.077	1.275	1.018	85	1.082	No
U2H006	1.010	1.267	1.072	1.246	77	1.005	Yes
U2H012	0.659	1.372	0.930	1.132	69	0.766	Yes
A2H013	0.014	1.782	0.475	0.983	35	0.356	No
C1H007	2.560	0.977	2.499	1.024	49	0.707	Yes
C4H004*	1.188	1.308	0.460	2.538	-169	1.624	Yes

* Zero predicted values treated as missing

Table 6.3 Modified Pitman calibration scheme

Predicted Mean for ln(Runoff)	Predicted StdDev for ln(Runoff)	Seasonal Flow Distribution	Recommended Recalibration
too high	too high	too peaked	increase ST
too high	too low	too uniform	decrease FT
too high	acceptable	too peaked	increase ST
too low	too high	too peaked	increase FT
too low	too low	too uniform	decrease ST
too low	acceptable	too uniform	decrease ST
acceptable	too high	acceptable	increase FT & ST
acceptable	too low	acceptable	decrease FT & ST
acceptable	acceptable	too uniform	decrease TL if DW > (4-d_L) or dec. GL/GW
acceptable	acceptable	too peaked	increase TL if DW < d_L or increase GL/GW

In Table 6.4 this calibration scheme is applied to the six South African catchments evaluated in Table 6.2. In all cases recalibration is recommended.

6.3.3 Monte Carlo Simulations of Runoff

Pitman (1973) calibrated models for three catchments, one humid, one semi-arid and one arid. In this section these calibrations are accepted, an error analysis for them is performed and their use in Monte Carlo simulations of runoff is indicated. Observed and/or predicted runoffs of zero require special treatment.

Table 6.4 Recommended changes in calibration

Gauge	Problem	Recommended Change
U2H013	Low Durb.Wat.	Increase TL
U2H006	Seas Dist^{n} too peaked Low Durb.Wat.	Increase TL Increase TL
U2H012	Over-est in Summer Over-est in Winter Low Durb.Wat Mean too high Std.Dev. too low	Increase TL Decrease GW Increase TL Decrease FT
A2H013	Low Durb.Wat. Mean too high Std.Dev. too low	Increase TL Decrease FT
C1H007	Seas Dist^{n} too peaked Low Durb.Wat.	Increase TL Increase TL
C4H004	Seas Dist^{n} too peaked Low Durb.Wat. Mean too low Std.Dev. too high	Increase TL Increase TL Increase FT

6.3.3.1 *Analysis for a humid catchment*

Pitman (1973) studied the Slang River at Vlak Drift (DWA Gauge V3H005). This is a 676 km^2 catchment with mean annual precipitation of 960mm. Consequently this can be viewed as a humid catchment. Only for one of the 228 months considered was the observed runoff recorded as zero, correct to two decimal places. To simplify the ensuing analysis in which observed runoffs were logged, this single value was replaced by a missing value. It would also have been perfectly feasible to replace this value by, say, 0.005.

The e_t errors defined as in Equation 6.1 were modelled by the following Box and Jenkins (1970) autoregressive one (AR1) model.

$$e_t - \phi e_{t-1} = a_t + \mu \qquad \text{Eq. 6.4}$$

where a_t represents an independent (uncorrelated) time series. The distribution for the a_t

values is approximately N(0,1.3000). The least squares estimates for ϕ and μ are 0.572 and -0.287 respectively.

In order to simulate ln(runoff) values for this catchment realistically, the following process should be used :

a) Generate independent N(0,1.3000) values for a_t, t=1,2,...228.
b) Assuming that $e_0 = \mu/(1-\phi)$ use Equation 6.4 to generate e_t, t=1,2,...228.
c) Simulated values for ln(runoff), s_t, t=1,2,...,228 can be obtained from

$$s_t = \ln(\hat{y}_t) + e_t \qquad \text{Eq. 6.5}$$

6.3.3.2 *Analysis for a semi-arid catchment*

Pitman predicted runoff for the Eland's River at Lindley's Poort Dam (DWA Gauge A2R07). The catchment area is 785 km^2 with a mean annual precipitation of 650mm. For the 336 months studied the observed runoff was recorded as zero, correct to two decimal places, for 31 months. However for no month was the predicted runoff equal to zero, correct to two decimal places. These zero observed values pose a problem. There are too many of them to ignore in a Monte Carlo simulation and it seems that the model has a particular problem with predicting these values. This problem is handled by analyzing prediction errors for zero and non-zero recorded values separately.

Initially only the error distribution for non-zero recorded values has been considered. Again an AR1 model can be used to model these errors, with e_t defined as :

$$e_t - \phi e_{t-1} = a_t + \mu \qquad \text{Eq. 6.6}$$

where ϕ and μ are estimated to be 0.52 and -0.15 respectively, and a_t represents a series of independent (uncorrelated) observations distributed approximately N(0,0.9216).

The population of zero recorded values is now considered. In Table 6.5 the probability of a zero recorded value for each of several predicted value ranges is given. This table can be used when deciding whether the simulated value for any month should be a zero.

In order to simulate ln(runoff) values realistically for this catchment the following process should be used :

a) Generate independent N(0,0.9216) values for a_t, t=1,2,...336.
b) Assuming $e_0 = \mu/(1-\phi)$ use Equation 6.6 to generate e_t, e_t, t=1,2,...336.
c) Generate a series of independent uniformly distributed values for u_t, t=1,2,...336
d) Simulated values for ln(runoff), s_t, t=1,2,...,336 can then be obtained as follows :

$$
\begin{aligned}
&\mathit{If}\ \hat{y}_t \in \mathit{Predicted\ value\ class}\ i\ \mathit{then} \\
&\quad s_t = \ln(0) \qquad\qquad\qquad \mathit{if}\ u_t < p_i \\
&\mathit{otherwise} \\
&\quad s_t = \ln(\hat{y}_t) + e_t
\end{aligned}
$$

Eq. 6.7

This procedure ensures that the autocorrelation structure of the ln(runoff) data is preserved. Months with zero recorded or simulated runoff have no effect on the autocorrelation structure of the recorded or simulated data.

Table 6.5 Probabilities of zero recorded values

Predicted Value Class i	Predicted Value Range	Probability of a Zero Recorded Value (p_i)
1	< 0.1	21.05 %
2	0.1 : 0.2	20.78 %
3	0.2 : 0.3	15.09 %
4	0.3 : 1.0	2.5 %
5	> 1.0	0 %

6.3.3.3 *Analysis for an arid catchment*

Pitman (1973) predicted runoff for the Ongers River at Smartt Syndicate dam (DWA Gauge D6R02). The catchment area is 13183 km^2 with a mean annual precipitation of 230mm. For the 300 months studied the observed runoff was recorded as zero, correct to two decimal places, for 106 months, while the predicted runoff was equal to zero, correct to two decimal places in 42 months. These zero values require special treatment.

Initially only the error distribution for non-zero recorded and predicted values is considered. In Figure 6.2 the logged observed values, $\ln(y_t)$, are plotted against the logged predicted values, $\ln(\hat{y}_t)$. This plot indicates that the size of the error is not independent of predicted value. Errors tend to be positive for low predicted values. That is runoff is under-estimated at low runoffs. Log-transformed runoff($\ln[y_t]$) can be predicted from Pitman predictions using the equation :

$$\ln(y_t) = 0.8 + 0.408\ln(\hat{y}_t) \qquad \text{Eq. 6.8}$$

The errors for this prediction, e_t, are independently distributed approximately N(0,1.7272).

Now consider the population of zero recorded and predicted values. In Table 6.6 the probability of a zero recorded value for each of several predicted value ranges is given. This table can be used when deciding whether the simulated value for any month should be zero.

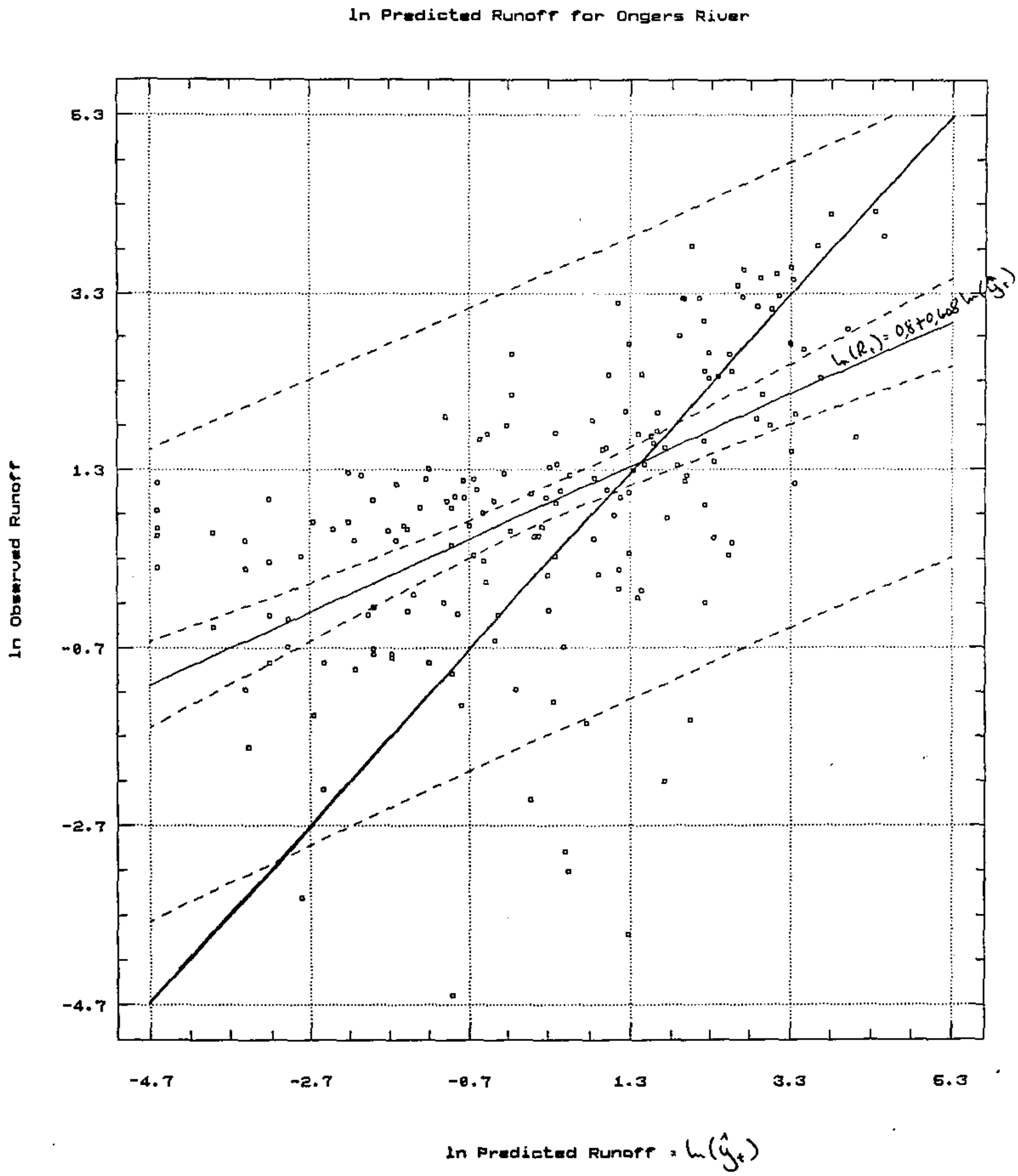

Figure 6.2 Ln(predicted runoff) based on ln(observed runoff) for Ongers River

Table 6.6 Probabilities of zero recorded values

Predicted Value Class i	Predicted Value Range	Probability of a Zero Recorded Value (p_i)
0	0	64.29 %
1	0 : 0.1	55.36 %
2	0.1 : 0.2	40.00 %
3	0.2 : 0.3	55.56 %
4	0.3 : 1.0	32.61 %
5	>1.0	11.50 %

If a predicted value is equal to zero but the recorded value is non-zero it is found that the distribution of logged observed values is N(-0.108,1.0547).

In order to simulate runoff values for this catchment realistically the following procedure should be used :

a) Generate independent N(0,1.7272) values for e_t, t=1,2,...300.
b) Generate a series of independent uniformly distributed u_t values for t=1,2,...300.
c) Generate a series of independent N(-0.108,1.0547) values for v_t, t=1,2,...300
d) Then simulated values for ln(runoff), s_t, t=1,2,...,228 can then be obtained using Equation 6.9.

$$\begin{array}{ll} \textit{If } \hat{y}_t \in \textit{Predicted value class } i \textit{ then} & \\ \quad s_t = \ln(0) & \textit{if } u_t < p_i \\ \quad s_t = v_t & \textit{if } \hat{y}_t = 0,\ u_t > p_i \\ \textit{otherwise} & \\ \quad s_t = 0.8 + 0.408\ln(\hat{y}_t) + e_t & \end{array} \qquad \text{Eq. 6.9}$$

Months with zero recorded or simulated runoff have no effect on the autocorrelation structure of the recorded or simulated data.

6.3.4 Summary

It has been recommended that the calibration be performed with respect to the means and variances of logged runoff values rather than unlogged runoff values. It has been shown that plots of e_t against $\hat{y}_t$ can give an indication of poor seasonal distribution and that the Durbin-Watson statistic can be used to identify miscalibrated lag parameters. As the final measure of calibration efficiency it is proposed that the R-square value explained in Appendix K3 be used. An improved calibration scheme based on these recommendations and summarised in Table 6.3, has been proposed.

When an observed or predicted value is zero and can therefore not be logged, this value should be regarded as missing for the sake of model calibration. However, in the case of error analysis for Monte Carlo simulations, such values may be too numerous to ignore and must therefore be given special treatment.

6.4 Phosphorus Export Models

Phosphorus export to rivers from non-point sources is influenced by runoff. If phosphorus export is to be simulated it is necessary for this relationship to be modelled.

However, whereas runoff data is continuously measured, phosphorus concentrations are collected by means of fixed interval sampling. Various methods (Walker, 1987) have been proposed for estimating average phosphorus loads from such data. Grobler and Rossouw (1988) have applied some of these methods in the case of South African data. They found that a flow stratified weighted regression gives the most accurate estimates for phosphorus load.

6.4.1 Introduction

The REM model for phosphorus export has the form :

$$Y_t = aX_t^{\,b} \qquad \text{Eq. 6.10}$$

where Y_t denotes the period t phosphorus load (mass time^{-1}) derived from non-point sources and X_t (m^3 time^{-1}) denotes the corresponding level of runoff. This model has been evaluated using American data for the Tindall and Maumee rivers in the United states of America and for six flow gauging stations situated in the summer rainfall region of South Africa. Model Equation 6.10 is usually fitted by simple least squares regression after taking log transformations as indicated below :

$$\ln Y = \ln a + b\ln X \qquad \text{Eq. 6.11}$$

Several questions regarding the suitability of this model and its fitting procedure have been raised. In this section these concerns will be addressed.

Firstly there is concern regarding the appropriateness of the form for model Equation 6.10 and hence Equation 6.11. Secondly there is a fear that the linearity of the Equation 6.11 relationship is fictitiously created as a result of the definition of phosphorus export. The phosphorous export values are an aggregation of discharge and concentration values. Thus it could be argued that a plot of phosphorous export against runoff is actually a plot of slightly distorted discharge against discharge. This would of necessity create a linear relationship between phosphorous export and runoff, even before log transformations are applied.

Thirdly there is concern regarding the degree of bias in the predictions of phosphorus export obtained from Equation 6.11, and finally there is concern regarding the effect of serial correlation which has been observed in the errors obtained when Equations 6.10 and 6.11 are fitted to data. Each of these areas of concern is addressed below.

6.4.2 Model Evaluation

6.4.2.1 *Model evaluation for two American rivers*

The monthly data used was collected for the Tindall and Maumee rivers in the United States for eight and five consecutive years respectively. This data was obtained by averaging six-hourly phosphorus concentrations measurements. The high sampling frequency on which this data was based means that the data used to test the various models was exceptionally accurate.

LOWESS smoothing is a smoothing method which can be used to expose the true form of the relationship between two variables. This techniques is described in Appendix H and Appendix L5. This method has been used to produce Figures 6.3 and 6.4. These figures suggest that a weak quadratic relationship may exist between logged phosphorus export and logged runoff for the Maumee river only. However, when this was tested by fitting the equation :

$$\ln Y = \ln a + b_1 \ln X + b_2 (\ln X)^2 \qquad \text{Eq. 6.12}$$

it was found that b_2 was not significantly different from zero. This means that for these two American rivers the simple linear regression Equation 6.11 gives an adequate representation of the phosphorus-runoff relationship.

As mentioned previously, phosphorus export is measured by using a sum of discharge-concentration products. Therefore as a broad simplification phosphorus export may be written as a product of average concentration and average runoff. Thus

$$\begin{aligned} Y &= CX = aX^b \\ \therefore\ C &= aX^{b-1} \end{aligned} \qquad \text{Eq. 6.13}$$

where C is average phosphorus concentration and X is average runoff. If b is not significantly different to unity then runoff does not influence phosphorus concentration. This means that model Equation 6.10 is trivial if b is not significantly different from unity. Before using these models to predict phosphorus export it is therefore essential to prove statistically that b is not equal to unity, hence proving a non-trivial relationship between phosphorus and runoff. Table 6.7 suggests that, for both the Tindall and Maumee rivers, the coefficient b was found to be nonsignificantly different from unity when non-linear regression was used to fit the model in Equation 6.10. However, when model Equation 6.11 was fitted, using simple linear regression, the opposite was found. This suggests that model Equation 6.11 is the preferable model for fitting the relationship between phosphorus load and runoff.

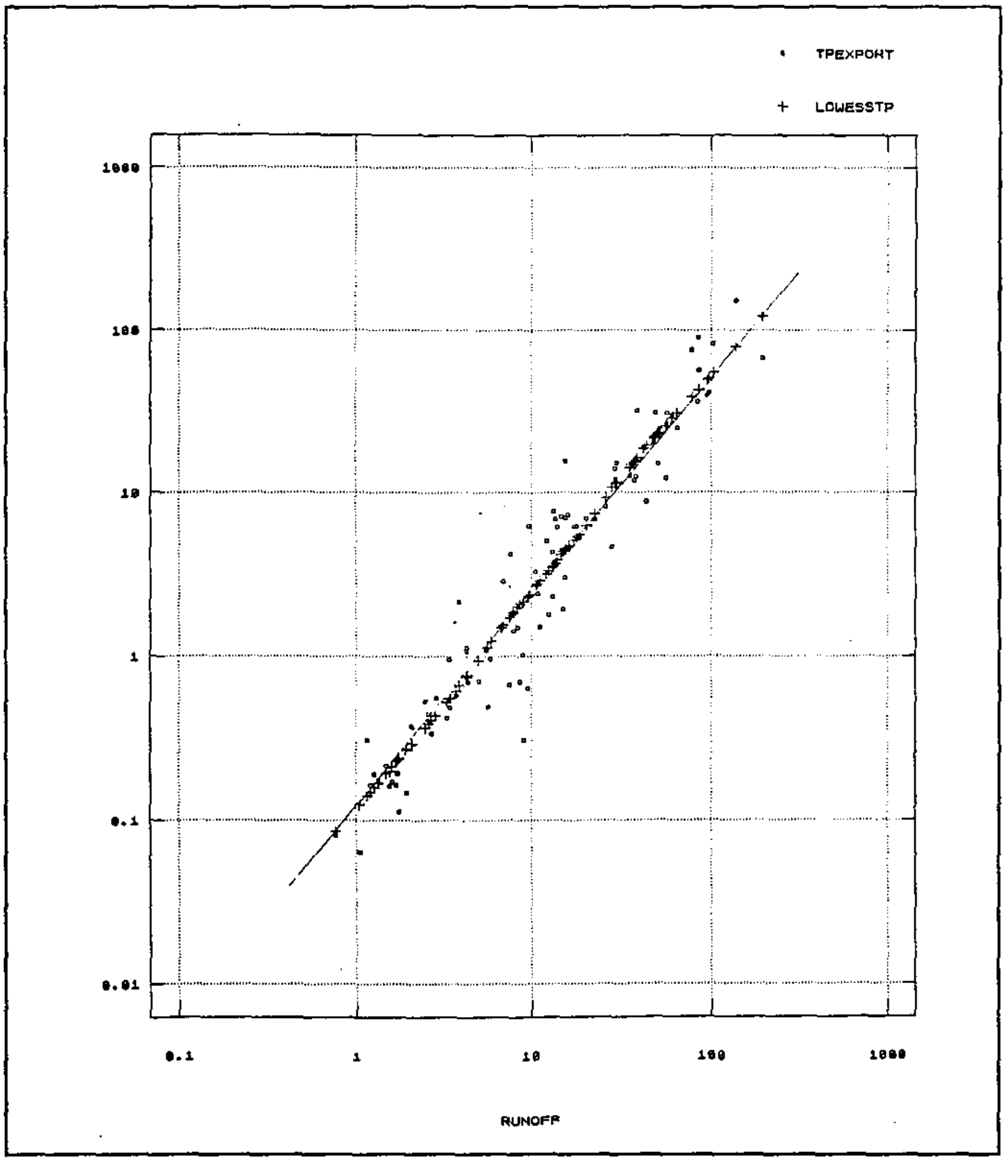

Figure 6.3 LOWESS smoothing total export : Tindall River

As indicated by Table 6.7 there is bias associated with the estimates for phosphorus export obtained when Equation 6.10 is fitted by non-linear regression and when Equation 6.11 is fitted using simple linear regression. The mean Y-value is over-estimated when Equation 6.10 is fitted and under-estimated when Equation 6.11 is fitted. From this point of view there is also no advantage in using model Equation 6.10 rather than model Equation 6.11 to describe the phosphorus-runoff relationship.

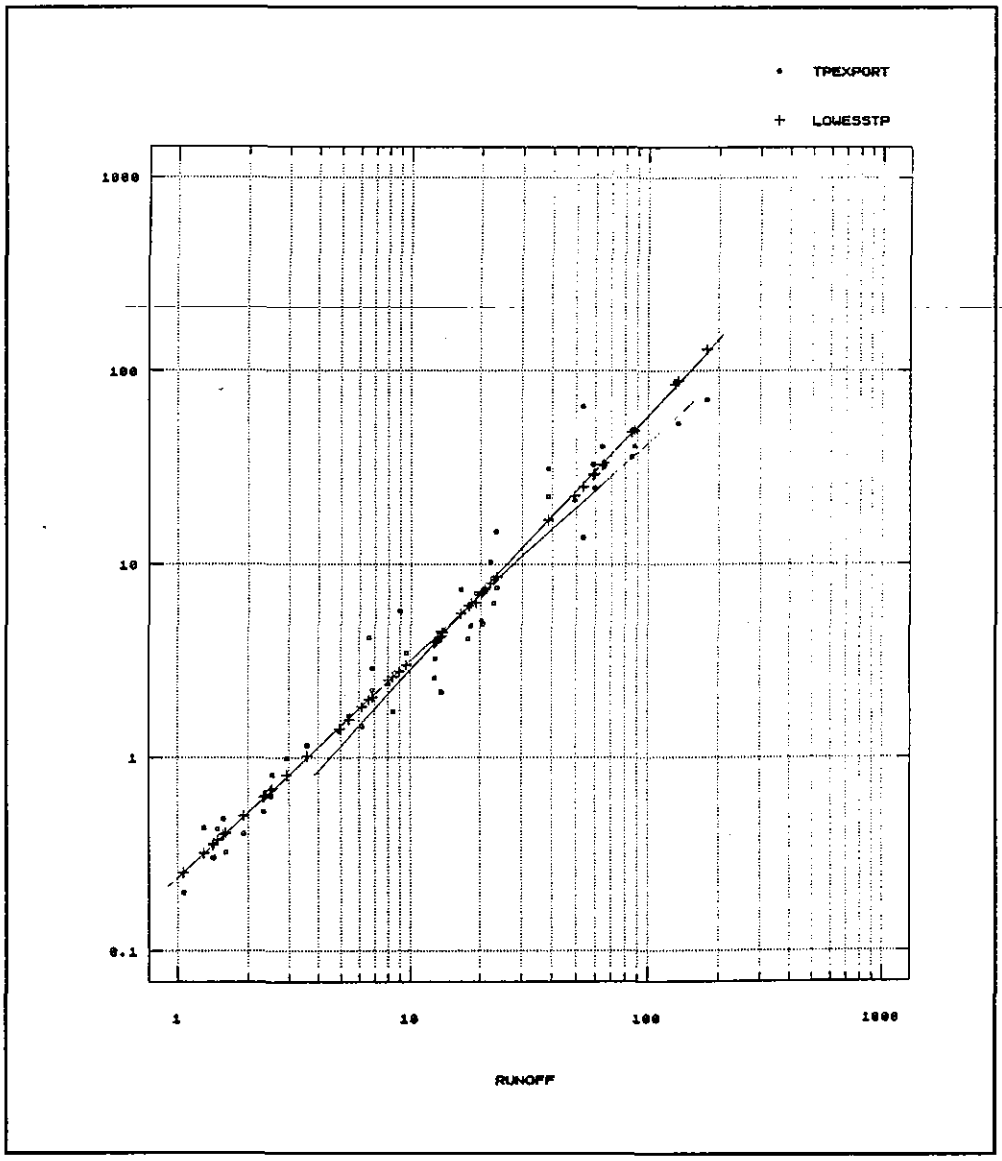

Figure 6.4 LOWESS smoothing total export : Maumee River

In Table 6.7 the last column gives a Durbin-Watson statistic for the residuals. This statistic can be used to determine whether the residuals (errors) are serially correlated. If residuals are serially correlated it means that the model is not complete. In addition it means that standard errors are under-estimated and the validity of all tests performed are dubious.

The Durbin-Watson statistic values, obtained when model Equation 6.11 is fitted, lie below their corresponding d_l values obtained from Appendix I. It can therefore be concluded that the residuals obtained from Equation 6.11 are serially correlated. This means that serial correlation must be incorporated into Equation 6.11.

Table 6.7 Bias estimation of phosphorus load

	Model	b (Std.Error)	Bias (%mean)	Durbin Watson
Tindall	4.4.1.1	1.09 (0.08)	7.8%	2.08 (n=92)
Tindall	4.4.1.2	1.37 (0.04)	-7.8%	1.45 (n=92)
Maumee	4.4.1.1	0.96 (0.070)	5.8%	1.67 (n=60)
Maumee	4.4.1.2	1.17 (0.035)	-7.0%	1.53 (n=60)

6.4.2.2 *Model evaluation for six South African rivers*

Next model Equation 6.11 was evaluated for six South African gauging stations. It was found that the mean level of the errors was not always independent of runoff. Model Equation 6.11 tended to under-estimate phosphorus export at both very low and very high runoff levels. This was confirmed using LOWESS smoothing (refer Appendix H and L5). This means that model Equation 6.11 is not sufficiently flexible to model the realities of the phosphorus export system for South African catchments in the summer rainfall region. The model

$$\ln Y_t = b_0 + b_1 \ln X_t + b_2 (\ln X_t)^2 \qquad \text{Eq. 6.14}$$

would be more appropriate. This model has been fitted in Table 6.8.

The values for the Durbin-Watson statistic given in Table 6.8 suggest that model Equation 6.14 is not sufficiently flexible to explain the lagged behaviour of phosphorus export systems in South African catchments. The effect of runoff is delayed in the sense that the current month's phosphorus export is affected by runoff in both the current and the previous month. In addition Table 6.8 indicates that bias is still a problem.

6.4.3 Model Development

6.4.3.1 *Elimination of bias*

When the errors obtained from model Equation 6.11 or model Equation 6.14 are distributed $N(\mu,\sigma^2)$, bias can be removed by multiplying each prediction by

$$\exp(\mu + \frac{1}{2}\sigma^2) \qquad \text{Eq. 6.15}$$

However, in practise μ and σ^2 are unknown and must be estimated by the error sample mean and variance.

Table 6.8 Performance of model Equation 6.14 for South African data

Gauge	Bias(%)	Durbin-Watson	b_1 Std.Error	b_2 Std.Error
A2H012	-2.5%	1.365 n=92	1.094 (0.009)	0.028 (0.004)
C1H007	-5.5%	0.890 n=102	1.394 (0.018)	0.110 (0.008)
C4H004	7.9%	1.252 n=89	1.646 (0.040)	0.084 (0.016)
U2H013	-5.3%	1.330 n=105	0.761 (0.065)	0.159 (0.014)
U2H012	2.0%	1.328 n=72	1.150 (0.025)	0.031 (0.006)
U2H006	1.9%	1.762 n=72	1.052 (0.008)	0.049 (0.003)

As indicated in Appendix K3.2 and L3, when these estimates are used in Equation 6.15 it is found that the predicted mean and the observed mean can be markedly different, indicating that the bias has not been successfully removed. A more satisfactory method of removing bias is to multiply all prediction for phosphorus load ($\hat{y}_t$) by the factor

$$\exp(k\mu + \frac{1}{2}k^2\sigma^2) \qquad \text{Eq. 6.16}$$

using the same estimators for μ and σ^2. The value of k is chosen in order to force the mean of the predicted Y-values ($\hat{y}_t$) to be equal to the observed sample mean for y_t.

Therefore :

$$\begin{aligned}\bar{y} &= \bar{\hat{y}} \exp(ku + \frac{1}{2}k^2\sigma^2)\\ \therefore k\mu &+ \frac{1}{2}k^2\sigma^2 - \ln(\frac{\bar{y}}{\bar{\hat{y}}}) = 0\\ \therefore k &= \frac{-\mu + \sqrt{\mu^2 + 2\sigma^2\ln(\frac{\bar{y}}{\bar{\hat{y}}}}}{\sigma^2}\end{aligned} \qquad \text{Eq. 6.17}$$

6.4.3.2 *Removal of serial correlation in errors*

When errors are serially correlated we require a procedure for identifying and fitting a model which incorporates a lagged relationship. This procedure is described in Appendix J using the Tindall total phosphorus data for purposes of illustration. This procedure is referred to as transfer model fitting in the statistical literature (Box and Jenkins, 1970). The appropriate transfer model for the Tindall data is described by the equation :

$$\ln Y_t = c\ln Y_{t-1} + b(\ln X_t - c\ln X_{t-1}) \qquad \text{Eq. 6.18}$$

The most appropriate transfer model for the South African catchments is described by the equation :

$$\begin{aligned}\ln y_t - c\ln y_{t-1} &= b_1(\ln X_t - c\ln X_{t-1}) \\ &+ b_2((\ln X_t)^2 - c(\ln X_{t-1})^2)\end{aligned} \qquad \text{Eq. 6.19}$$

The errors from this model have been found to be approximately normally distributed. These error distributions are easily applied to obtain Monte Carlo simulations of the phosphorus-runoff relationship.

6.4.4 Summary

Answers to questions concerning the relationship between phosphorus export(Y) and runoff(X) have been obtained using data for two rivers in the United States of America and six South African rivers.

Firstly, it has been found that the relationship between phosphorus and runoff can be described by the equation :

$$\ln Y_t = b_0 + b_1 \ln X_t \qquad \text{Eq. 6.20}$$

in the case of the American rivers but not in the case of all six South African rivers. A quadratic relationship given as Equation 6.14 is more appropriate for South African rivers.

Secondly it has been found that the estimates of phosphorus export (Y) obtained from these equations by anti-logging are biased by up to 7.9% of the mean phosphorus value. However, estimated bias can be eliminated by multiplying phosphorus predictions by the factor given as Equation 6.16, where μ and σ^2 were estimated from the residuals obtained from these equations. The optimum value for k appears to differ for each time series.

Finally it has been found that the problem of serially correlated errors can be solved by using transfer modelling.

6.5 Phosphorus Budget Models

6.5.1 Introduction

The REM model assumes that the mass of phosphorus in a reservoir at the end of month t, P_t (mass), can be described by the equation :

$$P_t = P_{t-1} + PIN_t - POUT_t - s_t\left(\frac{P_t + P_{t-1}}{2}\right) \qquad \text{Eq. 6.21}$$

where PIN_t(mass) denotes the phosphorus load entering the reservoir in month t, $POUT_t$ (mass) denotes the phosphorus load leaving the reservoir through the outflow in month t, and s_t denotes the sedimentation rate for month t. If it is assumed that the reservoir is thoroughly mixed, $POUT_t$ can be estimated as the product of average in-lake phosphorus concentration and outflow volume. Sas (1989) indicates that this is a reasonable assumption for shallow reservoirs, into which category most of South Africa's reservoirs fall. Under these conditions model Equation 6.21 simplifies to the following form :

$$P_t = \frac{P_{t-1}\left(1 - \frac{s_t}{2} - \frac{WOUT_t}{2W_{t-1}}\right) + PIN_t}{1 + \frac{s_t}{2} + \frac{WOUT_t}{2W_t}} \qquad \text{Eq. 6.22}$$

where W_t (10^6m^3) denotes the volume of water in the reservoir at the end of month t and $WOUT_t$ (10^6m^3) denotes the outflow for month t. Either a constant sedimentation rate (s_t=s) or a third-order concentration dependent sedimentation reaction ($s_t=k[P]_t^2$) are assumed throughout the reservoir. Both these models have been tested for the Hartbeespoort and Witbank dams using monthly data for the periods October 1980 to January 1989 and October 1986 to December 1989 respectively.

6.5.2 Model Evaluation

As indicated in Table 6.9 these two dams differ markedly in their physical and chemical characteristics.

Using nonlinear regression the sedimentation parameters, s for a constant sedimentation rate and k for a third order sedimentation reaction, were estimated and the performance of the "s" and "k" models was assessed in Table 6.10. Clearly the constant sedimentation rate s-models fitted the data for these reservoirs better than the third order reaction k-models.

Table 6.9 Characteristics for Hartbeespoort and Witbank Dams

	Hartbeespoort: Mean depth=9.6m		Witbank: Mean depth=10.6m	
Average Mthly. Values	Mean	Standard Dev.	Mean	Standard Dev.
Volume(10^6m^3)	118.9	50.6	82.9	19.1
P Conc(mg/l)	.440	.165	0.041	0.030
Inflow(10^6m^3)	12.78	8.30	9.26	16.13
Outflow(10^6m^3)	12.18	6.58	9.57	18.92

Table 6.10 Conventional REM phosphorus budget model performance

Model	Hartbeespoort Dam		Witbank Dam	
	s=0.27	$k=8.8\ 10^{-7}$	s=0.507	$k=3.7\ 10^{-5}$
Bias(%)	1.7%	8.9%	0.2%	-31.3%
Durb.Wats.	1.45	0.94 n=100	2.19	1.90 n=35
R^2(%)	64%	40%	74.4%	57.1%
Error Std.Dev(%)	16.6%	18.2%	42.9%	55.5%

6.5.3 Model Development

Grobler (1985a) explains that South African reservoirs often receive inflows rich in particulate phosphate which is lost through sedimentation at a faster rate than dissolved phosphorus. Butty, Walmsley and Alexander (1980) described the shape of the Witbank Dam as "narrow and sinuous, shallow in the upper reaches and increasing in depth up to the dam wall", which may account for the high sedimentation losses in the upper reaches of the reservoir. It seems therefore that a higher sedimentation rate for the inflow is called for as a result of the form of the incoming phosphorus and the shallowness of South African reservoirs in their upper reaches. This approach was also adopted by Prairie (1988) in a cross-sectional study for 122 Northern Hemisphere lakes.

This suggests a phosphorus budget model of the form :

$$P_t = (1 - s_1)P_{t-1} + (1 - s_2)PIN_t - POUT_t$$

$$ie.\ P_t = \frac{(1 - s_1 - \frac{WOUT_t}{2W_{t-1}})P_{t-1} + (1 - s_2)PIN_t}{1 + \frac{WOUT_t}{2W_t}} \qquad \text{Eq. 6.23}$$

where s_1 is the in-lake sedimentation rate and s_2 is the sedimentation rate for the inflow only. Calibration results are shown in Table 6.11. An in-lake sedimentation rate of 4.3% per month and 27.5% per month are suggested for Hartbeespoort Dam and Witbank Dam respectively. The sedimentation rate predicted for the inflow is 63.5% per month for Hartbeespoort Dam and 33.4% per month for Witbank Dam. The R^2 and error standard deviations indicate that model Equation 6.23 describes the data better than the constant sedimentation rate s-model Equation 6.21.

Table 6.11 Performance improved RSEM phosphorus budget models

	Hartbeespoort Dam	Witbank Dam
s_1 s_2	.043 .635	0.275 0.334
Durbin-Watson	1.81 (n=100)	2.61 (n=35)
R^2(%)	86%	87%
Error Std.Dev.(%)	15.7%	39.2%

6.5.4 Summary

The proposed phosphorus budget model differs from the REM model in only one respect. It allows for higher sedimentation rates in the current month's inflow and lower sedimentation rates for water which has been resident in the reservoir for longer than a month. This is an important modification on account of the large fluctuation in inflow volumes for South African reservoirs. For instance the inflow in a single month can reach a level close to the total dam volume for Witbank Dam in summer, while winter inflows have been known to fall to negligible levels.

However, the proposed phosphorus budget model has only been tested for two impoundments, the Witbank and Hartbeespoort Dams. The new model should be tested for several more South African impoundments before it can be accepted. Constant sedimentation rates have been assumed for s_1 and s_2. Sedimentation rates which are a function of phosphorus concentration may produce even better results.

6.6 Chlorophyll Concentration Model

6.6.1 Introduction

The OECD Eutrophication Study involved the examination of phosphorus loads and response characteristics of about 200 water bodies in 22 countries over a five year period. Jones and Lee (1982) developed a cross-sectional model to predict chlorophyll levels from this data. They found that the mean summer chlorophyll concentration (μg/l) could be predicted from mean summer phosphorus concentrations (μg/l) by means of the equation :

$$[Chl] = 0.45\,[P]^{0.79} \qquad \text{Eq. 6.24}$$

This equation was used by Grobler and Silberbauer (1984). They found that for 18 out of 19 South African impoundments this equation could be used to predict mean annual chlorophyll concentration from mean annual phosphate concentration. Only chlorophyll levels for Rietvlei Dam were poorly predicted by this equation, because algal growth was limited by nitrogen rather than phosphorus, it was thought.

However, there is some dissatisfaction with the idea of using phosphorus as the sole predictor of chlorophyll levels. Walmsley and Butty (1979) have confirmed that the trophic status of most South African impoundments is dependent on water turbidity as well as phosphorus loading. For impoundments when the mean annual Secchi disc transparency is greater than 0.4m, they suggest the following equation for the prediction of trophic status, [CHL] :

$$[CHL] = 1.62\,[PO] + 3.8 \qquad \text{Eq. 6.25}$$

where PO is the orthophosphate(PO_4) loading rate measured in $g/m^2/y$. For impoundments where the mean annual Secchi depth transparency is less than 0.4m they suggest the following equation :

$$[CHL] = 3.6\,[PO]\,(Se) - 0.71\left([PO] - \frac{1}{Se}\right) + 5.80 \qquad \text{Eq. 6.26}$$

where the Secchi depth (Se) is measured in metres.

6.6.2 Model Evaluation

6.6.2.1 *Model evaluation using new cross-sectional data*

The cross-sectional models mentioned above have been tested on fresh data. This data was extracted from two reports, namely Walmsley and Butty (1980) and Van Ginkel and Theron (1987). The first of these reports contains data for the period 1975-1978 for 17 impoundments. The second of these reports contains data for 25 impoundments collected during the period 1985-1986.

In Figure 6.5 the Jones and Lee (1982) OECD chlorophyll model Equation 6.24 was tested. For the 41 impoundments tested nine chlorophyll concentrations lay below the lower 95% prediction limit. This suggests that the Jones and Lee (1982) chlorophyll model is not suited to South African data.

Next the models of Walmsley and Butty (1979) were tested. Their clear water (secchi depth$>$0.4m) model was tested by fitting the model :

$$[CHL] = b_1\,[PO] + b_0 \qquad \text{Eq. 6.27}$$

to the data for clear impoundments. Their turbid water (secchi depth $<$0.4m) model was tested by fitting the model :

$$[CHL] = b_1\,[PO]\,(Se) - b_2)\,[PO] - \frac{1}{Se}) + b_0 \qquad \text{Eq. 6.28}$$

to the data for turbid impoundments.

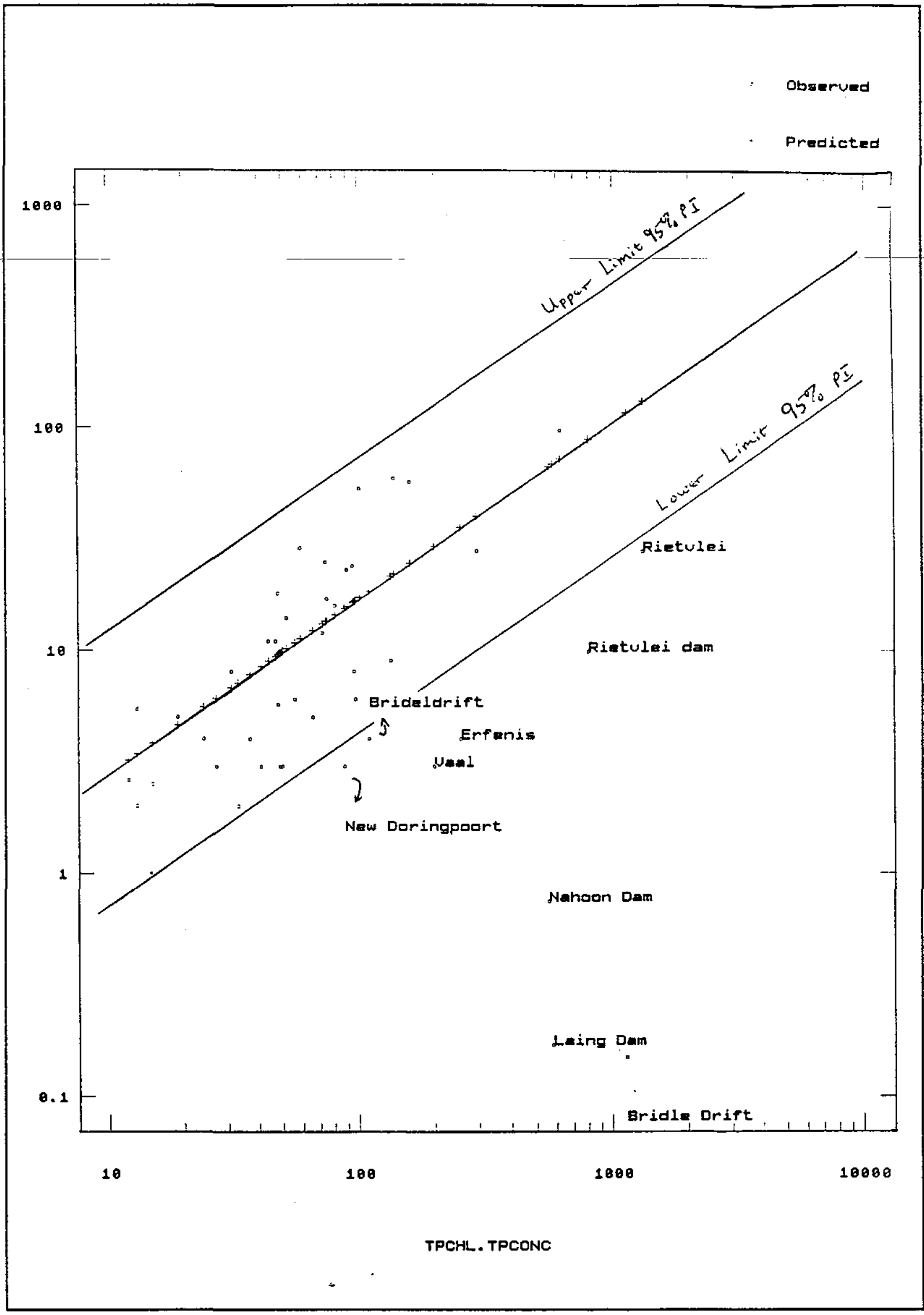

Figure 6.5 OECD model (Jones and Lee, 1982) for chlorophyll concentrations

For the clear water model Equation 6.27 the slope coefficient, b_1, was estimated to be equal to 1.02(0.36) and the intercept coefficient, b_0, to be 7.13(3.64). This equation explained only 25% of the variability in chlorophyll for the data base. The 90% confidence interval for the slope coefficient, b_1, did not include the Walmsley and Butty estimate for b_1, namely 1.62. This suggests that this Walmsley and Butty model is not robust.

For the turbid water model Equation 6.28 it was found that none of the coefficients were significantly different from zero and the R^2 for the fitted model was zero. This means that this Walmsley and Butty model is also not robust since it does not describe the chlorophyll-phosphorus relationship for the data.

6.6.2.2 *Model evaluation using time series data*

The Jones and Lee (1982) OECD model has been tested using monthly data for both summer and winter for the Hartbeespoort and Witbank Dams. The Hartbeespoort Dam data represents month end concentrations for the period July 1983 to January 1990. The Witbank data represents average monthly concentrations for most of the period July 1986 to December 1989.

As indicated in Figures 6.6 and 6.7 it seems that the uncalibrated Jones and Lee (1982) model Equation 6.24 is not suitable for either of these dams.

In an attempt to obtain a better fit, the Jones and Lee (1982) model was recalibrated for the Hartbeespoort and Witbank data. To simplify the analysis the model was transformed by logging, resulting in the following expression for chlorophyll concentration in terms of total phosphorus concentration, [TP].

$$\ln[Chl] = \ln a + b \ln[TP] \qquad \text{Eq. 6.29}$$

Table 6.12 indicates that the b-coefficients for both reservoirs are barely significantly different from zero, indicating a very weak relationship between phosphorus and chlorophyll concentrations.

Table 6.12 The conventional REM chlorophyll model

Reservoir	Hartbeespoort	Witbank
Durbin-Watson	1.38	2.02
R^2(%)	2%	7%
Error Std.Dev(%)	28.8%	43.0%
a	7.786	13.037
b(std error)	0.23(0.15)	0.34(0.19)

It seems therefore, that even in its recalibrated form, the Jones and Lee (1982) model should not be used to predict chlorophyll concentrations for the Witbank and Hartbeespoort Dams. However, their model is a cross-sectional model and it is perhaps doubtful whether this model was intended for dynamic time series simulations at single reservoirs, particularly since theirs is a model for mean summer conditions.

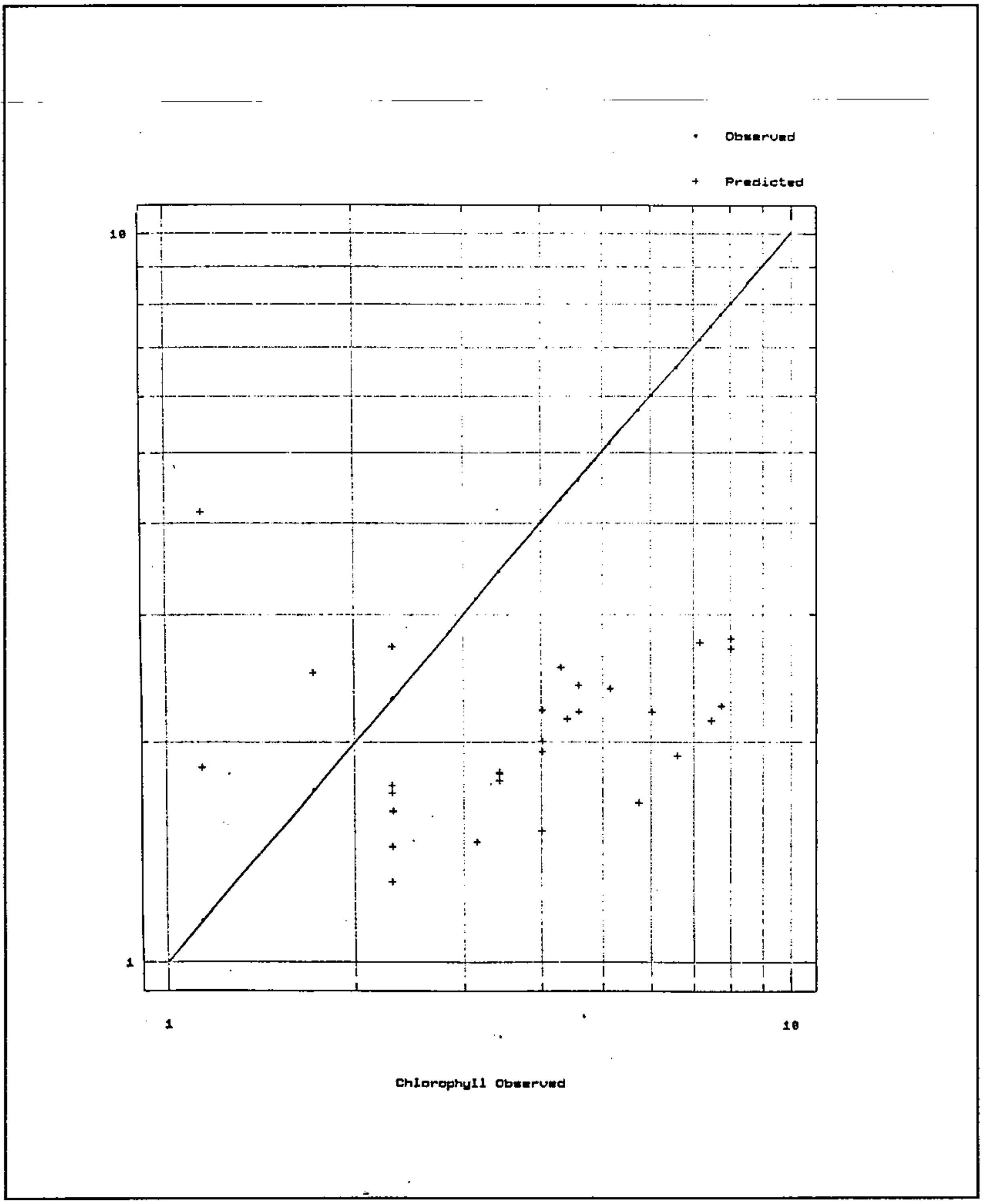

Figure 6.6 OECD chlorophyll model (Jones and Lee, 1982) for Witbank Dam

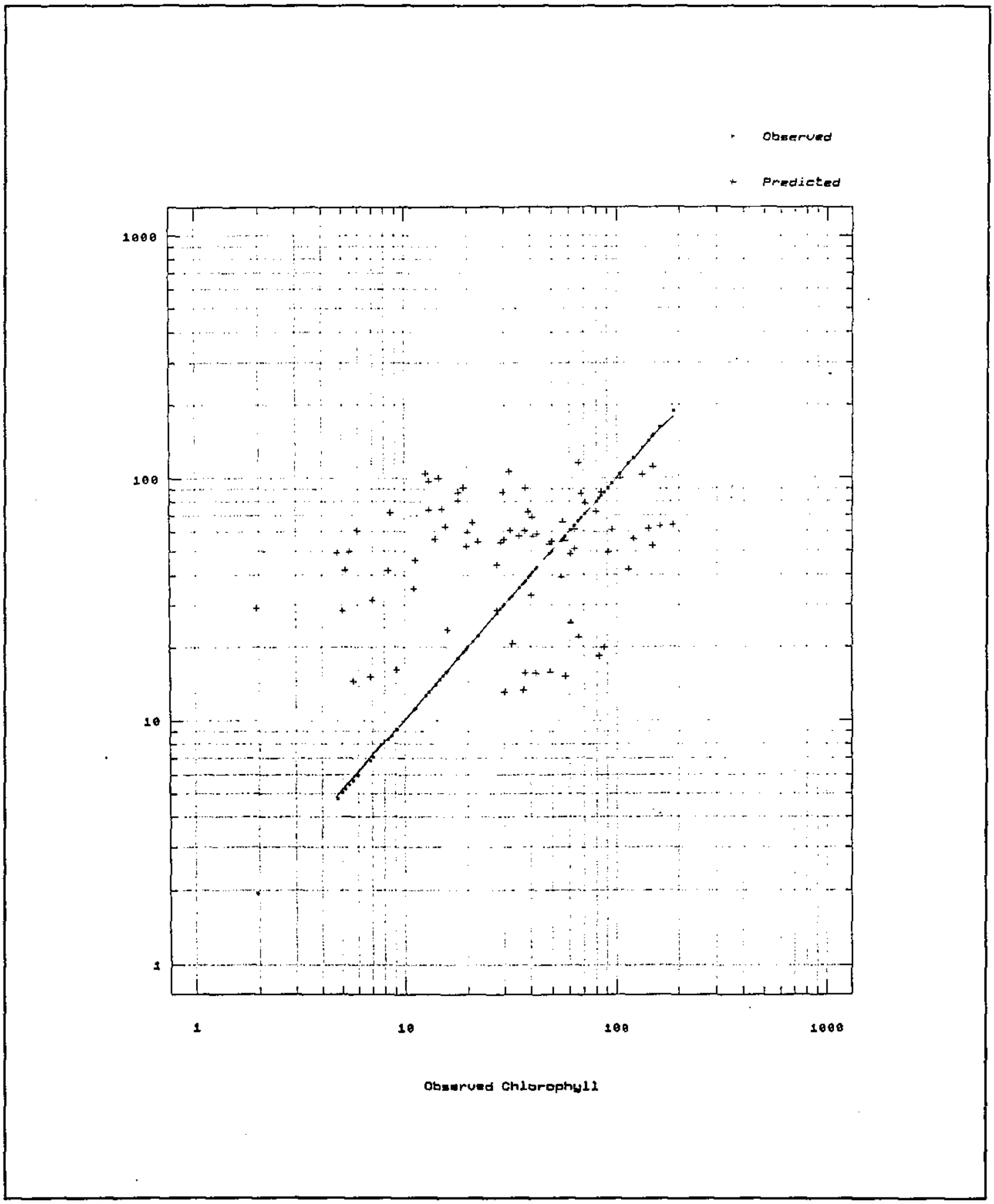

Figure 6.7 OECD chlorophyll model (Jones and Lee, 1982) for Hartbeespoort Dam

6.6.3 Model Development

Grobler and Silberbauer (1984) suggested that nitrogen levels affected the performance of the Jones and Lee (1982) total phosphorus model, and Walmsley and Butty (1979) found that orthophosphate levels and Secchi depth were the important predictor variables for their data.

The goal of this research was to test these suggestions where possible and to determine whether other nutrients should also be considered.

6.6.3.1 *Cross-sectional model development*

A new cross-sectional model has been developed from cross-sectional data for 40 South African reservoirs. Using total phosphorus, ammonia, Kjeldahl nitrogen and orthophosphate as initial predictors of chlorophyll, the significance of other variables, including other nutrients and turbidity measures was tested.

The Bon Accord Dam was excluded in this analysis on account of its extreme levels of pollution. The chlorophyll concentration for this dam was 682 μg/l. The next most polluted impoundments, Bloemhof and Rietvlei, had chlorophyll levels of only 28 μg/l.

Analyses were initially performed separately for clear impoundments (Secchi depth > 1m) and turbid impoundments (Secchi depth < 1m). In all cases the logged chlorophyll concentrations were regressed on log-transformed Kjeldahl nitrogen, ammonia, total phosphorus, orthophosphate and Secchi depth.

For the clear water dams (Secchi depth> 1m) it was found that only Kjeldahl nitrogen and total phosphorus made a significant contribution to the regression. It was found that 70% of the variability in logged chlorophyll concentrations could be explained by the equation :

$$\ln[CHL] = 3.05 + 0.815 \ln[KN] + 0.25 \ln[TP] \qquad \text{Eq. 6.30}$$

for the 19 clear water impoundments.

For the 21 more turbid impoundments (Secchi depth <1m) it was found that 77% of the variability in logged chlorophyll could be explained by the equation :

$$\ln[CHL] = 2.01 \ln[KN] - 1.82 \ln[TP] + 0.58 \ln[PO] \qquad \text{Eq. 6.31}$$

Attempts to improve the fit for these two equations by considering other nutrients, (such as sodium, potassium, calcium, magnesium, sulphates, chloride, reactive silicate, conductivity, alkalinity, dissolved Kjeldahl nitrogen and phosphorus, nitrates, nitrites, iron, manganese, temperature, dissolved oxygen, turbidity, pH, suspended solids, depth, retention time and hydraulic load), were unsuccessful.

6.6.3.2 *Dynamic (time series) model development*

The characteristics of the two reservoirs were considered in an attempt to understand their potential for algal growth. Table 6.13 describes the two reservoirs in terms of the available water quality data. As indicated in Table 6.13 the nutrient concentrations for Witbank Dam were lower than those for Hartbeespoort Dam for all nutrients except nitrates. In addition there was a marked difference in the total-nitrogen:total-phosphorus (TN:TP) ratios for the two reservoirs. The TN:TP ratio was much higher for the Witbank Dam than for the Hartbeespoort Dam. Ryding and Rast (1989) note that phosphorus concentrations limit algal growth for TN:TP ratios in excess of 7. At Witbank Dam the TN:TP ratio rarely falls below

7 while at Hartbeespoort Dam this ratio does not generally exceed 7 (National Institute for Water Research Report, 1985).

Table 6.13 Nutrient concentration of Hartbeespoort and Witbank Dams

Reservoir	Hartbeespoort		Witbank	
	Mean	Std Dev	Mean	Std Dev
Total Phosphorus (mg/l)	0.460	0.271	0.035	0.025
Kjeldahl Nitrogen (mg/l)	0.998	0.403	0.611	0.184
Ratio TN:TP	6.08	4.45	29.89	14.95
Ammonia (mg/l)	0.217	0.170	0.089	0.089
Nitrites (mg/l)	2.231	1.145	na	na
Nitrates (mg/l)	0.179	0.109	0.201	0.118
Orthophosphate (mg/l)	0.291	0.198	0.007	0.008
Total Dissolved salts (mg/l)	na	na	271	23
Secchi Depth (m)	1.32	0.72	1.46	0.46
Chlorophyll (μg/l)	47.2	41.8	4.61	3.38

The Jones and Lee (1982) OECD model is designed for reservoirs which are deficient only in phosphorus during the growing season. An attempt has been made to improve on their chlorophyll model by allowing additional nutrients to be growth limiting. All the nutrients for which data were available for the two dams were considered. Log transformations were applied to both chlorophyll and nutrient concentrations before performing a stepwise linear regression. As explained by Sas (1989), if no log transformation is applied, variability increases at the upper end of the chlorophyll scale. This can cause gross distortion in the regression coefficients.

For Hartbeespoort Dam it was found that by incorporating Kjeldahl nitrogen[KN], nitrates [NO3], nitrites [NO2], orthophosphate [PO4] and ammonia [NH4] in the regression as indicated in Equation 6.32 below, the R^2 was increased from 2% to 49%.

$$\ln[Chl] = 1.21\ln[TP] + 0.58\ln[KN] + 0.51\ln[NO3] - 0.36\ln[NO2] - 0.76\ln[PO4] - 0.67\ln[NH4] \quad \text{Eq. 6.32}$$

The P-value associated with the [TP] coefficient in this equation was 0.0021. This indicates a very strong relationship between phosphorus and chlorophyll concentrations, provided that the effect of other limiting nutrients is taken into consideration.

For Witbank Dam it was found that by incorporating total dissolved salts [TDS] (as a measure of water clarity), nitrates [NO3] and Kjeldahl nitrogen [KN] in the model as indicated in Equation 6.33, the R^2 was increased from 7% to 50%. Again the P-value associated with the [TP] coefficient was very low (0.0001), indicating a strong phosphorus:chlorophyll relationship.

$$\ln[Chl] = 0.70\ln[TP] + 5.10\ln[TDS] + 0.45\ln[NO3] - 24.23 - 0.65\ln[KN] \quad \text{Eq. 6.33}$$

Neither Equation 6.32 nor 6.33 should be regarded as final models. The R^2 value for Hartbeespoort Dam could almost certainly have been improved had data for dissolved salts been available. The intention here was merely to illustrate the necessity for considering all nutrients and turbidity/water clarity when trying to model chlorophyll concentrations.

6.6.4 Summary

There appear to be two problems with using the Jones and Lee chlorophyll model Equation 6.24 for REM modelling. Firstly this model is a cross-sectional model defined only for mean summer conditions. As such it is not appropriate for use in a dynamic context at a single impoundment. In other words it is not really appropriate in the context of REM modelling. Secondly this model assumes that phosphorus is always the limiting nutrient. Our analyses suggest that for South African impoundments, for both cross-sectional models and dynamic time series models for specific impoundments, phosphorus is not the only limiting nutrient. In addition it is suspected that water transparency must also enter into any equation used to predict phosphorus concentrations.

As discussed in the next section, the chlorophyll model is the weakest link in the REM modelling procedure. Four regression models have been developed for chlorophyll concentrations : a good cross-sectional model for clear water impoundments (Equation 6.30), a good cross-sectional model for more turbid impoundments (Equation 6.31), and fair dynamic time series models for the Hartbeespoort and Witbank Dams (Equations 6.32 and 6.33). More data is required to improve these models further. The importance of the chlorophyll model in the REM modelling procedure makes it imperative that more modelling research be conducted in this area.

At the moment REM modelling is in terms of phosphorus levels only. The chlorophyll concentration models developed in this study suggest that REM modelling needs to be extended to cover other nutrients in addition to phosphorus. This means that export and budget models will be needed for these nutrients too.

6.7 Uncertainty Analysis

6.7.1 Introduction

The objectives of this uncertainty analysis were twofold. Firstly the sensitivity of the conventional REM model was compared with the sensitivity of the newly developed RSEM model. This was done by comparing the change in simulated chlorophyll concentrations which occurred for the two models when point source phosphorus loads were decreased by 20%. Secondly the standard errors for the mean simulated values obtained from the two approaches was compared.

6.7.2 The Conventional REM and Improved RSEM Models

In previous studies no attempt has been made to quantify the level of uncertainty associated with the Reservoir Eutrophication Model (REM) developed by Grobler (1985a, 1985b, 1986). In this study, an uncertainty analysis has been attempted for the Hartbeespoort Dam using data collected from July 1983 to May 1987. Four types of prediction are usually involved in a REM simulation, namely runoff predictions and phosphorus export predictions for rivers, and phosphorus budget and chlorophyll concentration predictions for reservoirs.

In the past the Pitman (1973) model has been used to produce runoff prediction for rivers. Phosphorus (Y) export predictions for rivers have been obtained from runoff (X) using the equation :

$$Y = aX^{b} \qquad \text{Eq. 6.34}$$

Phosphorus budget predictions for reservoirs have been obtained assuming a constant sedimentation rate s, using phosphorus inflows and outflows, PIN and POUT, and the dynamic phosphorus budget model :

$$P_t = \frac{P_{t-1}(1-\frac{s}{2}) + PIN_t - POUT_t}{1+\frac{s}{2}} \qquad \text{Eq. 6.35}$$

Chlorophyll concentration predictions for reservoirs have been obtained from the phosphorus concentration [P] using the Jones and Lee (1982) OECD equation :

$$[Chl] = a[P]^{b} \qquad \text{Eq. 6.36}$$

In this study statistical analyses have been performed on the errors for these models. In all cases these analyses have suggested model improvements. In the case of the Pitman model, only calibration improvements were suggested. However, in the case of the other three models, fundamental changes in model form are recommended.

In the case of phosphorus export models it is recommended that lags in the runoff(R)-phosphorus(P) relationship should be reflected in the model. In addition it is recommended that the tendency for phosphorus loads to be under-estimated, at both very low and very high runoffs, should be corrected by means of a quadratic term as indicated in Equation 6.37. Y_t can be obtained by anti-logging and correcting for bias.

$$\ln Y_t - c\ln Y_{t-1} = b_1(\ln R_t - c\ln R_{t-1}) + b_2([\ln R_t]^2 - c[\ln R_{t-1}]^2)$$

Eq. 6.37

It is recommended that in the phosphorus budget model (Equation 35), higher sedimentation rates should be allowed for the inflow. The following equation is suggested :

$$P_{t+1} = (1-s_1)P_t + (1-s_2)PIN_t - POUT_t \qquad \text{Eq. 6.38}$$

where s_1 denotes the in-lake sedimentation rate and s_2 denotes the inflow sedimentation rate.

In the case of the chlorophyll concentration model (Equation 6.36) it is recommended that, if possible, all growth-limiting nutrient concentrations, as well as some measure of water clarity, should be incorporated in the model.

In this section the conventional REM and the newly developed RSEM models for Hartbeespoort Dam have been compared using Monte Carlo simulations. The effect of a 20% drop in point source phosphorus has been compared for the two models.

6.7.3 Calibrated Models for Hartbeespoort Dam

The phosphorus export models (Equations 6.34 and 6.37) were fitted for the Magalies river which flows into the Hartbeespoort Dam. The resulting models for ln(phosphorus export) for month t were :

$$\ln \hat{y}_t = -1.63 + 1.0388[\ln R_t] \qquad \text{Eq. 6.39}$$

for the conventional REM model (Equation 6.34) and

$$\begin{aligned}\ln \hat{y}_t = {} & .33\ln \hat{y}_{t-1} + 1.1(\ln R_t - 0.33\ln R_{t-1}) + \\ & 0.028([\ln R_t]^2 - .33[\ln R_{t-1}]^2)\end{aligned} \qquad \text{Eq. 6.40}$$

for the newly developed RSEM model (Equation 6.37), R indicating runoff.

The phosphorus budget models (Equations 6.35 and 6.38) were fitted for the Hartbeespoort Dam giving rise to the following expressions for the phosphorus budget at the end of month t.

$$\hat{P}_t = \frac{P_{t-1}\left(1 - \frac{0.27}{2} - \frac{WOUT_t}{2W_{t-1}}\right) + PIN_t}{1 + \frac{0.27}{2} + \frac{WOUT_t}{2W_t}} \qquad \text{Eq. 6.41}$$

for the conventional REM model (Equation 6.35) and

$$\hat{P}_t = \frac{\left[(1-.043) - \frac{WOUT_t}{2W_{t-1}}\right]P_{t-1} + (1-0.635)PIN_t}{1 + \frac{WOUT_t}{2W_t}} \qquad \text{Eq. 6.42}$$

for the newly developed model (Equation 6.38).

The calibrated conventional and newly developed ln(chlorophyll) models were, respectively,

$$\ln[\hat{Chl}] = 2.05 + 0.234\ln[P] \qquad \text{Eq. 6.43}$$

and

$$\ln[\hat{Chl}] = 1.213\ln[TP] + 0.582\ln[KN] + 0.504\ln[NO3]$$
$$-0.674\ln[NH4] - 0.762\ln[PO4] - 0.359\ln[NO2]$$

Eq. 6.44

Table 6.14 below compares the goodness-of-fit for the conventional and newly developed models in terms of their R^2 values. Where modelling errors were serially correlated a correction was made to ensure that the R^2 values were reliable. Table 6.14 indicates that the newly developed models are always superior to the conventional models. This is particularly apparent in the case of the phosphorus budget and chlorophyll models. However, the R^2 for the newly developed chlorophyll model is still somewhat disappointing. Attention must be paid to developing this model. Although the Pitman model calibration has produced a very low R^2 this of less concern for this reservoir. Non-point source phosphorus comprises less than 10% of the total phosphorus input to the Hartbeespoort Dam, so the effect of the Pitman model errors on the simulated chlorophyll levels is much diluted. However, for dams where non-point source phosphorus represents a larger proportion of the phosphorus in a dam, it is essential that the R^2 values for the Pitman model be improved.

Table 6.14 REM modelling efficiency

REM Model	Model Form	R^2(%)
ln [Runoff] Magalies	Pitman	35
Phosphorus Export Magalies River	Conventional 4.7.3.1	96.6
	New 4.7.3.2	99.1
Phosphorus Budget Hartbeespoort Dam	Conventional 4.7.3.3	64
	New 4.7.3.4	86
ln [Chlorophyll Concentration] Hartbeespoort Dam	Conventional 4.7.3.5	2
	New 4.7.3.6	49

6.7.4 Error Analyses for Hartbeespoort Dam

Analysis of the Pitman model fit for the Magalies catchment indicated that the logged runoff prediction errors, r_t, followed an autoregressive(2) process of the form :

$$r_t - 0.55r_{t-1} - 0.35r_{t-2} = a_t$$

Eq. 6.45

with the a_t independently distributed $N(-0.057,(0.704)^2)$. The predicted runoff values obtained from the Pitman model were used in conjunction with this error model to generate simulated runoffs (10^6m^3) for the period August 1983 to May 1987. The same simulated runoff values were used as input to both the conventional REM and newly developed RSEM models.

Error analyses for the conventional logged phosphorus export model (Equation 6.39), for the Magalies river, yielded serially correlated errors, y_t, which could be described by the autoregressive(1) model :

$$y_t - 0.407 y_{t-1} = a_t \qquad \text{Eq. 6.46}$$

The distribution for the independent a_t was well approximated by a $N(0,(0.105)^2)$ distribution. Error analysis for the newly developed logged phosphorus export model (Equation 6.40), for the Magalies River (A2M13), yielded independent $N(-1.128,(0.070))^2$ errors. These models and their corresponding error distributions were used to simulate phosphorus export for the Magalies river for the period August 1983 to May 1987. All phosphorus load were expressed in tons.

The errors, p_t, for the conventional phosphorus budget model (Equation 6.41) were found to be serially correlated but could be described by the autoregressive (1) model :

$$p_t - 0.35 p_{t-1} = a_t \qquad \text{Eq. 6.47}$$

with the a_t independently distributed $N(-0.628,(8.080)^2)$. The errors for the newly developed phosphorus budget model (Equation 6.42) were independently distributed $N(-0.074,(7.392)^2)$. These models and their error distributions were used to simulate the total phosphorus loads for Hartbeespoort Dam for the above 46 month period. Average simulated phosphorus concentrations were obtained by dividing the total phosphorus load by the volume of water in the dam.

The errors, c_t, for the conventional ln[Chlorophyll] model (Equation 6.43) were also serially correlated but could be described by the autoregressive (1) model :

$$c_t - 0.304 c_{t-1} = a_t \qquad \text{Eq. 6.48}$$

with the a_t independently distributed $N(0.004,(0.9437)^2)$. The errors for the newly developed ln(Chlorophyll) model (Equation 6.44) were independently distributed $N(0.002,(0.624)^2)$. These models, and their associated error distributions, were used to simulate logged chlorophyll concentrations for the period August 1983 to May 1987. Chlorophyll concentrations were expressed in $\mu g/l$.

6.7.5 Monte Carlo Simulation

The conventional and newly developed REM models have been applied to 46 months of Hartbeespoort Dam data in order to simulate monthly chlorophyll levels. In the initial simulation the 1983 point source phosphorus load entering the dam was assumed to be 238 tons, increasing by 5% per annum. In the second simulation this load was reduced by 20% in all months. Less than 10% of the total phosphorus load entering this dam has a non-point source.

Working with water inflows for 1981, the rivers feeding the Hartbeespoort Dam it was found that these inflows could be calculated as 3.3 times the inflow from the Magalies River. Total phosphorus inflows from non-point sources were therefore estimated to be 3.3 times the phosphorus export for the Magalies River. The remaining phosphorus inflow was assumed to be point source in origin.

Observed values were used for [KN], [NO2], [NO3], [NH4] and [PO4] in the RSEM chlorophyll model (Equation 6.44). The simulation involved 100 iterations. The Figure 6.8 flow chart illustrates these simulations, while Figure 6.9 displays the results.

	(1)	Iteration, $k = 1$
	(2)	Initialise
	(3)	$t = 1$
Simulated Magalies Runoff	(4)	$\ln R_t = \ln \hat{R}_t + r_t$
Simulated Magalies P Export	(5)	$\ln Y_t = \ln \hat{y}_t + y_t$
Simulated Non-Point Source P	(6)	$K\ Y_t$ with $K=3.3$
Point Source P	(7)	PSP_t
Phosphorus Inflow	(8)	$K\ Y_t + PSP_t$
Phosphorus Budget	(9)	$P_t = \hat{p}_t + p_t$
ln Chlorophyll	(10)	$\ln C_t = \ln \hat{C}_t + c_t$
	(11)	$t = t + 1$ until $t > 46$
	(12)	$k = k + 1$ until $k > 100$
Mean values ln Chl	(13)	$Ave_k (\ln C_t)$
Mean value ln Chl	(14)	$Ave_t [Ave_k (\ln C_t)]$

Figure 6.8 Simulation flow chart : Hartbeespoort Dam

As indicated in Table 6.15 the mean chlorophyll concentrations simulated by the conventional REM model declined by only 4.6% when the point source phosphorus declined by 20%. In contrast the mean chlorophyll concentrations simulated by the newly developed RSEM model declined by 25.5% for a 20% decline in point source phosphorus.

As suggested by Figure 6.9 the conventional REM model yields relatively little variation in chlorophyll concentrations, despite large variations in phosphorus loads. This is to be expected on account of the very low R^2 of the conventional phosphorus:chlorophyll model. By including the effect of other growth-limiting nutrients, the newly developed phosphorus: chlorophyll model explains the phosphorus:chlorophyll relationship much more accurately. As a result more variability is found in the simulated chlorophyll values, in response to changes in phosphorus load, for the newly developed RSEM model.

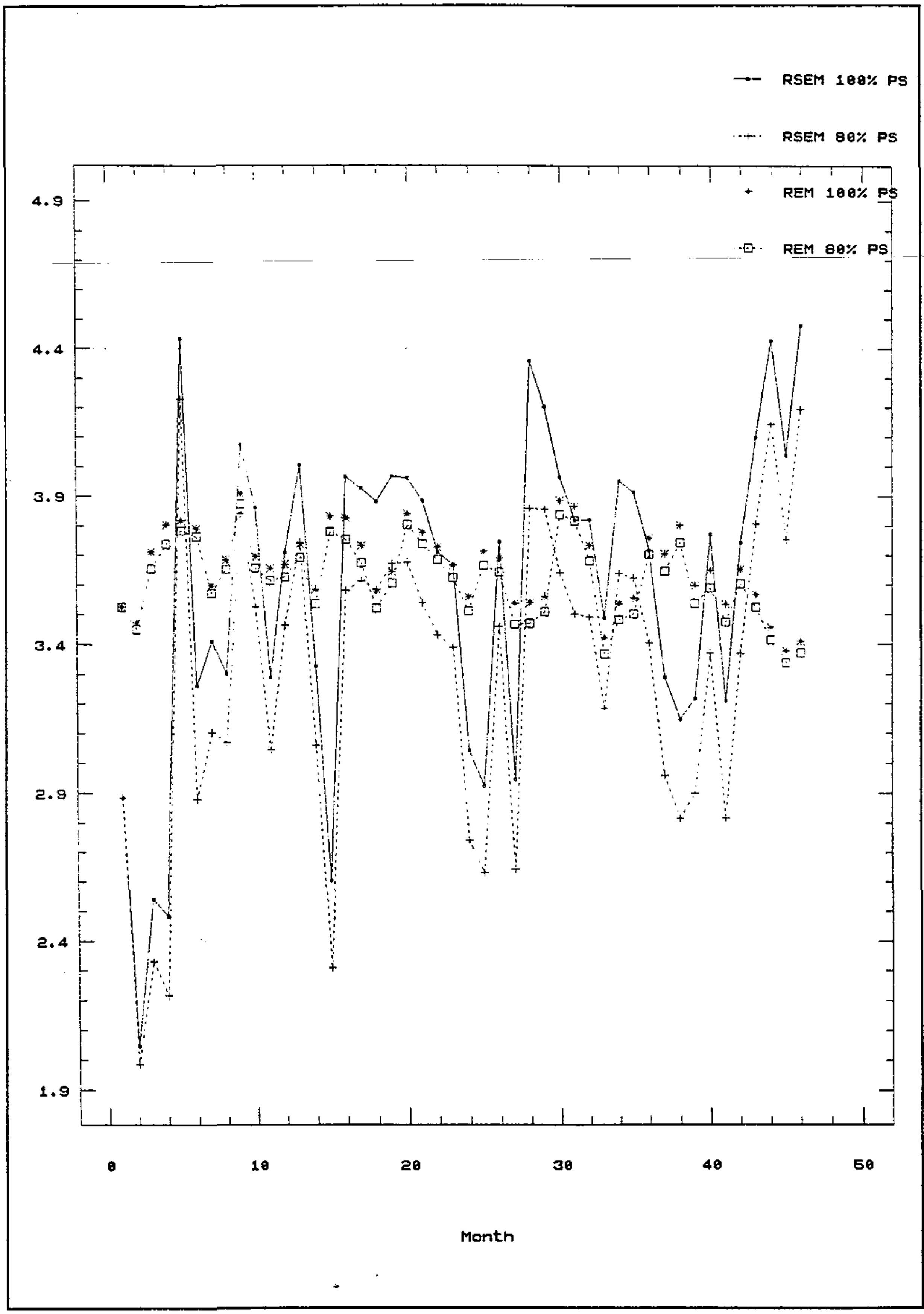

Figure 6.9 Ln[CHL] simulation : RSEM and REM models

Table 6.15 Simulation results

Scenario/Model	Mean Chlorophyll Concentration	Percentage Reduction
Conventional REM Model		
100% Point Source P	38.9	4.6%
80% Point Source P	37.1	
Newly Dev. RSEM Model		
100% Point Source P	36.8	25.5%
80% Point Source P	27.2	

In Figures 6.10 to 6.13 the simulated chlorophyll concentrations for the two models are plotted together with their standard errors for 100% and 80% point source phosphorus load. Comparing Figures 6.10 and 6.11 it can be seen that there is no significant difference in simulated chlorophyll concentrations when the conventional REM model is used. However, comparing Figures 6.12 and 6.13 it can be seen that in the case of the newly developed RSEM model there is a significant difference in simulated chlorophyll concentrations.

In Figure 6.14 the simulated chlorophyll levels for the new RSEM model have been compared with the true chlorophyll concentrations observed at Hartbeespoort Dam during this period. This figure suggests that the true chlorophyll concentrations were more variable than those simulated using the newly developed RSEM model, indicating that the RSEM model is still too insensitive. This was expected on account of the relatively low R^2 (49%) obtained for the RSEM chlorophyll model.

6.7.6 Summary

In the case of Hartbeespoort Dam the results obtained from the conventional REM model appear to be misleading. The conventional REM model has suggested that a 20% reduction in point source phosphorus will cause an insignificant decrease in chlorophyll concentration of only 4.6% on average. The newly developed model has suggested a significant decline in chlorophyll concentration of 25.5% on average. From this it appears that the conventional REM model is far too insensitive to changes in phosphorus levels. This is thought to be largely the result of the use of an inappropriate model for chlorophyll concentrations. The newly developed RSEM model is certainly much more sensitive to changes in phosphorus level, but this model too appears to under-estimate the variability present in the true chlorophyll concentrations.

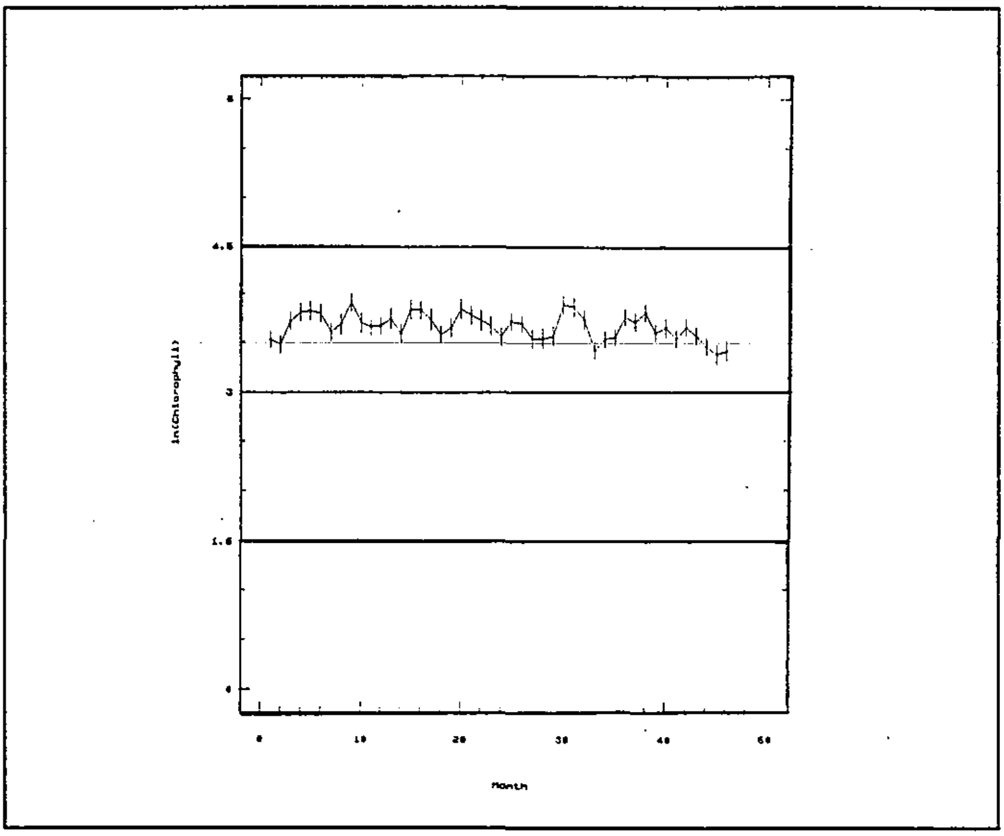

Figure 6.10 Conventional REM model : 100% point source phosphorus load

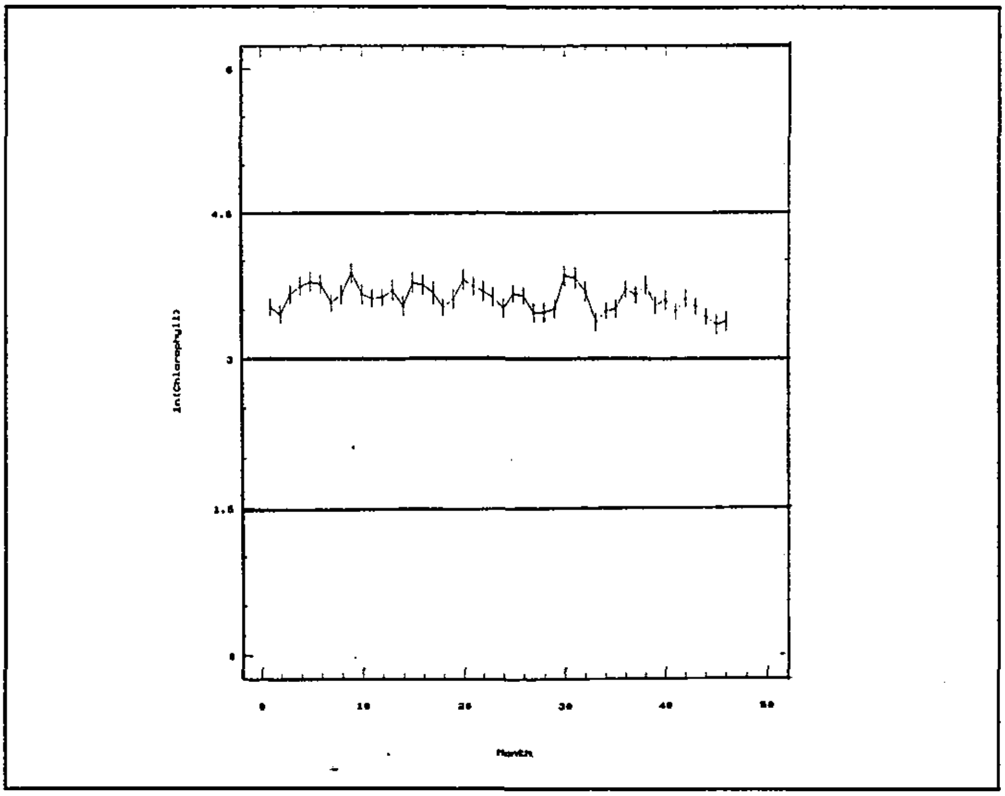

Figure 6.11 Conventional REM model : 80% point source phosphorus load

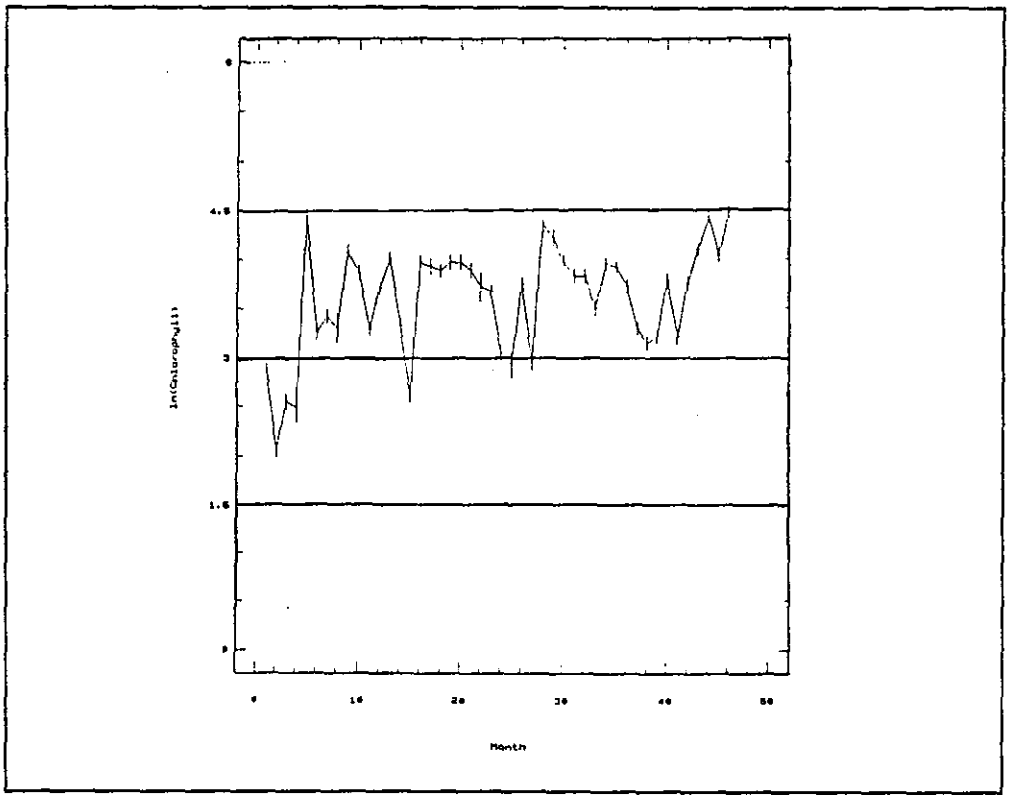

Figure 6.12 Newly developed REM model : 100% point source phosphorus load

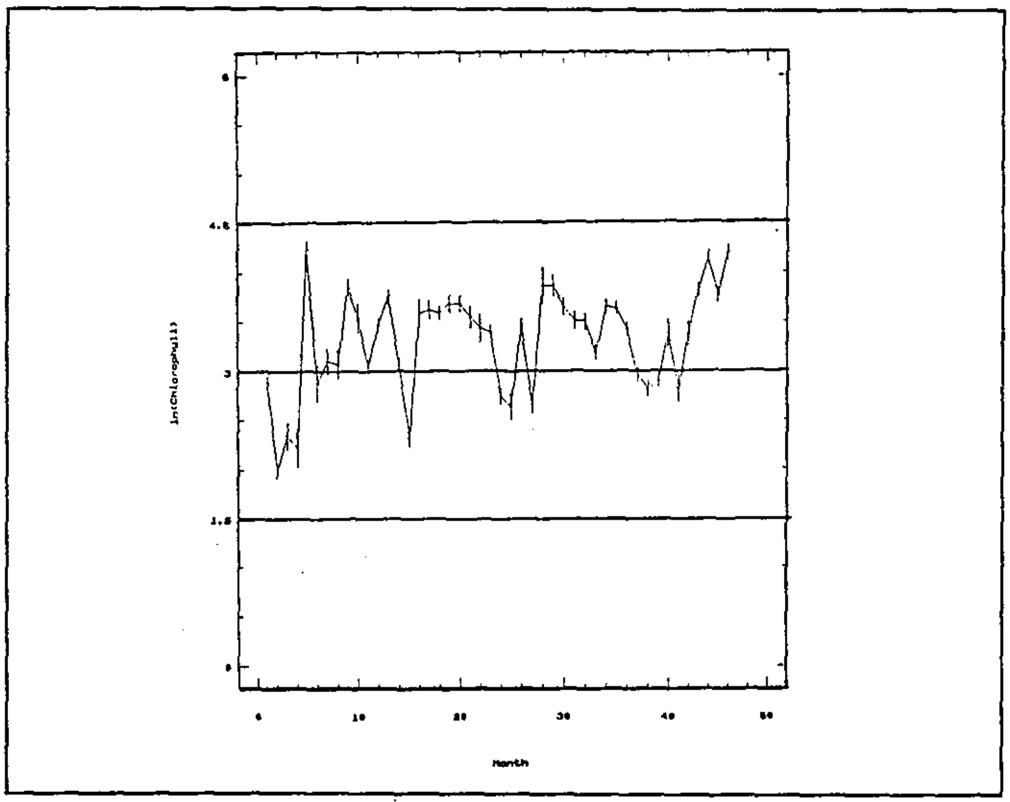

Figure 6.13 Newly developed REM model : 80% point source phosphorus load

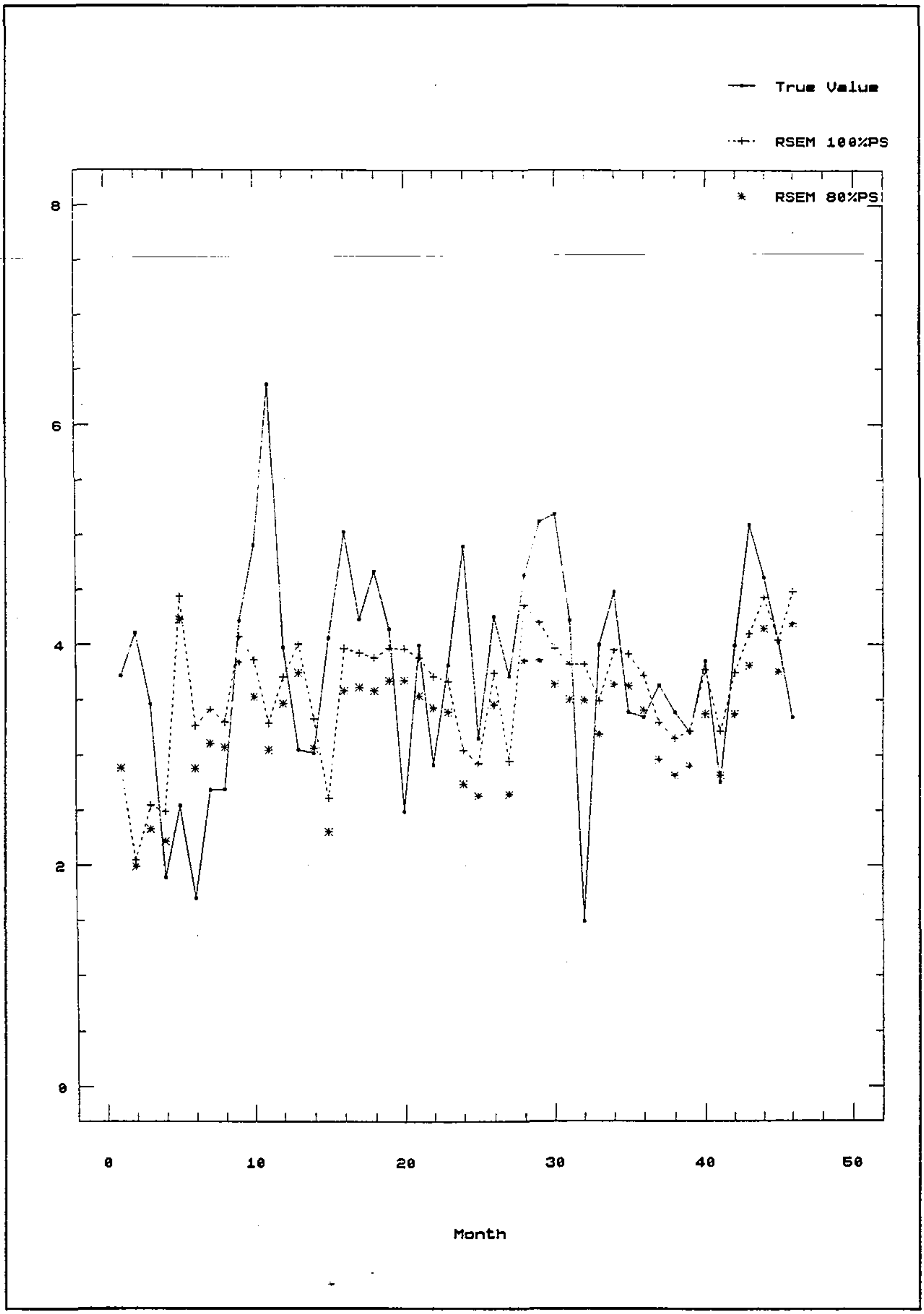

Figure 6.14 Ln([Chlorophyll]) : True and RSEM simulated values

The second objective was to compare the standard errors associated with the mean of the simulated logged chlorophyll concentrations for the REM and RSEM models. As indicated by the standard error bars in Figures 6.10 and 6.11, the standard errors for the conventional REM model hardly vary over time and are very similar for the 80% and 100% point source phosphorus scenarios. However, considering the standard error bars for the newly developed RSEM in Figures 6.12 and 6.13, much more variability is evident for the RSEM model. In general, standard errors are lower for the RSEM model than for the REM model. But, for a few months, the standard errors for the RSEM model are larger than for the REM model. Furthermore it appears that, for the RSEM model, the standard errors are generally slightly higher for the 80% point source scenario than for the 100% point source scenario.

It seems, therefore, that the newly developed RSEM model is more sensitive than the conventional REM model in two respects. For the RSEM model the means of the simulated ln(chlorophyll) values and the standard errors associated with these means both respond more to changes in phosphorus levels than is the case for the conventional REM model.

7. SUMMARY AND CONCLUSIONS

7.1 The Deterministic Model

The introduction of the phosphorus (P) standard for effluent and the REMDSS model in recent years has assisted water quality managers in the control of eutrophication in southern African reservoirs. One of the basic data requirements of the control strategies is quantification of P loads exported from catchments and their transport by rivers to the receiving waterbodies. Stochastic models relating P export to streamflow by means of regression analyses have been reported but little research has been attempted in the deterministic modelling of P export.

This report has described the development of such a model which, although based on deterministic principles, can more likely be described as a physical conceptual model relying heavily on *a priori* parameter estimation followed by parameter optimization based on the results of several objective functions. The model uses observed streamflow as the process driver, however provision is made for streamflow to be generated by any of a number of suitable hydrological rainfall-runoff models. The Pitman monthly model is suggested and described in this report due to its use and acceptability in engineering circles.

Calibration methods have been described, and while automatic parameter optimization may preferred as the most accurate method, coarse manual fitting methods are used most frequently by the practising engineer due to the time and cost constraints of automatic optimization techniques.

Parameter transfer and sensitivity have been described. Transfer of parameters from calibrated, gauged catchments to ungauged catchments was not recommended due to the small data set used and the resulting uncertainty regarding transferability of parameters. Sensitivity of the parameters has been illustrated and should be used in conjunction with the model to determine the relative importance of accuracy with which each parameter should be estimated or measured.

Results based on data from nine catchments have been presented. The results show acceptable simulation of P loads exported from the catchments. Short data record lengths of observed P, however, remain a problem which can only be improved by the passage of time.

7.2 Stochastic Models

As mentioned in section 6.1 of this report, this study was undertaken in order to address some of the research requirements identified by Grobler and Silberbauer (1984). In particular a method for the quantification of model uncertainty has been developed. This involves the complete description of errors for the various models which make up the REM model, and the use of Monte Carlo simulation in order to assess the compounding effect of errors on the chlorophyll concentration values produced by the REM model.

In addition improvements have been suggested for all the models comprising the REM model.

Improvements to the calibration procedure for the Pitman models have been suggested and a new phosphorus export model has been developed. The new phosphorus export model is sufficiently flexible to describe the lagged nature of the runoff-export relationship observed for South African rivers. The phosphorus budget model has been modified to accommodate the lack of mixing in South African reservoirs and their dynamic (variable) nature. The scope of the chlorophyll concentration model has been expanded to include the growth limiting effects of additional nutrients.

It has been shown, by means of Monte Carlo simulation, that these improvements to the REM model have resulted in greater sensitivity, in the case of Hartbeespoort Dam. This suggests that changes to the REM model such as those mentioned above can be used to improve the efficiency of REM modelling as a tool for assessing the effect of phosphorus controls on water quality.

The Reservoir Eutrophication Model is an important tool for the assessment of the future trophic status of South African reservoirs. However, this tool is only as good as the sub-models used to simulate phosphorus export, phosphorus budgets and chlorophyll concentrations. It has been shown that the conventional REM model does not portray accurately the behaviour of all South African reservoirs. The further development of reservoir specific eutrophication models (RSEM's) is recommended in order to produce a more reliable modelling tool.

7.3 Research Requirements

7.3.1 *The Deterministic Model*

In viewing the Phosphorus Export Model (PEM) as a first approximation to accurate deterministic modelling of P export from non-point source dominated catchments, the need for further research becomes obvious.

One of the more urgent cases in point is the need for more accurate information regarding soil erosion and sediment loss from catchments in southern Africa. The USLE was originally designed for use with small agricultural plots and its use in large catchments is in doubt. The information required to use the USLE is also a problem area as parameters such as land-use, soil erodibility, slope length and slope gradient are not readily available in most areas of the region except in specific research catchments or gleaned by intensive field survey.

Another area for further research is the need to base the model on more deterministic principles, thus reducing the reliance on parameter calibration and increasing the transferability of the parameters to ungauged areas. One major task is consolidating the mass of, often conflicting, research concerning P processes in research areas that has been reported in the scientific literature and applying it to the P export problem. A point to be kept in mind is the time scales involved in eutrophication responses in reservoirs. These are commonly of the order of months and even years. The P export model thus should use a monthly time scale with the associated problem that most of the research reported in the literature involves continuous or daily time scales.

Data problems concerning the USLE method have been addressed, however a major problem facing deterministic modelling of P export from non-point source dominated catchments is the lack of data concerning initial P storage in and on the catchment soils, as well as the P replenishment rate by virtue of atmospheric deposition and weathering of rocks and minerals, amongst others.

If the problems mentioned above can be addressed and the present PEM is used as a basis for a new improved PEM, then it may be possible to develop a fully deterministic model with the advantage of minimum calibration and the ability to transfer parameters.

7.3.2 Stochastic Models

The newly developed reservoir specific eutrophication modelling (RSEM) procedure can definitely be improved further. It is suggested that the first priority should be the development of a dynamic (time series) chlorophyll concentration model. A cross-sectional chlorophyll concentration model is inappropriate in the context of REM modelling on account of differences in nutrient loadings for South African impoundments. Instead reservoir specific dynamic (time series) models are required.

The best available chlorophyll model for Hartbeespoort at this stage uses only six nutrient concentrations (TP, KN, NH_4, NO_2, NO_3, PO_4). Analysis for Witbank Dam has indicated that water clarity (measured by the concentration of total dissolved salts) has a dramatic effect on algal growth. This variable and perhaps silica concentration should be studied with a view to improving the chlorophyll concentration model. If such studies could be performed for several dams, it is likely that a general form for the chlorophyll model will emerge. Such a general model is required in order to simplify the application of RSEM modelling in future.

More developmental work is also required for the phosphorus budget model. The phosphorus budget model developed in this study, which allows for higher sedimentation rates in the inflow, has only been tested for two dams. It is essential that the form of this model be validated for more South African reservoirs. In addition it has been suggested that concentration dependent sedimentation rates rather than constant sedimentation rates should be examined in the context of this new model.

It has been suggested that the REM model needs to be extended to incorporate additional nutrients other than phosphorus, since phosphorus is certainly not the only growth limiting nutrient. This means that the runoff-export relationships and reservoir budget relationships for these nutrients will have to be modelled in the future. Models to predict water clarity may also be necessary.

Finally, in this study an uncertainty/sensitivity analysis has been performed for only one South African reservoir, namely Hartbeespoort Dam. Such Monte Carlo simulations need to be performed for other dissimilar South African dams in order to confirm the conclusions reached here.

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Appendix A : Parameter Maps and Figures (Pitman, 1973) for use with the Pitman Monthly Runoff Model

<u>NB</u> : The reader should note that the parameter maps produced for the "Water Resources of South Africa" series (1981) by the HRU, have, in all regions where basin studies have been undertaken for the DWA, been replaced by new parameter sets or maps. These are reported in a wide variety of reports on basin studies and it is left to the user of the Pitman (1973) model to obtain and use this data as they see fit.

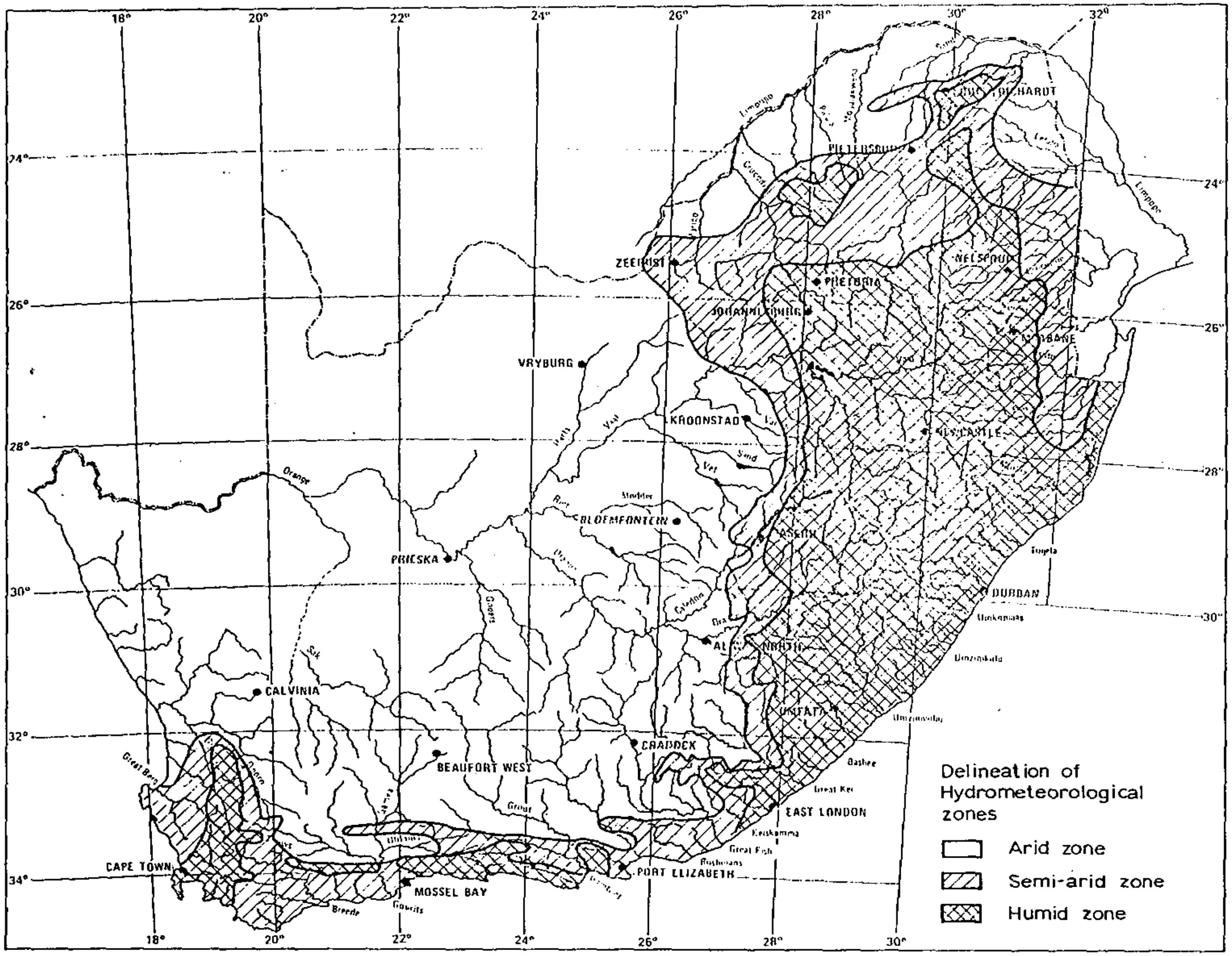

Figure A1 Delineation of hydrometeorological zones (Pitman, 1973)

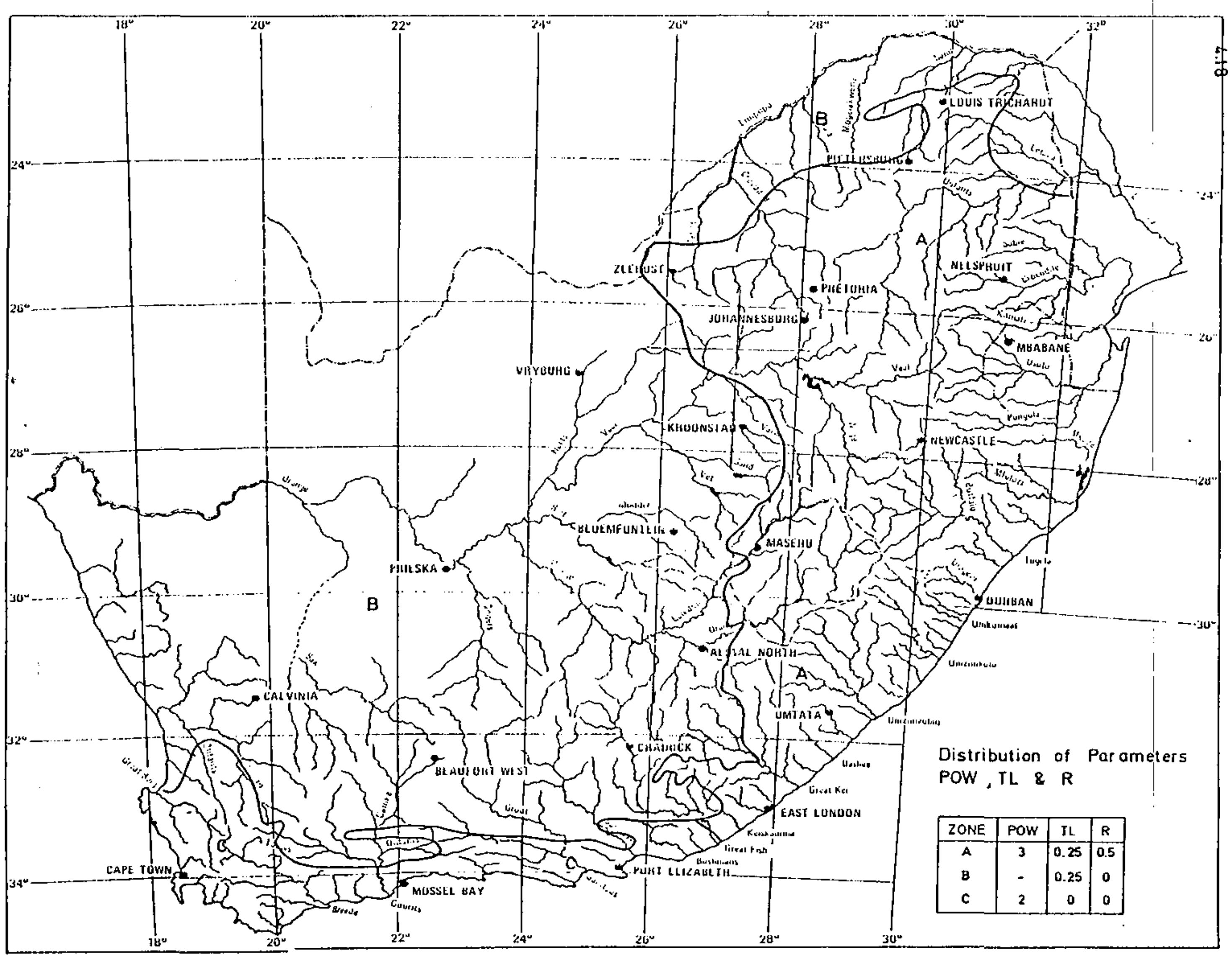

Figure A2 Distribution of parameters POW, TL and R (Pitman, 1973)

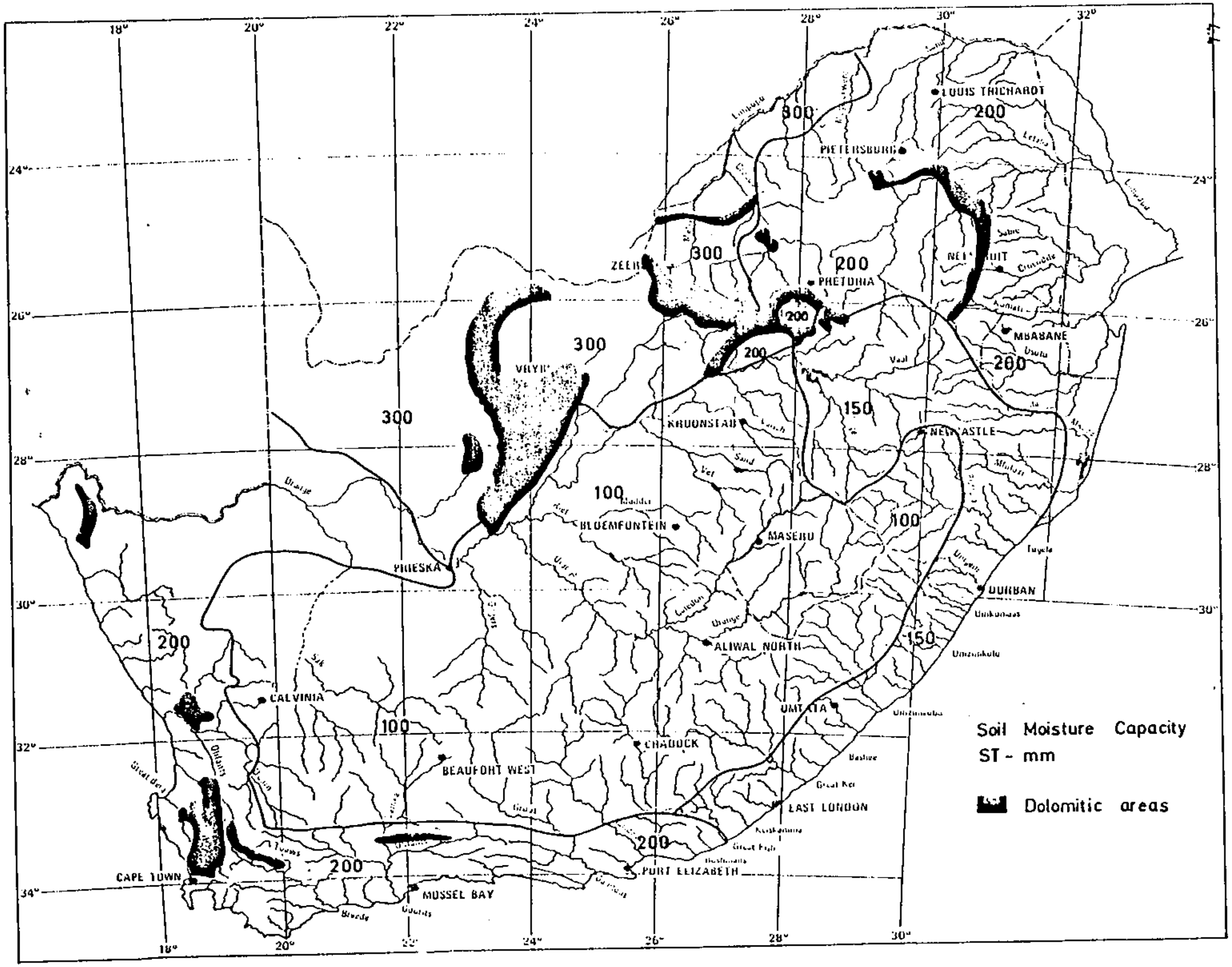

Figure A3 Soil water capacity ST (mm) (Pitman, 1973)

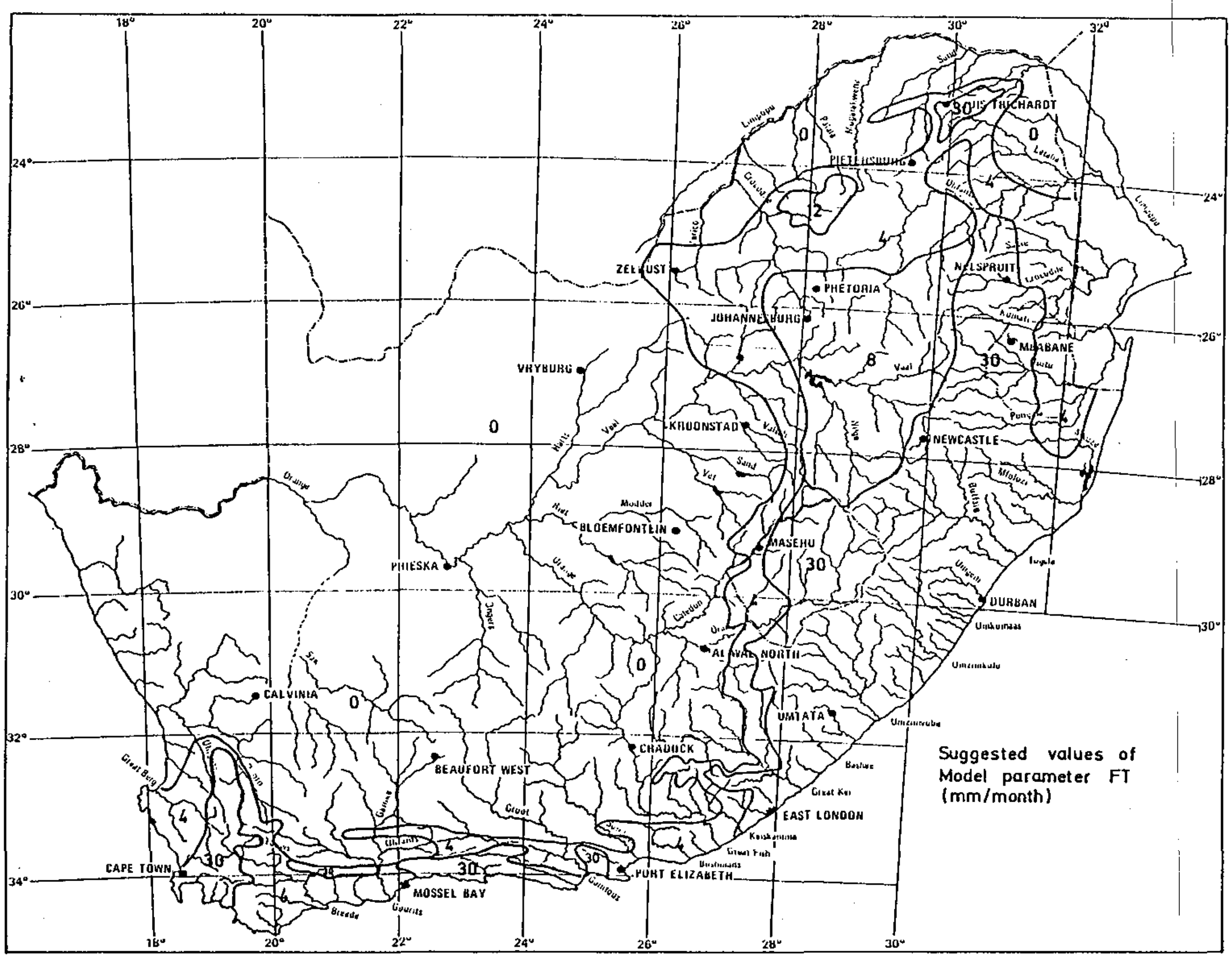

Figure A4 Suggested values of model parameter FT (mm/month) (Pitman, 1973)

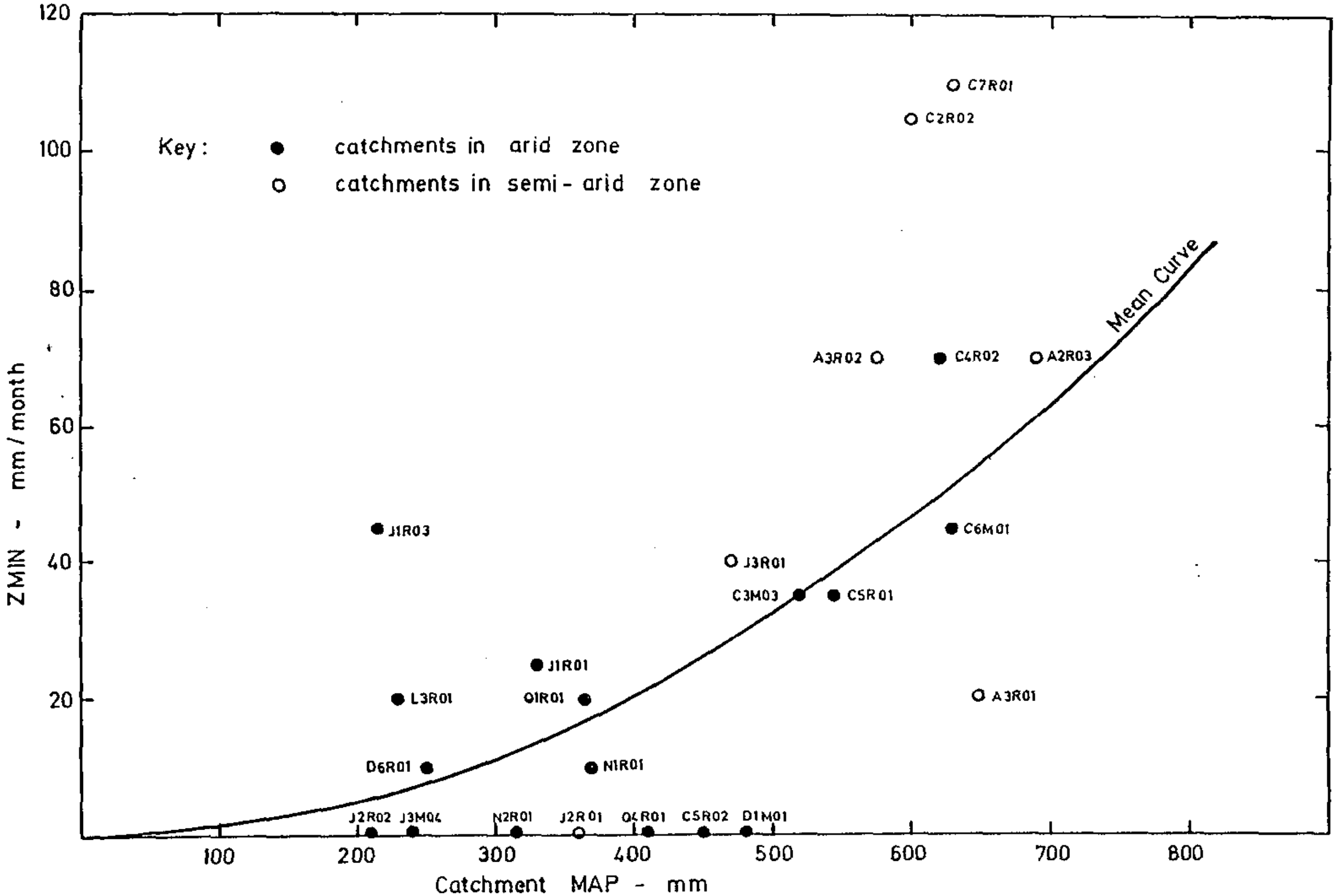

Figure A5 Observed relationship between parameters MAP and ZMIN (Pitman, 1973)

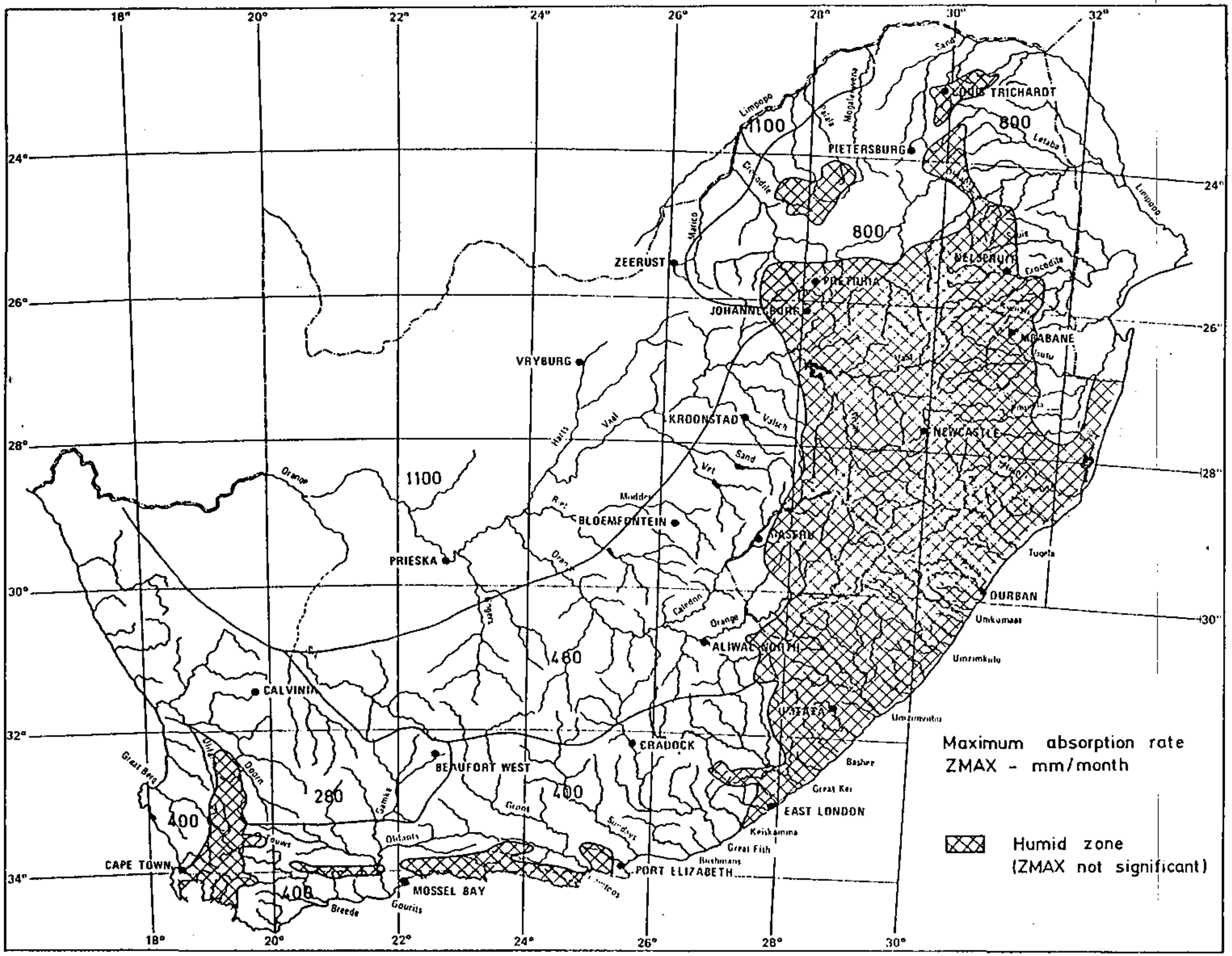

Figure A6 Maximum absorbtion rate ZMAX (mm/month) (Pitman, 1973)

Appendix B : Evaporation Maps (Pitman, 1973) for use with the Pitman Monthly Runoff Model

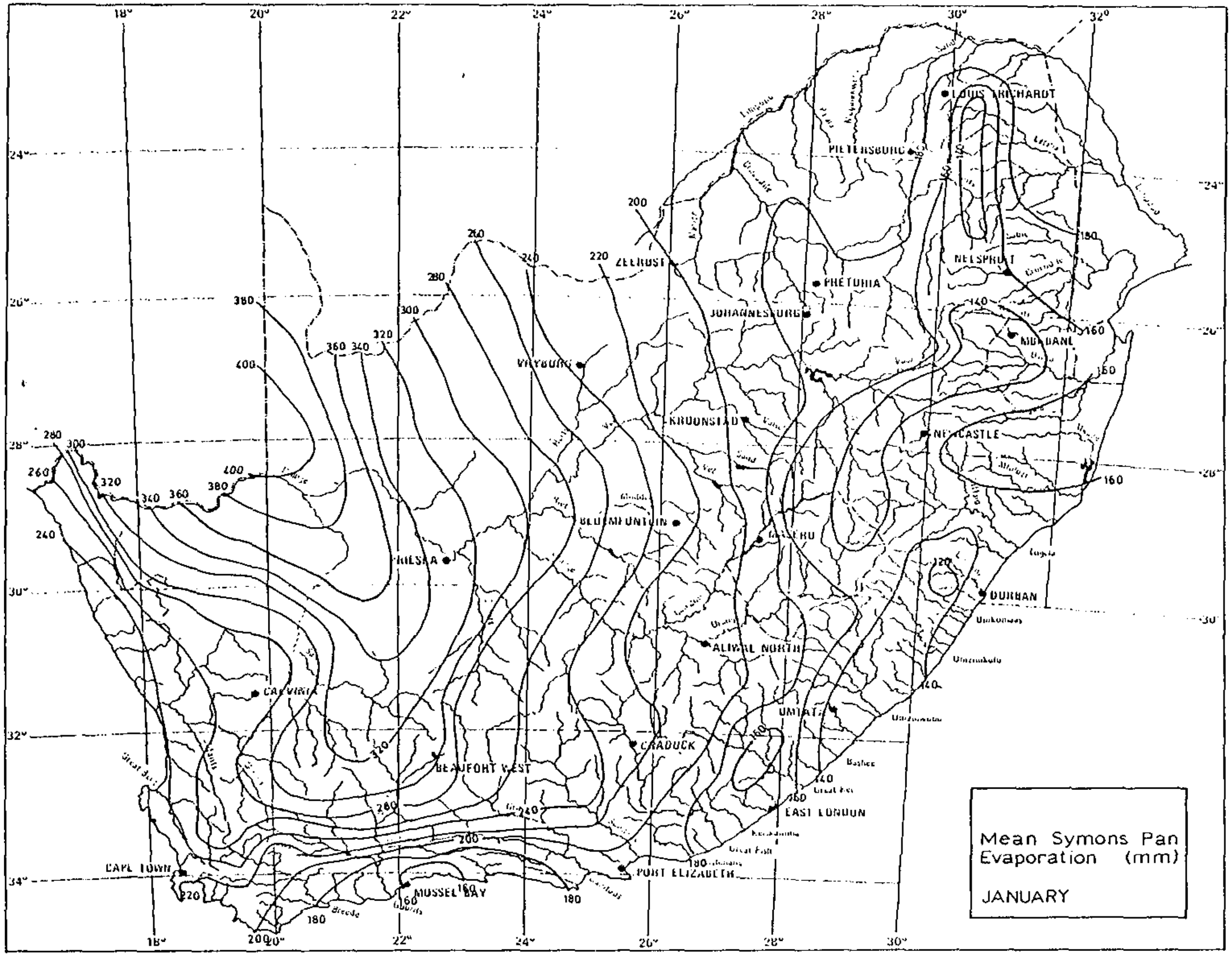

Figure B1 Mean Symons Pan evaporation (mm) for January (Pitman, 1973)

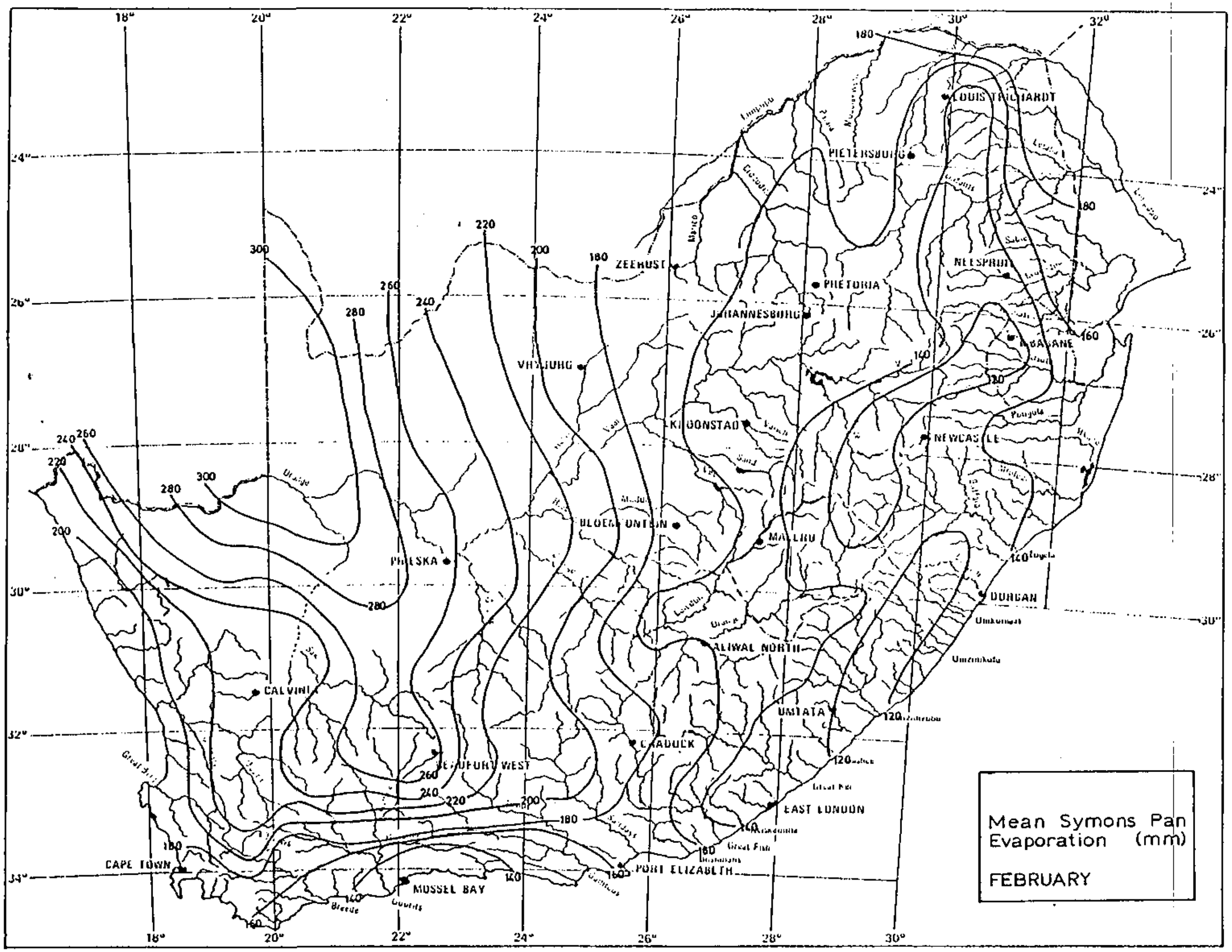

Figure B2 Mean Symons Pan evaporation (mm) for February (Pitman, 1973)

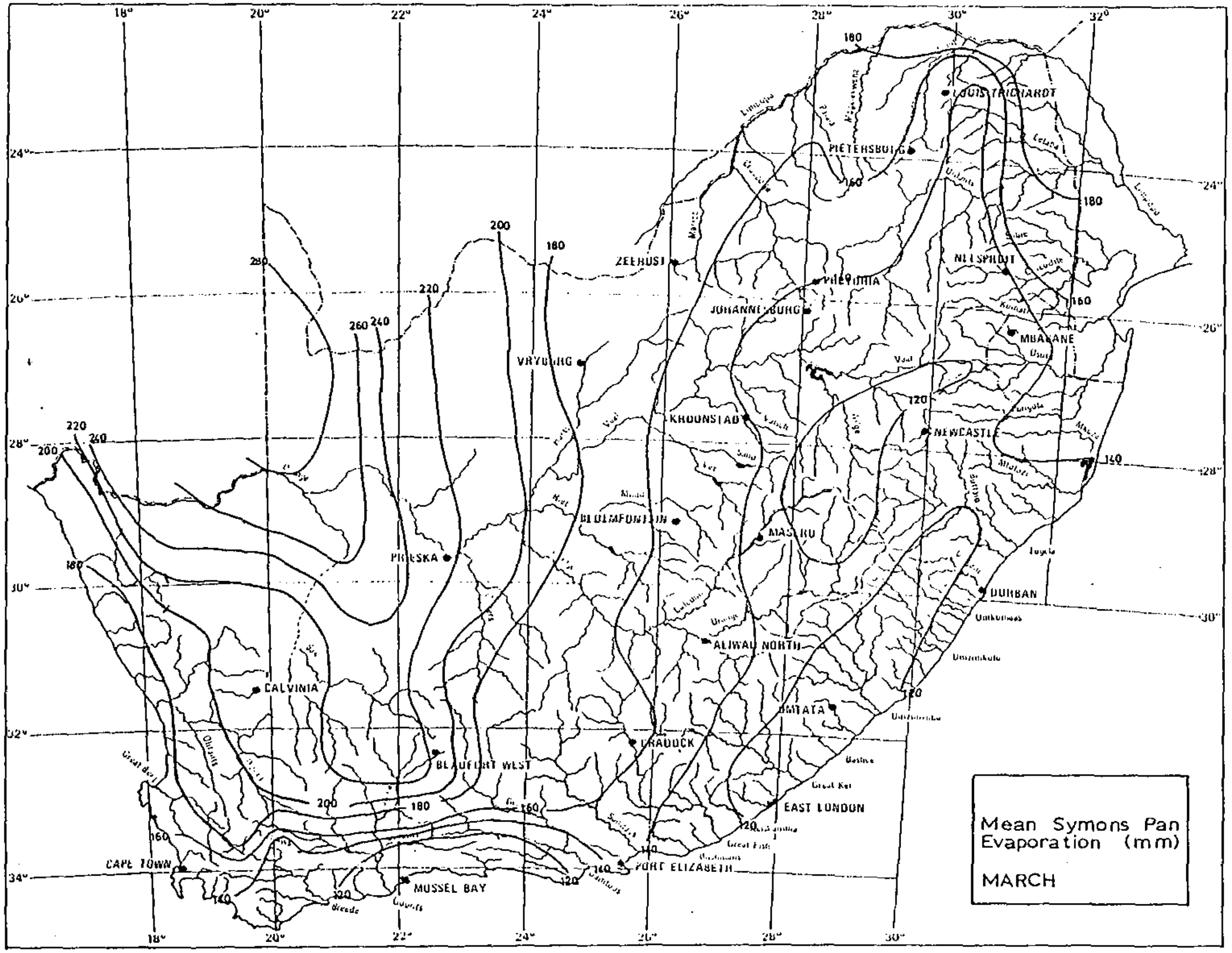

Figure B3 Mean Symons Pan evaporation (mm) for March (Pitman, 1973)

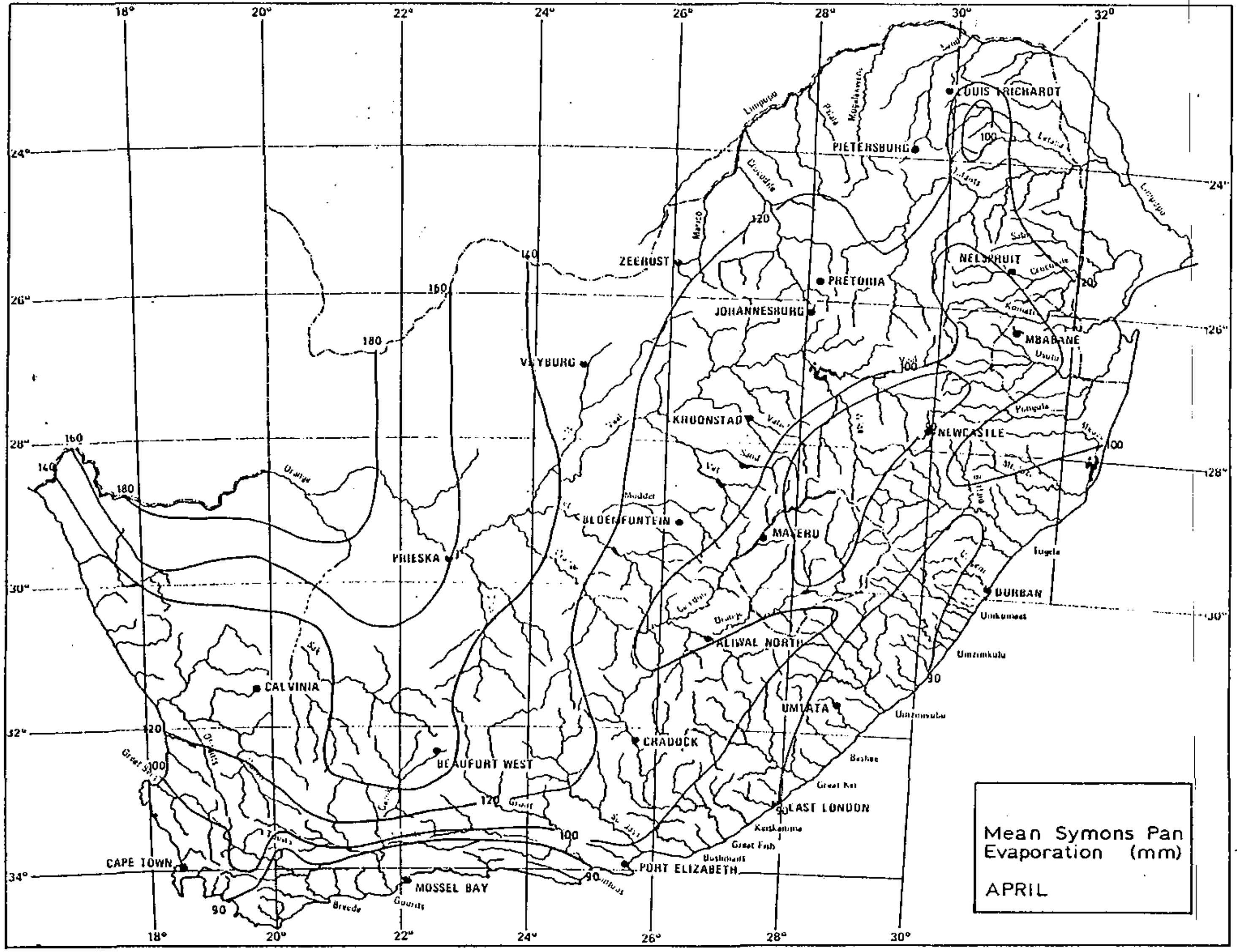

Figure B4 Mean Symons Pan evaporation (mm) for April (Pitman, 1973)

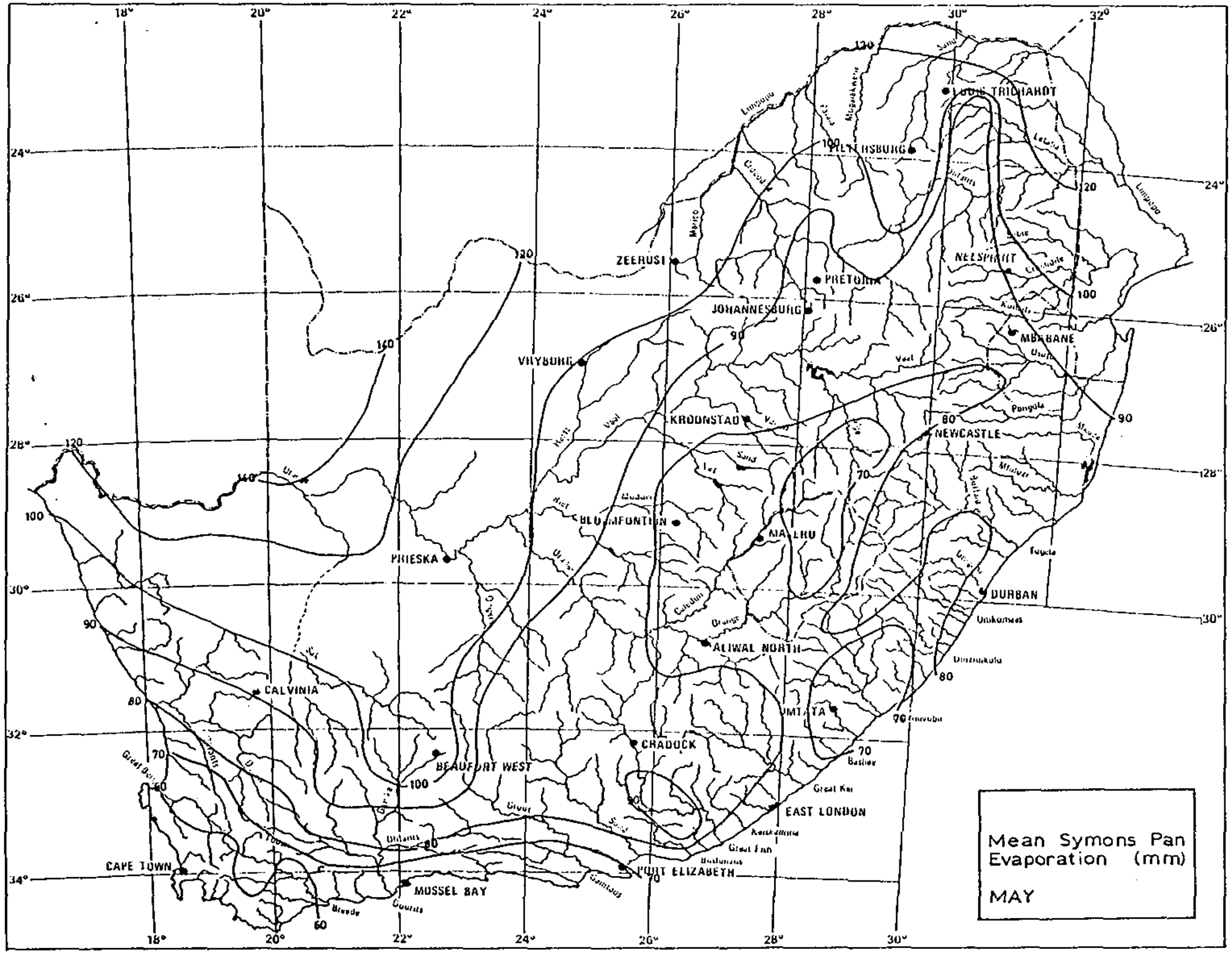

Figure B5 Mean Symons Pan evaporation (mm) for May (Pitman, 1973)

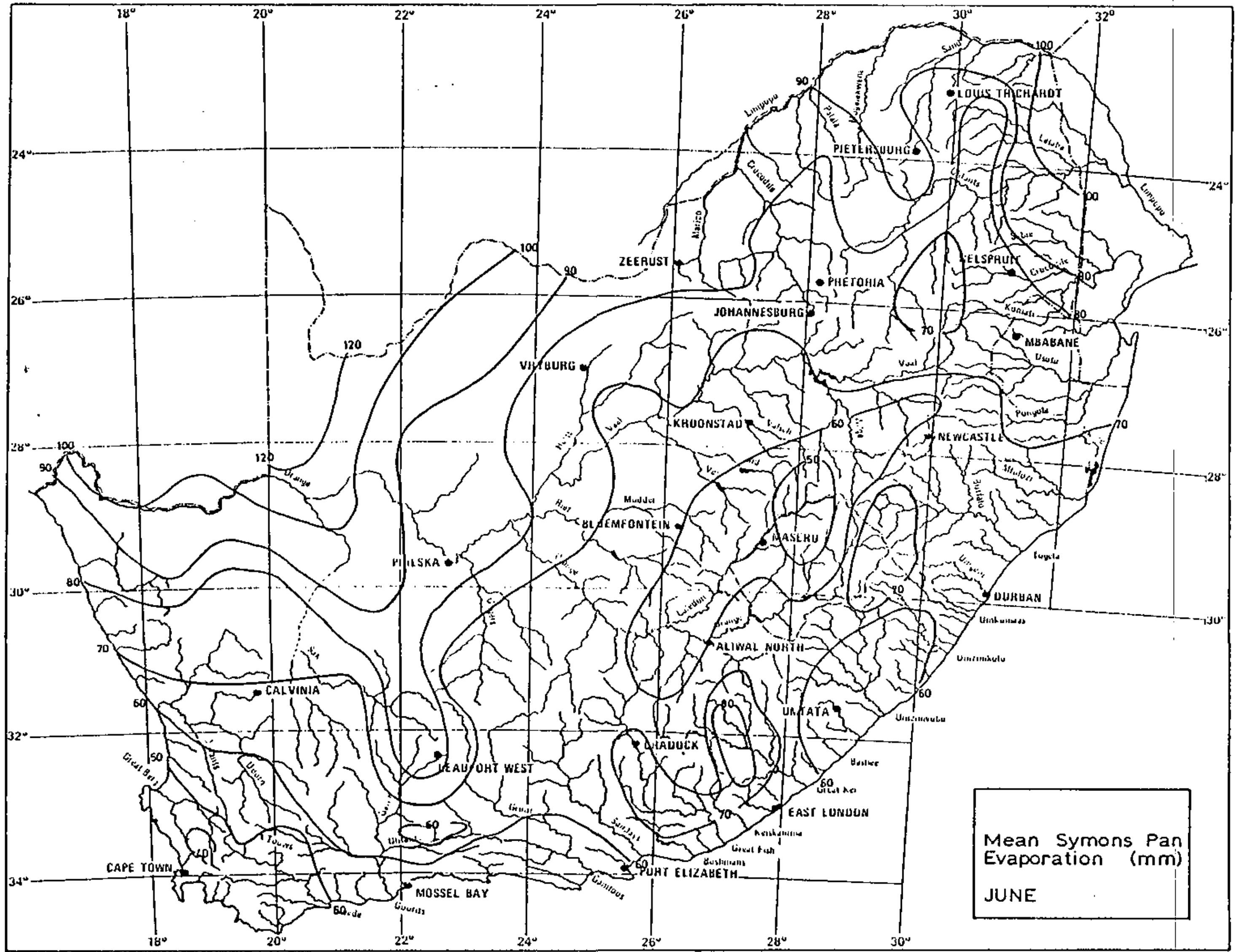

Figure B6 Mean Symons Pan evaporation (mm) for June (Pitman, 1973)

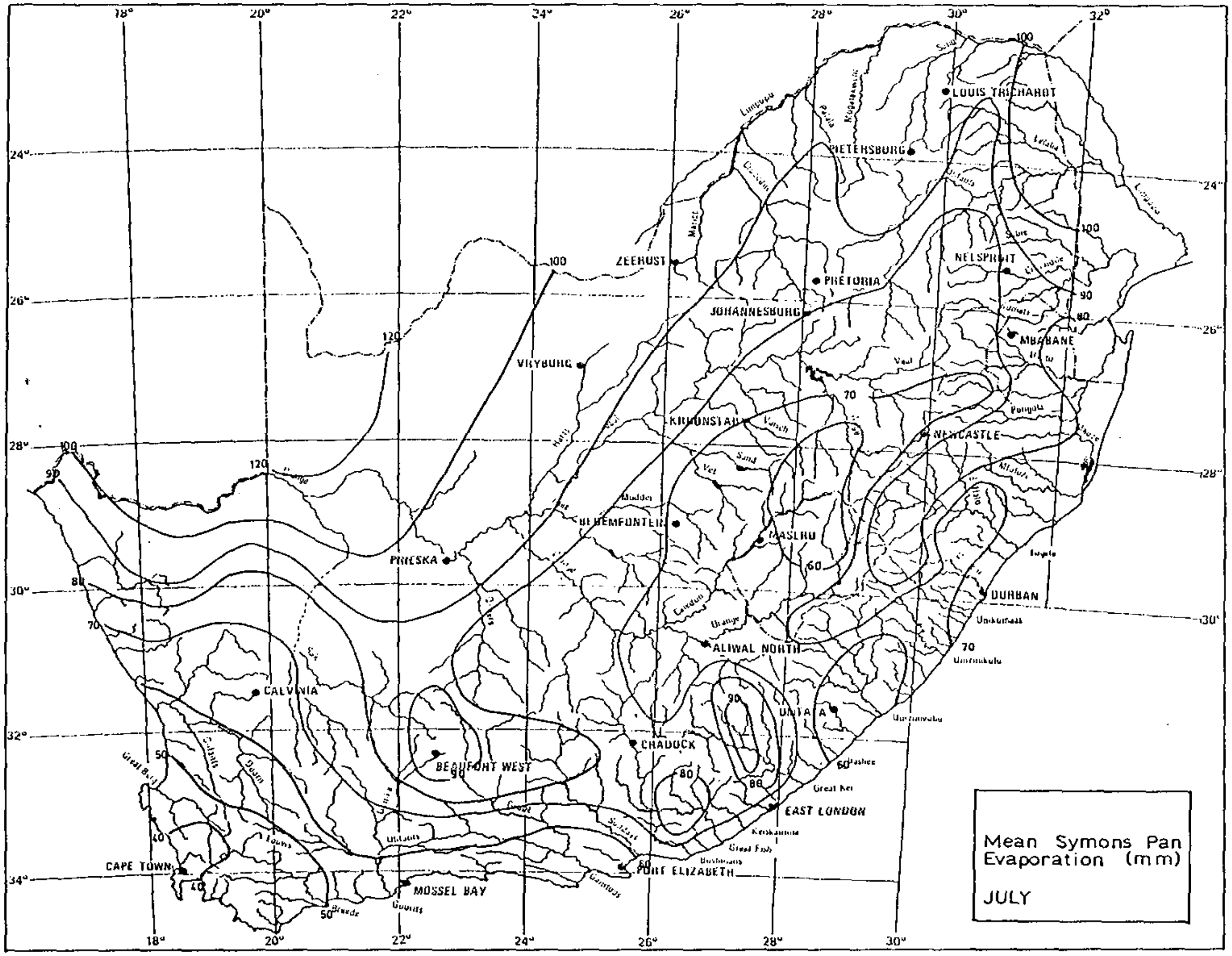

Figure B7 Mean Symons Pan evaporation (mm) for July (Pitman, 1973)

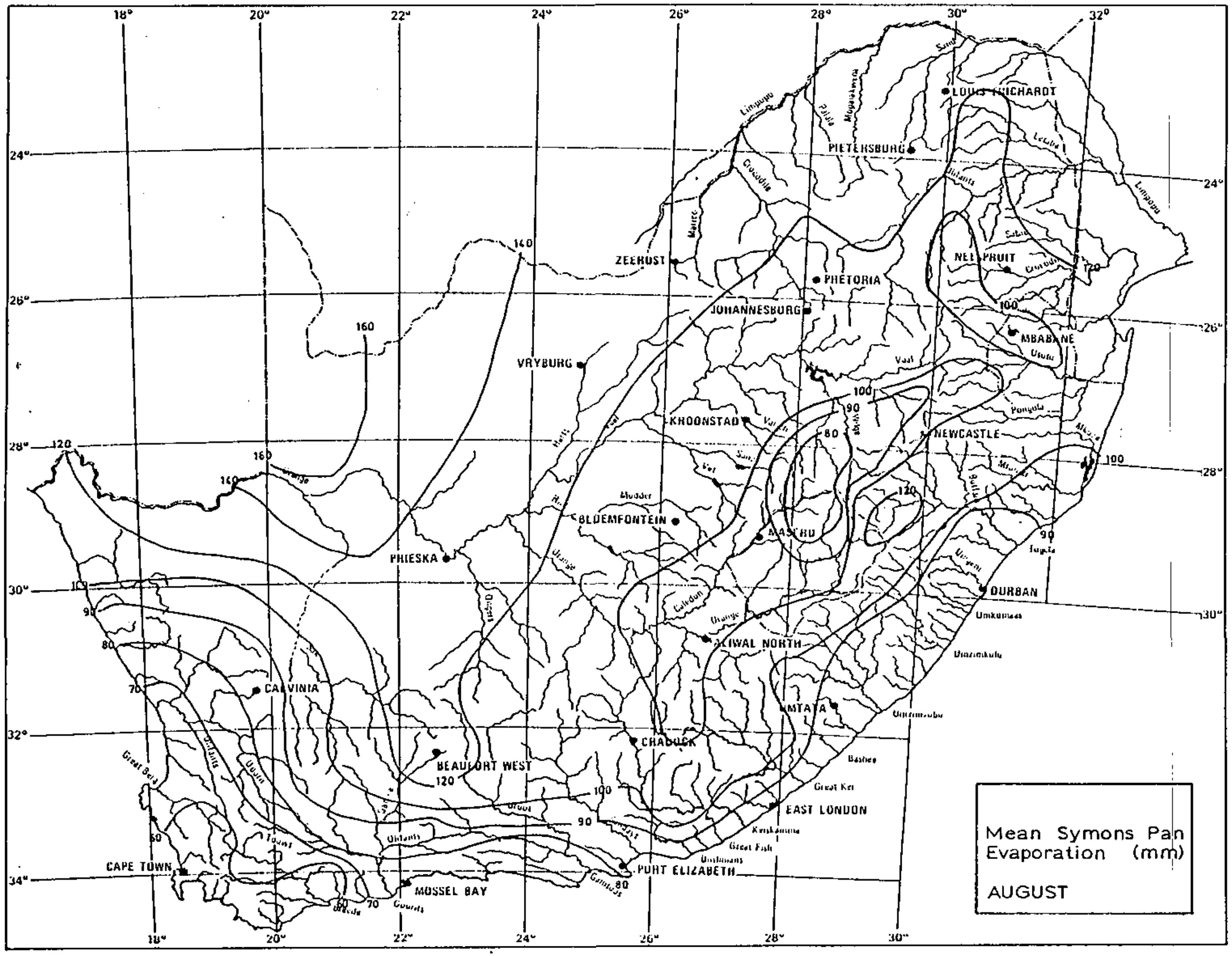

Figure B8 Mean Symons Pan evaporation (mm) for August (Pitman, 1973)

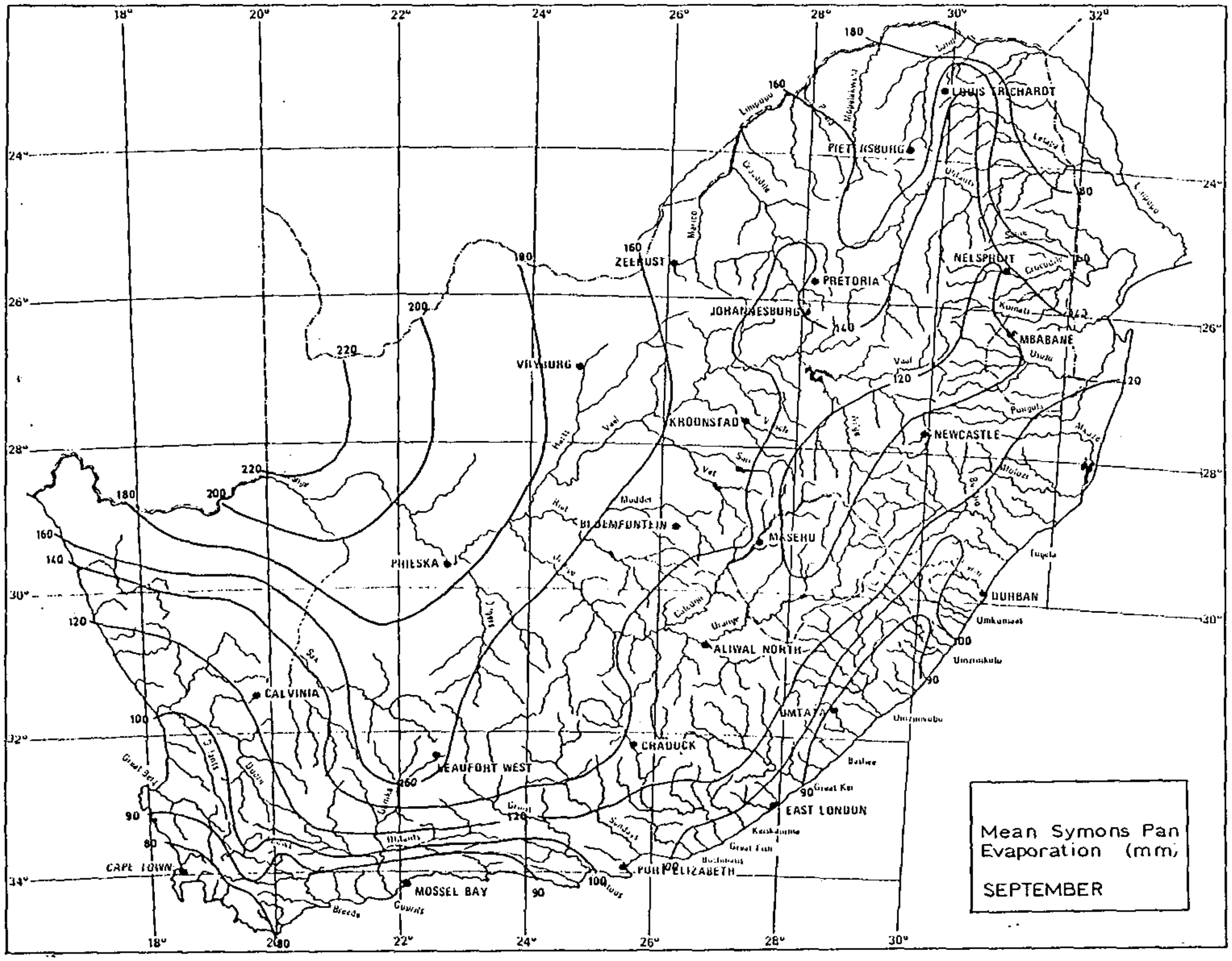

Figure B9 Mean Symons Pan evaporation (mm) for September (Pitman, 1973)

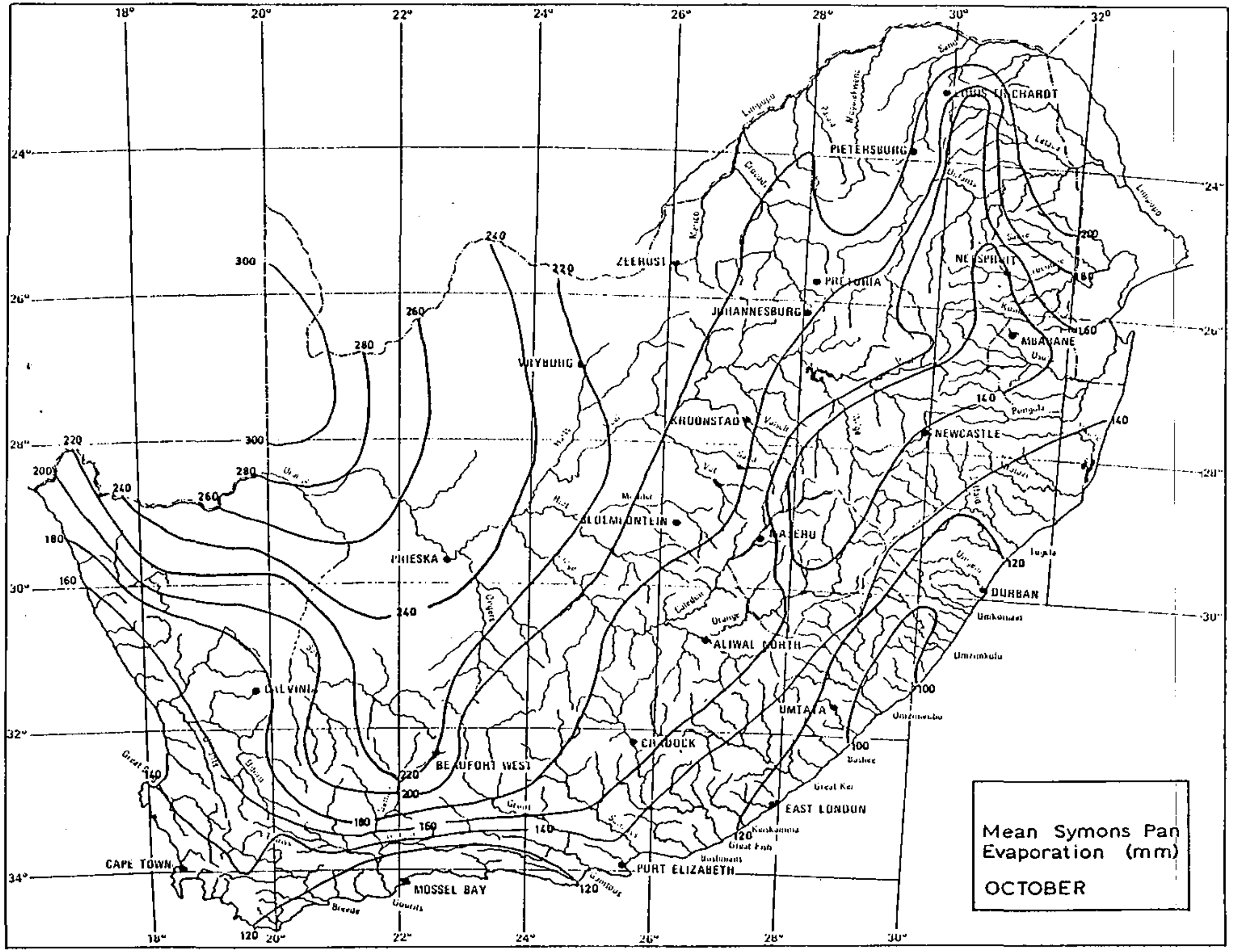

Figure B10 Mean Symons Pan evaporation (mm) for October (Pitman, 1973)

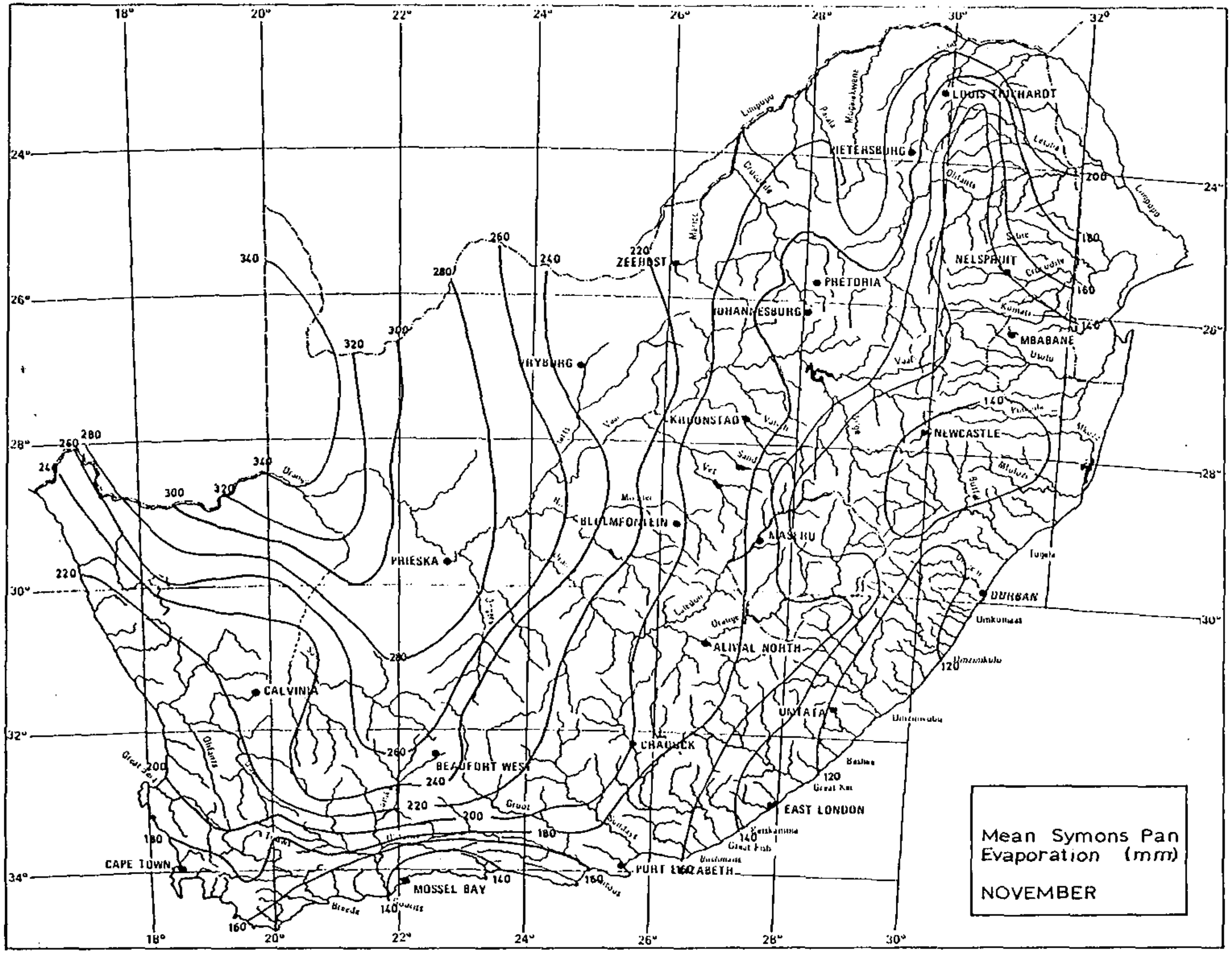

Figure B11 Mean Symons Pan evaporation (mm) for November (Pitman, 1973)

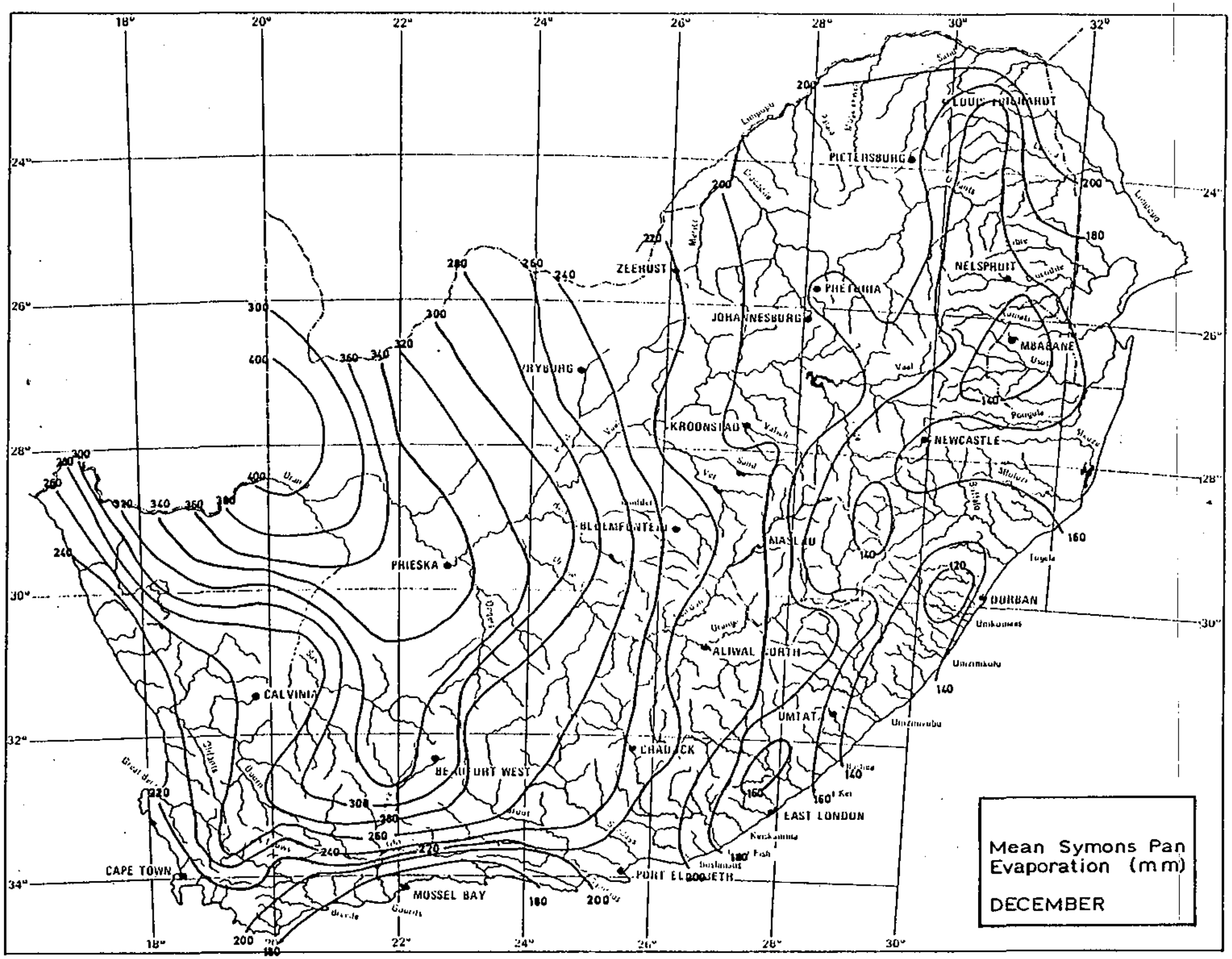

Figure B12 Mean Symons Pan evaporation (mm) for December (Pitman, 1973)

Appendix C : Calibrated Pitman Model Parameters (Pitman, 1973)

Pitman (1973) calibrated the Pitman Monthly Runoff Model for the test catchments shown in Figure C1. The best-fit values and simulation information for each catchment are given.

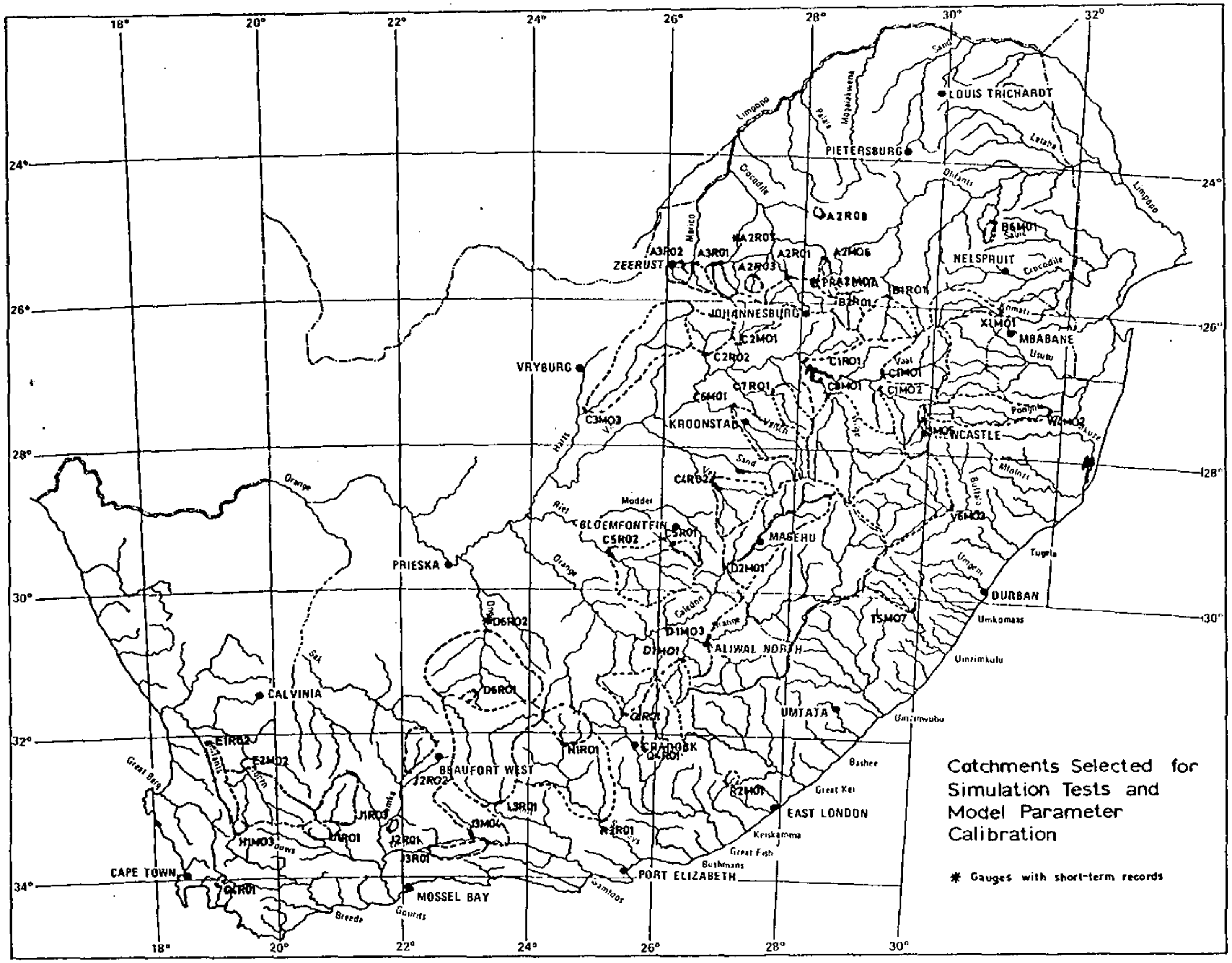

Figure C1 Catchments selected for Pitman simulation tests and model parameter calibration (Pitman, 1973)

Gauge : A2R001 Catchment area : 4144 km^2 MAP : 730 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	200.0	10.0	2.0	0.01	-	-	1.5	0.2	2.0	0.5

Gauge : A2R003 Catchment area : 490 km^2 MAP : 690 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	250.0	3.0	-	0.0	70.0	720.0	1.5	0.2	-	0.5

Gauge : A2H006 Catchment area : 1028 km^2 MAP : 710 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	200.0	4.0	-	0.01	-	-	1.5	0.2	-	0.5

Gauge : A2H007 Catchment area : 142 km^2 MAP : 750 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
1.0	0.0	500.0	7.0	-	0.05	-	-	1.5	0.0	-	0.5

Gauge : A2R008 Catchment area : 127 km^2 MAP : 700 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	175.0	1.0	4.0	0.0	-	-	1.5	0.4	4.0	0.5

Gauge : A3R001 Catchment area : 1308 km^2 MAP : 650 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	350.0	5.0	-	0.0	20.0	1100.0	1.5	0.2	-	0.5

Gauge : A3R002 Catchment area : 750 km^2 MAP : 575 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	400.0	2.0	-	0.0	70.0	900.0	1.5	0.2	-	0.5

Gauge : B1R001 Catchment area : 3618 km^2 MAP : 720 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	150.0	6.0	-	0.0	-	-	1.5	0.3	-	0.5

Gauge : B2R001 Catchment area : 1251 km^2 MAP : 715 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	175.0	9.0	2.0	0.0	-	-	1.5	0.2	0.2	0.5

Gauge : B6H001 Catchment area : 508 km^2 MAP : 1160 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
1.0	0.0	300.0	40.0	-	0.0	-	-	1.5	0.5	-	0.5

Gauge : C1H001 Catchment area : 8254 km^2 MAP : 780 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	125.0	7.0	-	0.0	-	-	1.5	0.3	-	0.5

Gauge : C1R001 Catchment area : 38518 km^2 MAP : 750 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	125.0	9.0	-	0.0	-	-	1.5	0.2	-	0.5

Gauge : C1H002 Catchment area : 4201 km^2 MAP : 770 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	200.0	8.0	-	0.0	-	-	1.5	0.25	-	0.5

Gauge : C2H001 Catchment area : 3564 km^2 MAP : 670 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	500.0	4.0	3.9	0.0	-	-	1.5	0.0	3.0	0.5

Gauge : C2R002 Catchment area : 3790 km^2 MAP : 600 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	300.0	2.0	-	0.0	105.0	615.0	1.5	0.2	-	0.5

Gauge : D6R001 Catchment area : 243 km^2 MAP : 250 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	10.0	450.0	1.5	0.3	-	0.0

Gauge : E1R002 Catchment area : 2056 km^2 MAP : 750 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	250.0	30.0	-	0.05	-	-	1.5	0.0	-	0.0

Gauge : E2H002 Catchment area : 6944 km^2 MAP : 370 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	150.0	27.0	-	0.03	-	-	1.5	0.0	-	0.0

Gauge : G4R001 Catchment area : 67 km^2 MAP : 1160 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	200.0	200.0	-	0.1	-	-	1.5	0.0	-	0.0

Gauge : H1H003 Catchment area : 658 km^2 MAP : 940 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	500.0	30.0	-	0.0	0.0	600.0	1.5	0.0	-	0.0

Gauge : J1R001 Catchment area : 761 km^2 MAP : 330 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	200.0	0.0	-	0.0	25.0	600.0	1.5	0.3	-	0.0

Gauge : J1R003 Catchment area : 3994 km^2 MAP : 215 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	45.0	150.0	1.5	0.3	-	0.0

Gauge : J2R001 Catchment area : 176 km^2 MAP : 360 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	200.0	50.0	-	0.0	0.0	380.0	1.5	0.0	-	0.0

Gauge : J2R002 Catchment area : 2222 km^2 MAP : 210 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	0.0	290.0	1.5	0.3	-	0.0

Gauge : J3R001 Catchment area : 1505 km^2 MAP : 470 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
2.0	0.0	200.0	6.0	-	0.0	40.0	380.0	1.5	0.2	-	0.0

Gauge : J3H004 Catchment area : 4330 km^2 MAP : 240 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	0.0	440.0	1.5	0.3	-	0.0

Gauge : N1R001 Catchment area : 3740 km^2 MAP : 370 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	10.0	500.0	1.5	0.3	-	0.0

Gauge : N2R001 Catchment area : 16985 km^2 MAP : 315 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	0.0	420.0	1.5	0.3	-	0.0

Gauge : Q1R001 Catchment area : 4483 km^2 MAP : 365 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	20.0	500.0	1.5	0.3	-	0.0

Gauge : Q4R001 Catchment area : 4460 km^2 MAP : 410 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
-	0.0	100.0	0.0	-	0.0	0.0	430.0	1.5	0.3	-	0.0

Gauge : R2H001 Catchment area : 28 km^2 MAP : 1690 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	300.0	20.0	-	0.0	-	-	8.0	0.0	-	0.5

Gauge : T5H007 Catchment area : 3559 km^2 MAP : 1020 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	100.0	35.0	10.0	0.0	-	-	1.5	0.3	2.0	0.5

Gauge : V6H002 Catchment area : 12862 km^2 MAP : 920 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	100.0	35.0	-	0.0	-	-	1.5	0.3	-	0.5

Gauge : W4H002 Catchment area : 7122 km^2 MAP : 890 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	150.0	35.0	-	0.0	-	-	1.5	0.3	-	0.5

Gauge : X1H001 Catchment area : 5444 km^2 MAP : 870 mm

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
3.0	0.0	200.0	22.0	6.0	0.0	-	-	1.5	0.3	3.0	0.5

Appendix D : The Universal Soil Loss Equation (USLE)

(This information from Crosby, Smithen and McPhee, 1981, unless referenced otherwise)

D1 Introduction

The sediment produced by the erosion of sloping lands, gullies and streambeds and transported to surface water is generally recognized as the greatest single pollutant from non-point sources. Sediment reduces water quality and often degrades deposition areas. Sediment occupies space needed for water in storage reservoirs, lakes and ponds; restricts streams and drainageways; alters aquatic life and reduces the recreational and consumptive use value of water through turbidity. More importantly, sediment, particularly that produced from eroded topsoil, carries other water pollutants such as nitrogen, phosphorus, organic matter, pesticides and pathogens (McElroy *et al.*, 1976).

Erosion of soil by water can take a variety of forms. Sheet erosion is the uniform removal of a thin layer of soil, normally by the impact of falling raindrops. Channel erosion exists as rill erosion, gully erosion, and streambank erosion, caused by detachment and transportation of sediment by flowing streams of water. Rill erosion is the result of soil removal by small concentrations of soil water such as that often found between rows of cultivated crops planted up and down slopes. Channels formed in rill erosion are small enough to be smoothed completely by cultivation methods (McElroy *et al.*, 1976).

Gully erosion, similar to rill erosion, is also caused by temporary concentration of surface runoff. However erosion by gullying cuts deeply enough into soil/subsoil that channels so formed cannot be smoothed completely by ordinary tillage tools (McElroy *et al.*, 1976).

Streambank erosion refers to carrying off of the soil material on the sides of a permanent streambed, including those with intermittent flow, by the energy of moving water. Sediments are also produced from mass soil movement, which is the downslope movement of a portion of land surface under the effect of gravity (McElroy *et al.*, 1976).

D1.1 *Mechanics of erosion*

In general the most important contributor of sediment is surface erosion. Erosion agents including water, wind and rain splash, work continuously to break down the earth's surface to produce sediment from cropland, forests, pastures, construction sites and mining sites.

The basic mechanisms of soil erosion by water consist of :

a) soil detachment by raindrops,
b) transport by rainfall,
c) detachment by runoff, and
d) transport by runoff.

The damage caused by raindrops hitting the soil at a high velocity is the first step in the erosion process. Raindrops shatter the soil granules and clods, reducing them to smaller particles and thereby reducing the infiltration capacity of soil. The force of the raindrops also carries the splashed soil, resulting in movement of soil downslope.

When the rate of rainfall exceeds the rate of infiltration, depressions on the surface fill and overflow, causing runoff. Runoff water breaks suspended soil particles into smaller sizes, which helps to keep them in suspension (McElroy *et al.*, 1976).

D1.2 *Factors affecting surface erosion*

Factors which have been considered the most significant in affecting erosion of top soil consist of (McElroy *et al.*, 1976) :

a) Rainfall characteristics : define the ability of the rain to splash and erode soil. Rainfall energy is determined by drop size, velocity and intensity characteristics of rainfall.

b) Soil properties : affect both detachment and transport processes. Detachment is related to soil stability, basically the size, shape, composition, and strength of soil to water, which determines infiltration capabilities and drainage characteristics; by porosity, which affects storage and movement of water; and by soil surface roughness, which creates a potential for temporary detention of water.

c) Slope factors : define the transport portion of the erosion process. Slope gradient and slope length influence the flow and velocity of runoff.

d) Land cover conditions : affect detachment and transportation of soil. Land cover by plants and their residues provides protection from impact of raindrops. Vegetation protects the ground from excessive evaporation, keeps the soil moist, and thus makes the soil aggregates less susceptible to detachment. In addition, residues and stems of plants furnish resistance to overland flow, slowing down runoff velocity and reducing erosion.

e) Conservation practices : concern modification of the soil factor or the slope factor, or both, as they affect the erosion sequence. Practices for erosion control are designed to do one or more of the following: (a) dissipate raindrop impact forces; (b) reduce quantity of runoff; (c) reduce runoff velocity; and (d) manipulate soils to enhance the resistance to erosion.

D1.3 *Affect of man's activities on surface erosion*

Man alters surface erosion primarily by changing cover and altering the hydraulic system through which the water and sediment are transported. Activities which impact surface erosion can be categorised into four classes : cropping practices, silviculture activities, mining activities and construction activities. Depending on the initial status of the land and the nature of activity a wide range of impact can be expected (McElroy *et al.*, 1976).

D1.3.1 Surface erosion from croplands

Cropping practices change the soil cover so that it favours one type of plant and discourages the growth of others. The practices expose the soil and leave it loose and liable to erosion. Soil erosion can be affected by cropping practices such as tillage, irrigation, planting, fertilization, and residue disposition (McElroy *et al.*, 1976).

Tillage detaches soil and promotes oxidation of organic matter in soils. These processes decrease aggregation and reduce the infiltration capacity. Ploughing creates a plough pan. Agricultural machinery compresses the soil, reducing large-pore space, and consequently, its infiltration capacity. All this results in higher runoff and erosion rates.

Crop planting varies in its effect on erosion, depending on the species, the stand density, the distance between the rows, and the direction of the rows with respect to the slope. The denser and the more nearly on the contour the planting is made, the less erosion will result.

Fertilization helps to ensure stands, causes faster and heavier growth, and is consequently a help in protecting the soil and in creating beneficial residues. Manure can serve both as a fertilizer and a ground cover.

Crop residues help to protect soil from detachment by rainfall and runoff. They also contribute to making up organic matter in soils and therefore increase soil stability against water erosion.

D1.3.2 Surface erosion from forests

Forestland generally can be characterized by: (a) a vegetative canopy above the ground surface; (b) a layer of decayed and undecayed plant remains on the surface; and (c) a system of living and dead roots within the soil body. These conditions insulate the soil against the impact of rain, obstruct overland flow, and retard movement of soil by water action. These conditions reduce erosion and sediment production to a minimum (McElroy *et al.*, 1976).

Major causes of erosion on forestlands include :

a) Damage to cover from cutting, logging, and reforestation activities, and construction of roads and fire breaks.

b) Damage to cover because of fire, grazing, and recreational activity.

c) Damage on land reverting to forest cover from other land use, such as strip mines, and on which adequate cover conditions have not developed.

D1.3.3 Surface erosion from pastures

The dense cover of grasses, legumes, and other low growing plants is generally effective in protecting the soil from erosion by rainfall and runoff. Consequently, the amount of erosion from a well-managed pasture is small.

Overgrazing is the major cause of accelerated erosion on pasturelands. The grazing animals may eat the forage down to the ground, lessening the effectiveness of plants in intercepting the raindrops. Open spots on pasturelands can erode as rapidly as cultivated fields (McElroy *et al.*, 1976).

D1.4 *Sediment delivery ratio*

Sediment loadings to surface waters are dependent on erosion processes at the sediment sources and on the transport of eroded material to the receptor water. Only a part of the material eroded from upland areas in a catchment is carried to streams or lakes. Varying proportions of the eroded materials are deposited at the base of slopes or on flood plains.

The portion of sediment delivered from the erosion source to the receptor water is expressed by the delivery ratio.

Factors affecting sediment delivery ratio - Many factors influence the sediment delivery ratio. Variations in delivery ratio may be dependent on some or all of the following factors and others not identified (McElroy *et al.*, 1976).

> **Proximity of sediment sources to the receptor water -** eg. channel-type erosion produces sediment that is immediately available to the stream transport system, and therefore has a high delivery ratio. Materials derived from surface erosion, however, often move only short distances and may lodge in areas remote from the stream, and therefore have a low delivery ratio.
>
> **Size and density of sediment sources -** when the amount of sediment available for transport exceeds the capability of the runoff transport system, deposition occurs and the sediment delivery ratio is decreased.
>
> **Characteristics of transport system -** runoff resulting from rainfall is the chief agent for transporting eroded material. The ability to transport sediment is dependent on the velocity and volume of water discharge.
>
> **Texture of eroded material -** in general, the delivery ratio is higher for silt or clay soils than for coarse textured soils.
>
> **Availability of deposition areas -** deposition of eroded material mostly occurs at the foot of upland slopes, along the edges of valleys and in valley flats.
>
> **Relief and length of watershed slopes -** the relief ratio of a catchment has been found to be a significant factor influencing the sediment-delivery ratio. The relief ratio is defined as the ratio between the relief of the catchment between the minimum and maximum elevation, and the maximum length of catchment.

D2 History

Throughout the USA and particularly in the Corn Belt run-off plots were established in the years after the depression and droughts of the 1930's in order to obtain practical soil conservation data. Soil loss equations were first developed in 1940 and were refined during the early 1950's. The USLE was developed at the National Run-off and Soil Loss Data Centre which was established in 1954 by the USDA in co-operation with Purdue University. Data from 49 locations which contributed 10 000 plot years of basic run-off and soil loss data were statistically analyzed by Wischmeier and Smith (1978) who managed to create order out of the masses of often apparently unrelated data and to reduce the complexities of soil loss to manageable proportions. After 1960 rainfall simulators were used on field plots in 16 states to fill some of the gaps in the data needed for factor evaluation. Developments since 1965 have expanded the use of the USLE by providing techniques for estimating site values of its factors for alternative land uses, climate conditions and management practices.

It is important to appreciate that the USLE was initially developed statistically from a wealth of data and that the component factors have a statistical and not a physical origin. The equation is essentially valid for estimating average annual soil loss due to sheet and rill erosion over a long period of time (10-20 years), and is not intended to provide soil loss estimates for individual storms or single seasons.

The USLE soil loss equation is :

$$A = RKLSCP$$

in which :
- A = the computed soil loss per unit area (t/ha),
- R = the rainfall and run-off factor,
- K = the soil erodibility factor,
- L = the slope-length factor,
- S = the slope-steepness factor,
- C = the cover and management factor, and
- P = the support practice factor.

D3 The Individual Factors

The USLE was developed in the USA but has subsequently been used in other countries with success. It has its critics but remains the best estimator available. Input data has been developed experimentally in the USA and some other countries but not in South Africa. We shall now consider each factor individually and assess the availability of suitable input data for the application of the equation in South Africa.

D3.1 *Rainfall and runoff factor (R)*

Rills and sediment deposits observed after an unusually intense storm have sometimes led to the conclusion that significant erosion is associated with only a few storms, or that it is solely a function of peak intensities. However, more than 30 years of measurement in the USA and elsewhere have shown that this is not the case. The data show that a rainfall factor used to estimate average annual soil loss must include the cumulative effects of the many moderate-sized storms, as well as the effect of the occasional severe ones.

The numerical value used for R in the soil loss equation must quantify the raindrop impact effect and the amount and rate of run-off likely to be associated with the rain.

R is the so-called EI_{30} factor. By definition the value of EI_{30} for a given rainstorm equals the product of total storm energy (E) times the maximum 30 minute intensity (I_{30}). The product term, EI, is a statistical interaction term that reflects how total energy and peak intensity are combined in each particular storm. Technically it indicates how particle detachment is combined with transport capacity.

EI_{30} does not explain all discrepancies, there are other rainfall factors that can be used and which might provide better estimates under specific localised conditions but EI_{30} appears adequate and generally applicable and is internationally accepted. Smithen (1980) has developed EI_{30} values for the Republic which can be used with confidence. Representative values are provided in Table D1. Values for locations within the main regions have been extrapolated and can be found in Crosby, Smithen and McPhee (1981). Figure D1 shows estimated average EI_{30} values for southern Africa.

Table D1 EI_{30} values for representative stations

Location	Years of data	Average	Lowest	Highest
Pretoria	19	294	86	432
Pietersburg	19	223	79	382
Jan Smuts	23	206	99	658
Bloemfontein	19	142	32	408
Durban	19	364	144	642
Port Elizabeth	19	158	35	1007
D.F. Malan	20	66	23	122

D3.2 *Soil erodibility factor (K)*

The meaning of the term 'soil erodibility' is distinctly different from that of the term 'soil erosion'. The soil loss, A, in the soil loss equation, may be influenced more by land slope, rainstorm characteristics, cover, and management than by inherent properties of the soil. However, some soils erode more readily than others even when all other factors are the same. This difference, caused by properties of the soil itself, is referred to as the soil erodibility. Differences in the natural susceptibilities of soil to erosion are difficult to quantify from field observation. Even a soil with a relatively low erodibility factor may show signs of serious erosion when it occurs on long or steep slopes and/or in localities with numerous high-intensity rainstorms. A soil with a high natural erodibility factor, on the other hand, may show little evidence of actual erosion under gentle rainfall when it occurs on short and gentle slopes, or when the best possible management is practised. The effects of rainfall differences, slope, cover, and management are accounted for in the prediction equation by the symbols, R, L, S, C and P. Therefore, the soil erodibility factor, K, must be evaluated independently of the effects of the other factors.

Initially K had to be obtained experimentally but a nomograph was developed which enabled K to be estimated from the mechanical analysis of the soil. Unfortunately it requires that the fine sand fraction must be divided into very fine sand and sand (0.10 mm forming the dividing line) which is not commonly done in mechanical analysis in South Africa. The nomograph is presented in Figure D2. Care must be taken in interpreting the 'soil structure' component in the top right hand corner. This refers to structure and not tilth and 'very fine granular' is a 'good' soil more erosion resistant than 'blocky, platy or massive' which is a 'bad' soil. The nomograph can be used in South Africa provided it is limited to 'normal' soils; sodic soils would, for example, yield different results.

Approximate K values can be allocated to each soil form and series in terms of the rating given in Tables D2 and D3.

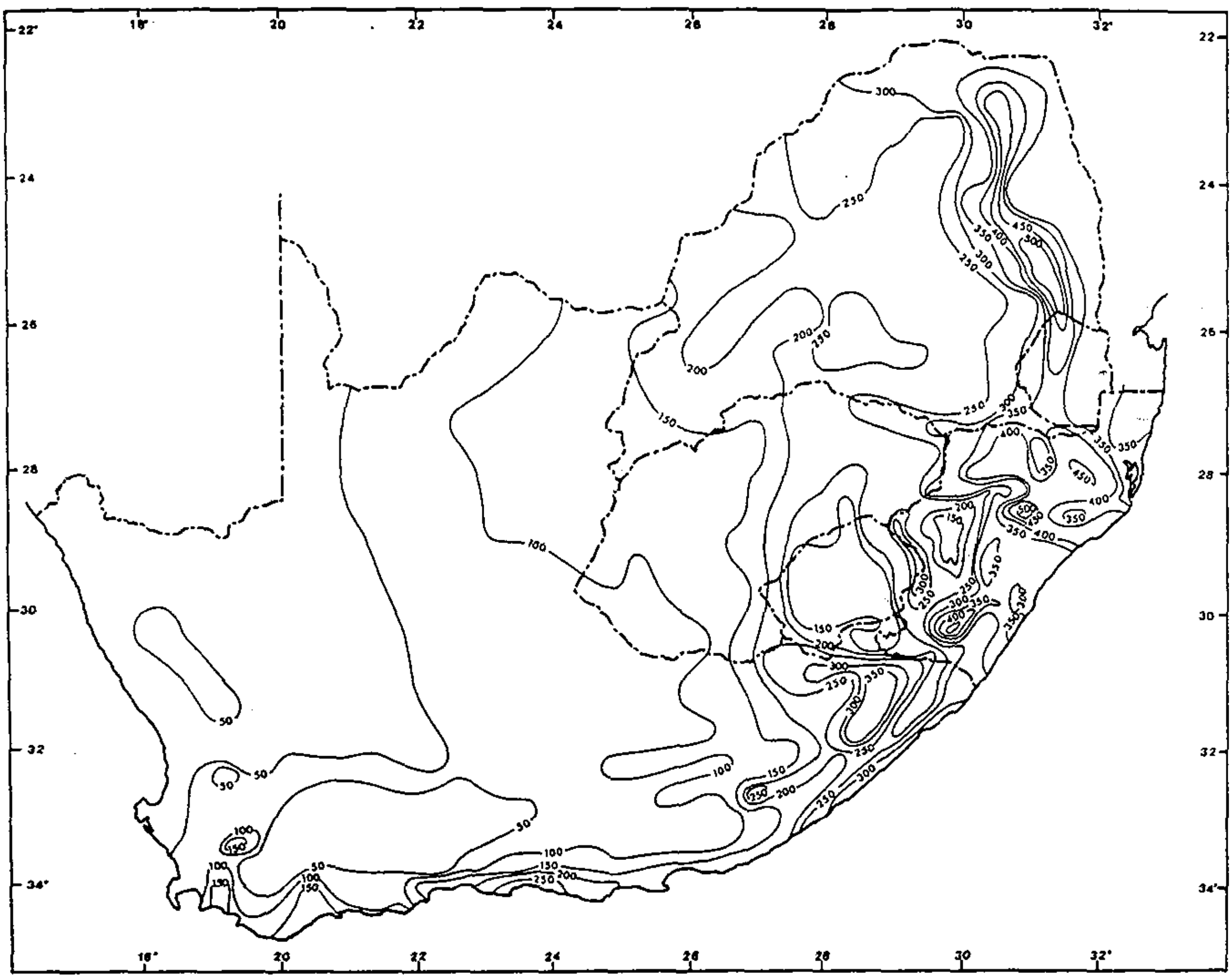

Figure D1 Estimated average annual EI_{30} values (Smithen and Schulze, 1982)

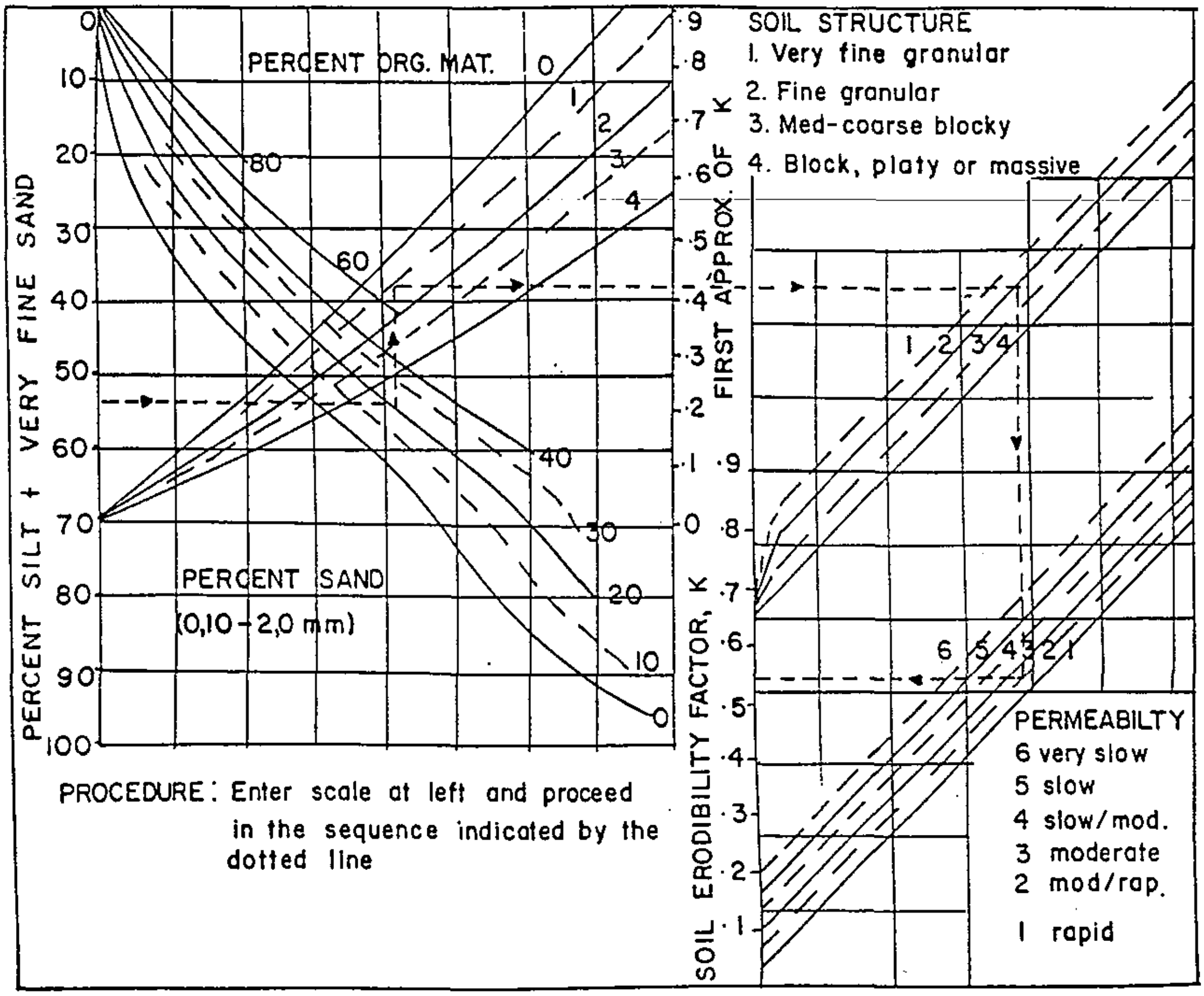

Figure D2 Soil erodibility nomograph

Table D2 K values for erodibility classes

Erodibilty Class	K value
Very high	> 0.70
High	0.50-0.70
Moderate	0.25-0.50
Low	0.13-0.25
Very low	< 0.13

Table D3 Erodibility rating for selected South African soils

Code/Series	Erodibility
Avalon Form	
Av 13 Ashton	High
Av 26 Avalon	Mod.
Av 27 Bergville	Low
Av 24 Leksand	High
Av 17 Normandien	V. low
Av 16 Ruston	Low
Bonheim Form	
Bo 41 Bonheim	Mod.
Bo 30 Dumasi	Mod.
Bo 31 Glengazi	Low
Bo 40 Weenen	High
Cartref Form	
Cf 12 Arrochar	High
Cf 13 Byrne	Low
Cf 21 Cartref	High
Cf 22 Cranbrook	Mod.
Cf 11 Rutherglen	High
Clovelly Form	
Cv 33 Annandale	High
Cv 36 Blinkklip	Mod.
Cv 17 Clovelly	V. low
Cv 47 Klippan	Low
Cv 27 Newport	V. low
Cv 16 Oatsdale	Mod.
Cv 23 Ofasi	High
Cv 26 Southwold	Low
Cv 13 Vidal	High
Estcourt Form	
Es 36 Estcourt	High
Es 14 Grasslands	V. high
Es 16 Rosmead	High
Es 34 Uitvlugt	V. high

Table D3 Continued

Code/Series	Erodibility
Fernwood Form	
Fw 11 Ferwood	High
Glenrosa Form	
Gs 15 Glenrosa	Mod.
Gs 18 Robmore	Low
Gs 19 Saintfaiths	V. low
Gs 23 Southfield	High
Griffin Form	
Gf 12 Griffin	V. low
Gf 30 Runnymeade	High
Gf 21 Umzimkulu	Low
Hutton Form	
Hu 18 Balmoral	V. low
Hu 24 Clansthal	Mod.
Hu 27 Doveton	V. low
Hu 17 Farningham	V. low
Hu 16 Hutton	Low
Hu 26 Msinga	Low
Hu 28 Vimy	Low
Inanda Form	
Ia 11 Inanda	V. low
Katspruit Form	
Ka 10 Katspruit	Mod.
Kroonstad Form	
Kd 17 Avoca	High
Kd 13 Kroonstad	V. high
Kd 14 Mkambati	V. high
Kd 19 Volksrust	Mod.
Longlands Form	
Lo 22 Albany	Mod.
Lo 21 Longlands	High
Lo 11 Waaisand	High
Lo 13 Winterton	Low

Table D3 Continued

Code/Series	Erodibility
Mispah Form	
Ms 23 Mispah	High
Oakleaf Form	
Oa 43 Allanridge	High
Oa 36 Jozini	Low
Oa 37 Koedoesvlei	V.low
Oa 30 Oakleaf	High
Rensburg Form	
Rg 20 Rensburg	High
Shortlands Form	
Sd 21 Glendale	Low
Sd 20 Kinross	Mod.
Sd 22 Shortlands	Low
SterkSpruit Form	
Ss 27 Antioch	High
Ss 23 Stanford	V. high
Ss 26 Sterkspruit	High
Swartland Form	
Sw 32 Hogsback	Mod.
Sw 30 Rosehill	High
Sw 31 Swartland	High
Westleigh Form	
We 12 Rietvlei	Mod.
We 13 Sibasi	Low
We 11 Westleigh	High

D3.3 *Topographic factor (LS)*

Both the length and steepness of the land slope substantially affect the rate of soil erosion by water. The two effects have been evaluated separately in research and are presented in the soil loss equation by L and S, respectively. In field applications, however, considering the two as a single topographic factor, LS, is more convenient.

LS is the ratio of soil loss per unit area from a field slope to that from a 22 m length of uniform 9 percent slope under otherwise identical conditions. This ratio for specified combinations of field slope length and uniform gradient may be obtained directly from the slope-effect chart given in Figure D3.

Slope length is defined as the distance from the point of origin of overland flow to the point *where either the slope gradient decreases enough that deposition begins, or the run-off water enters a well-defined channel that may be a part of a drainage network or a constructed channel. Thus in a contoured land, the slope length, L, would be equal to the distance between contours (Schmidt, 1989). A change in land cover or a substantial change in gradient along a slope does not begin a new slope length for purposes of soil loss estimation.*

The effect of slope length on annual run-off per unit area of cropland may generally be assumed negligible. However, the soil loss per unit area generally increases substantially as slope length increases. The greater accumulation of runoff on the longer slopes increases its detachment and transport capacities. Run-off from cropland generally increases with increased slope gradient, but the relationship is influenced by such factors as type of crop, surface roughness, and profile saturation. Soil loss increases much more rapidly than run-off as slopes steepen.

The slope gradient factor is expressed as the mean catchment slope (%) and is obtained from topographic maps (Schmidt, 1989).

In practice the curves are sufficient to determine the LS factor but sophisticated modifications for varying slopes etc. are available. There are doubts on the validity of the LS factor outside the L range 10 m - 100 m. There is no reason to believe that relationships in South Africa will differ from the standards developed in the USA and we have nothing to lose by accepting the LS factor as modified in the USA from time to time.

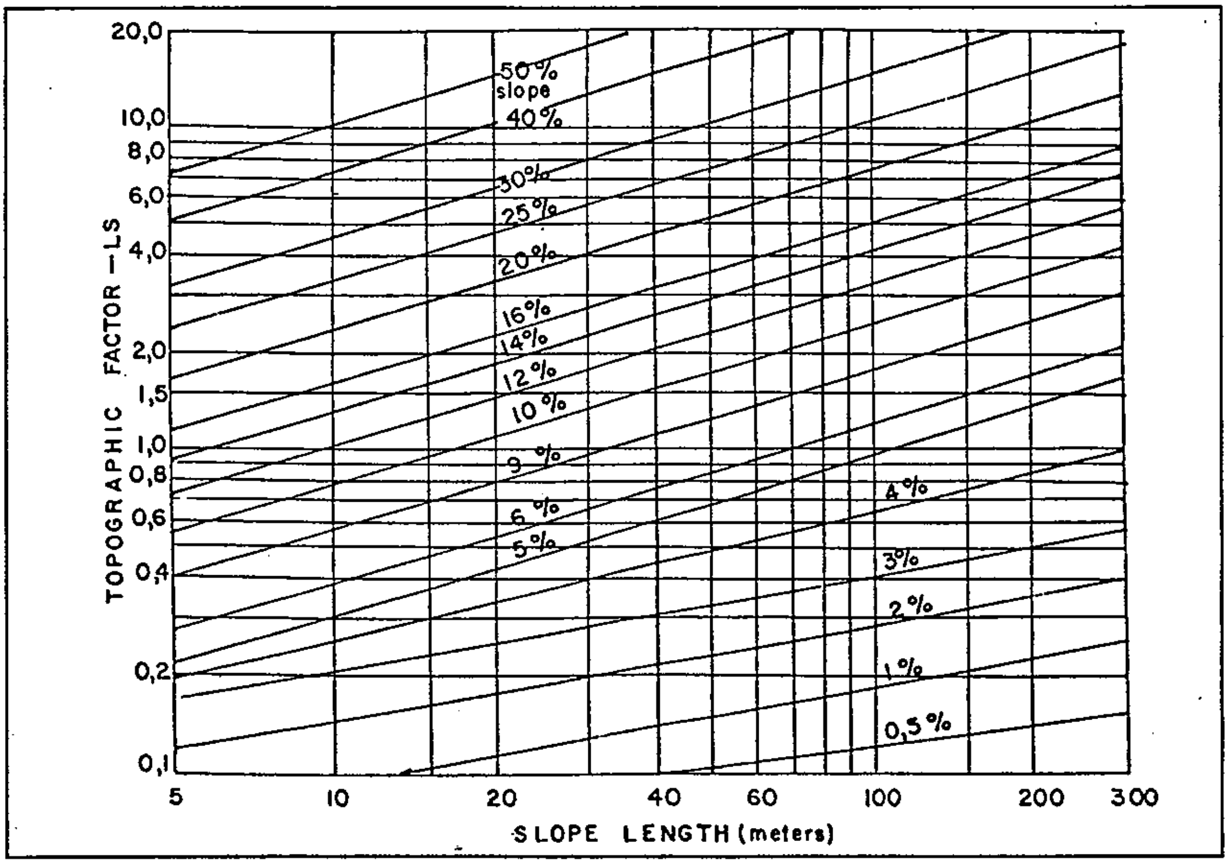

Figure D3 Slope-effect chart

The slope length (in metres), is often difficult to estimate in the field but can be related to slope gradient S (Williams and Berndt, 1977), and has been given by Schulze (1979) as :

$$L = 100 - (3S) \qquad \text{for } S < 25\%$$

and

$$L = 25 \qquad \text{for } S \geq 25\%$$

The equation used to generate the slope-effect chart shown in Figure D3 is given by Schmidt (1989) as :

$$LS = (L/22.1)^m * ([0.043S^2 + 0.3S + 0.43]/6.613)$$

in which : L = slope length (m) determined by equation or from field layout,
S = slope of land (%), and
m = 0.2 for $S < 1\%$ (Mitchell and Bubenzer, 1980),
0.3 for $S \leq 3\%$ and $S \geq 1\%$,
0.4 for $S < 5\%$ and $S > 3\%$, and
0.5 for slope $\geq 5\%$

D3.4 *Cover and management factor (C)*

Cover and management effects cannot be independently evaluated because their combined effect is influenced by many significant interrelations. Almost any crop can be grown continuously, or it can be grown in rotations. Seedbeds can be clean cultivated, or they can be protected by prior crop residues. They can be left rough, with much available capacity for surface storage and reduction of run-off velocity, or they can be smoothed by secondary tillage.

Crop residues can be removed, left on the surface, incorporated near the surface, or ploughed under. When left on the surface, they can be chopped or dragged down, or they can be allowed to remain as left by the harvesting operation. The effectiveness of crop residue management will depend on the amount of residue available. This, in turn, depends on the amount and distribution of rainfall, on the fertility level, and on the management decisions made by the farmer.

The canopy protection of crops not only depends on the type of vegetation, the stand, and the quality of growth, but it also varies greatly in different months or seasons. Therefore, the overall erosion-reducing effectiveness of a crop depends largely on how much of the erosive rain occurs during those periods when the crop and management practices provide the least protection.

Factor C in the soil loss equation is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow. This factor measures the combined effect of all the interrelated cover and management variables.

The correspondence of periods of expected highly erosive rainfall with periods of poor or good plant cover differs between regions or locations. Therefore, the value of C for a particular cropping system will not be the same in all parts of the country. Deriving the *appropriate C values for a given locality requires knowledge of how the erosive rainfall in that locality is likely to be distributed through the 12 months of the year and how much erosion control protection the growing plants, crop residues, and selected management practices will provide at the time when erosive rains are most likely to occur.*

Quantitative evaluation of crop and management effects.

Leaves and branches that do not directly contact the soil have little effect on amount and velocity of run-off from prolonged rains, but they reduce the effective rainfall energy by intercepting falling raindrops. Waterdrops falling from the canopy may regain appreciable velocity but less than the terminal velocities of free-falling raindrops. The amount by which energy expended at the soil surface is reduced depends on the height and density of the canopy.

Residue mulches and stems from close-growing vegetation are more effective than equivalent percentages of canopy cover. Mulches intercept falling raindrops so near the surface that the drops regain no fall velocity, and they also obstruct run-off flow and thereby reduce its velocity and transport capacity.

If the cover includes both canopy and mulch, the two are not fully additive; the impact energy of drops striking the much is dissipated at that point regardless of whether canopy interception has reduced its velocity.

In the USA where crop rotations including 'grass' crops are common and conservation tillage is becoming increasingly practised, residual effects are important; but in South Africa they can probably be ignored. It appears that with information available to agronomists in South Africa it is possible to estimate canopy and mulch cover for various tillage practices, which permits the estimation with a reasonable degree of accuracy.

The rainfall and run-off factor, R, in the soil loss equation does not completely describe the effect of local differences in rainfall pattern on soil erosion. The erosion control effectiveness of a cropping system on a particular field depends, in part, on how the year's erosive rainfall is distributed. Therefore, expected monthly distribution of erosive rainfall at a particular location is an element in deriving the applicable value of cover and management, C.

Smithen (1980) has developed monthly EI_{30} distribution for the main areas in South Africa which can be used in computing the C factor.

Representative data are presented in Table D4 for five major stations - Pretoria, Bloemfontein, Grootfontein (Cape), Durban and Port Elizabeth. The total EI_{30} values (commencing date July 1) for a 12 month period are divided into five equal amounts each representing a 20% increase in the cumulative EI_{30} value and the date on which each period ends is given. For example, in the case of Pretoria, 20% of the average annual EI_{30} is experienced by November 17, 40% by December 20, 60% by January 15 and so on.

Table D4 Annual 1 July - 30 June distribution of EI_{30} for some major stations

Period	% of total EI_{30} values	Pretoria	Bloemfon-tein	Grootfon-tein	Durban	Port Elizabeth
1	20	Nov. 17	Dec. 7	Nov. 22	Nov. 1	Sep. 1
2	40	Dec. 20	Jan. 3	Jan. 28	Jan. 8	Nov. 20
3	60	Jan. 15	Feb. 1	Feb. 20	Feb. 5	Mar. 1
4	80	Feb. 14	Feb. 9	Mar. 15	Feb. 22	Apr. 20
5	100	Apr. 7	Mar. 22	May 7	May 1	Jun. 7

This information is shown graphically in Figure D4.

In order to establish the average annual C value one must consider the protection afforded to the soil in relation to the number of EI_{30} units to which it is subjected. The protection afforded can be considered in three categories (all components of C) viz. canopy cover, mulch cover and tillage residual/effect.

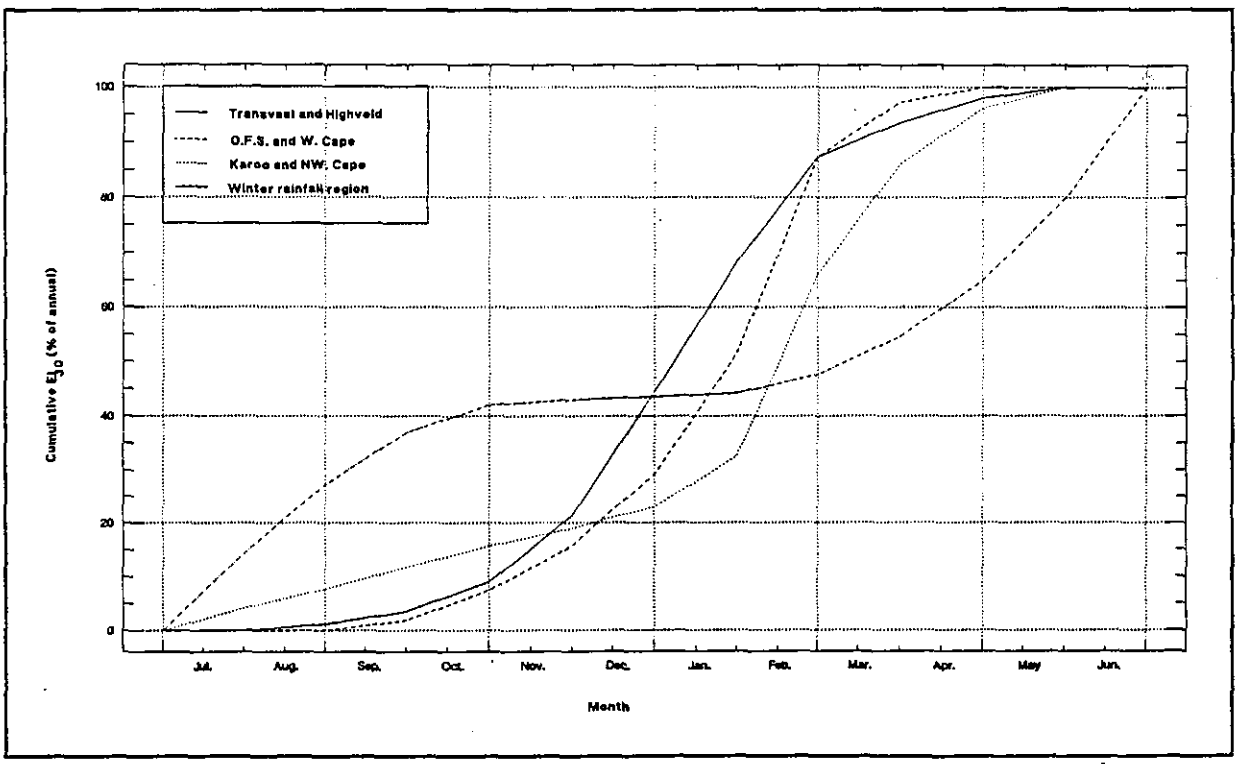

Figure D4 Typical EI_{30} distribution curves for the indicated areas (Smithen, 1981)

The effects of the first two sub-factors are normally considered together, and values for the soil-loss ratio are obtained from Figure D5 which provides combined canopy and mulch effects. As an example, consider mature maize (average fall of drops from canopy 1 m, with a canopy cover of 80%) in the two cases when there is no mulch and when there is a mulch cover of 40%. The soil-loss ratio will be 0.47 and 0.20 respectively. In the case of cultivated crops these two graphs can be used to estimate the soil-loss ratio at any stage of crop growth provided reasonably good estimates are made of canopy and mulch cover.

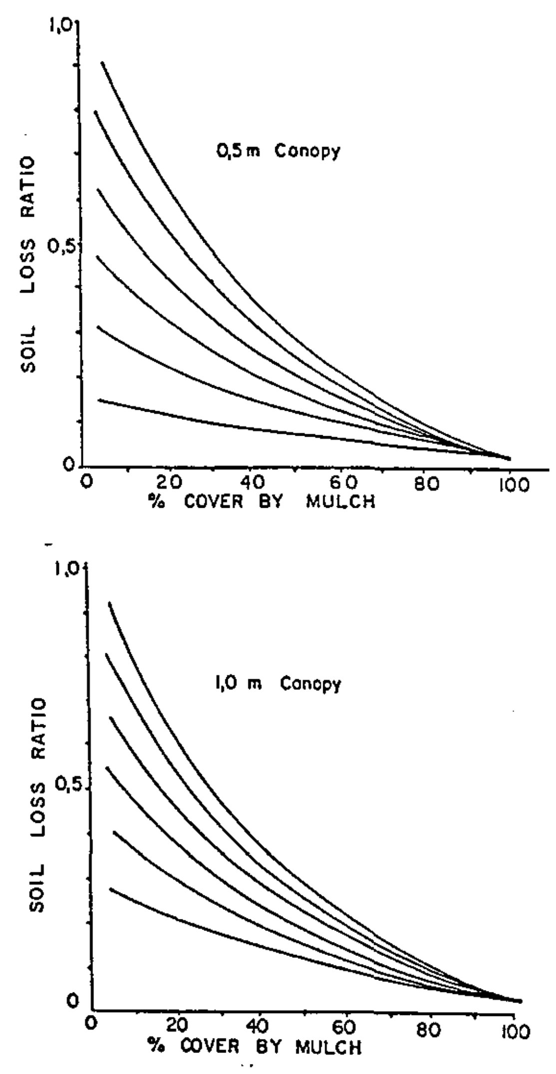

Figure D5 Combined mulch and canopy effects when average fall distance of drops from canopy to the ground is 0.5m and 1.0m

The third sub-factor is more difficult to assess. It is suggested that 0.50 be used for periods when the seed bed is cloddy or for the first year after a grass crop has been ploughed in. The application of this sub-factor requires further refining.

In order to arrive at an average annual C factor the growth habit and canopy cover of crops must be estimated over the season. There are various ways in which this can be done - the following method verges on the naive but can be regarded as a starting point. Plot the dates for cumulative EI_{30} values in 20% increments along the X-axis of a graph against percentage canopy cover curve. This will vary with crop but work undertaken by McPhee (1980) has provided guidelines. Typical characteristic curves for maize, potatoes and soyabeans are shown in Figure D6. In the case of maize, anticipated maximum cover can be related to plant population, as shown in Table D4, and date of peak canopy cover approximates to date of tasselling.

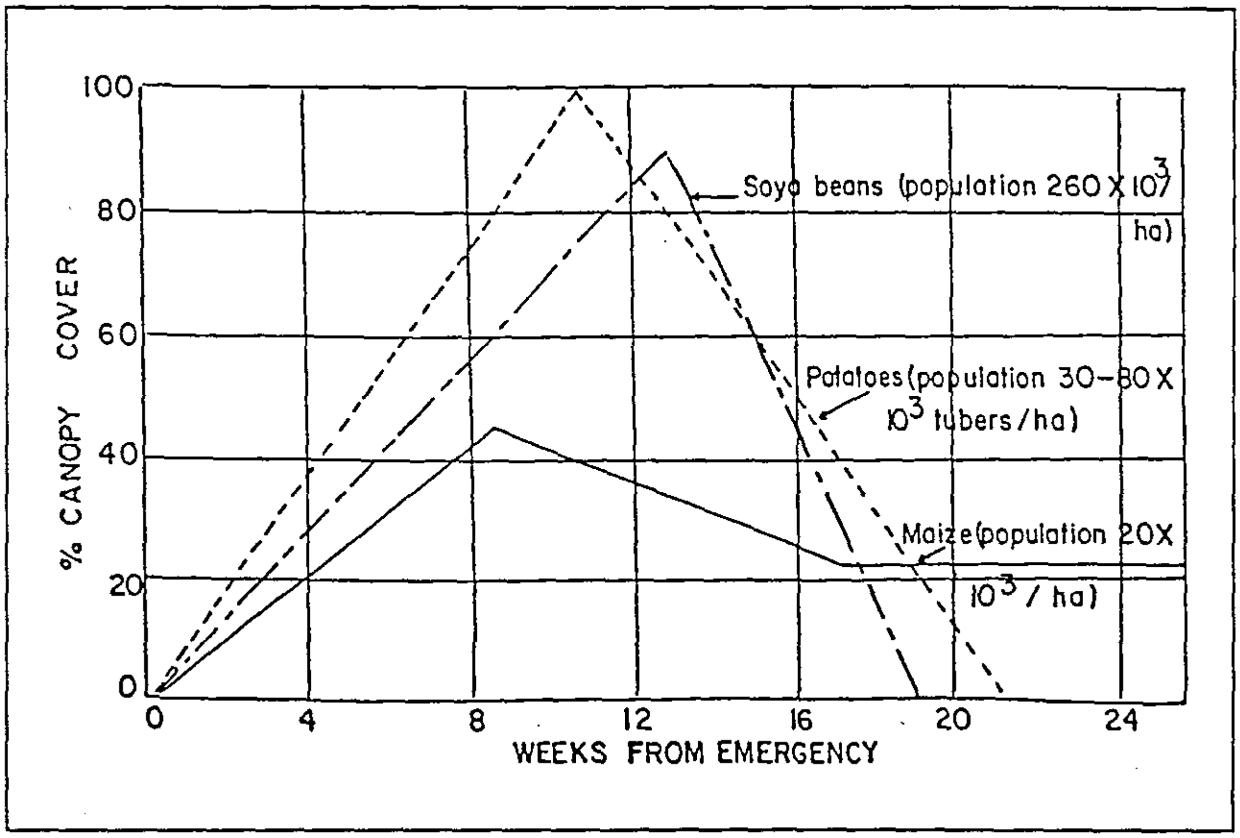

Figure D6 Schematic representation of typical canopy cover development for selected crops

Table D4 Approximate maximum canopy cover (%) of maize in relation to plant population

Plant pop./ha	10 000	20 000	30 000	40 000	50 000
Canopy cover (%)	30	40	50	60	70

It is now a relatively simple matter to complete a table in which average canopy cover for each 20% EI_{30} period is entered and to derive appropriate soil-loss ratio. The annual average C value is obtained by dividing the sum of the soil-loss ratios by the number of EI_{30} periods.

The following examples are given to demonstrate this approach :

a) Maize is planted in the vicinity of Pretoria with a plant population of 30 000 and emergence date 1 November. The plant residue cover (from previous season) is estimated at 20%. From mid-February onwards this cover is augmented by late summer grass growth which is not controlled by cultivation, resulting in a total estimated ground cover of 40%, below the canopy. The seedbed before planting is cloddy and tasselling is estimated in mid-January. The canopy cover graph is given in Figure D7.

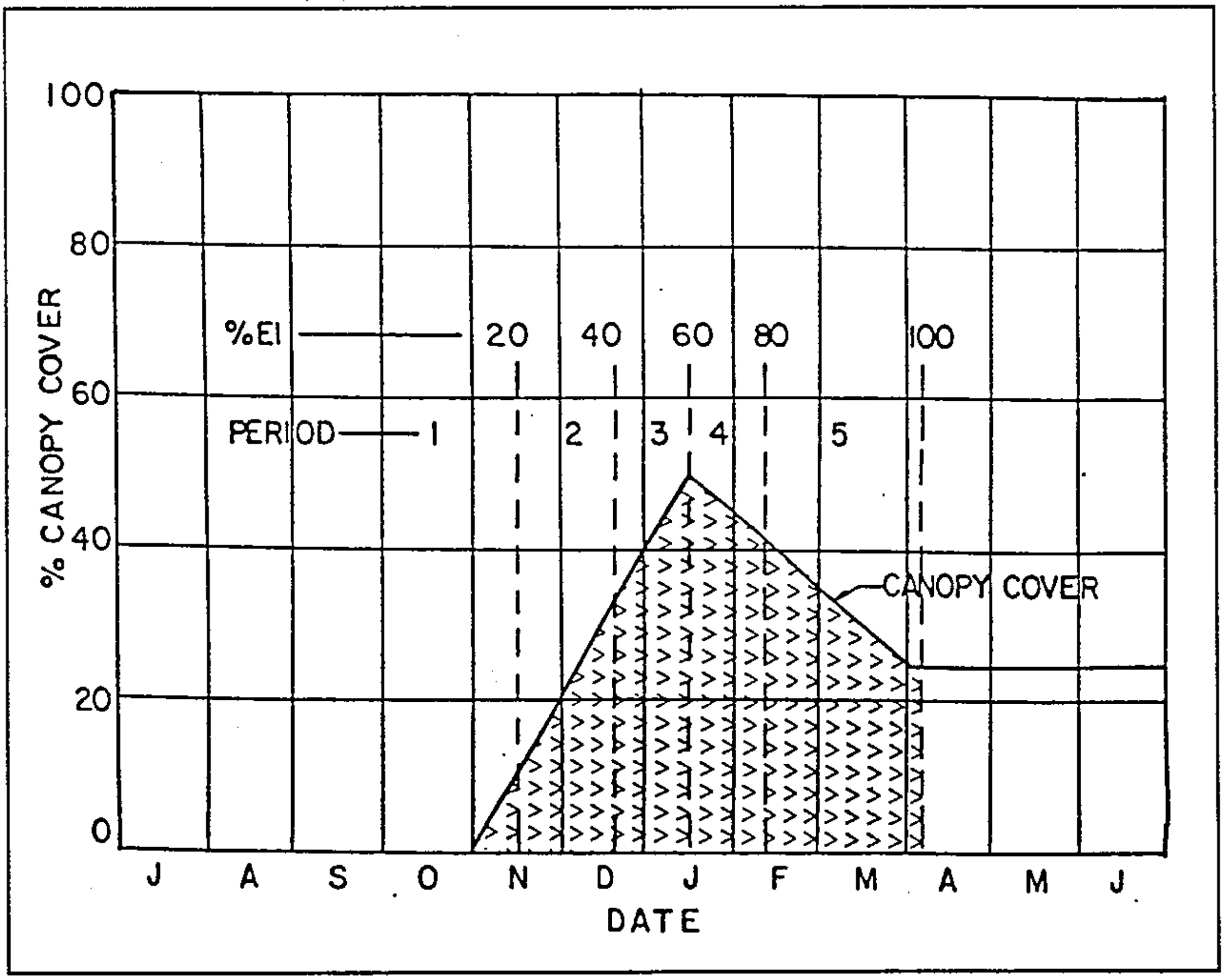

Figure D7 Canopy cover development for maize at Pretoria

It is now possible to develop the "C" table given as Table D5 below.

Table D5 "C" table for maize at Pretoria

Period	% of total annual EI_{30} values	Canopy cover (%)	Mulch cover (%)	Soil loss ratio (1)	Soil loss ratio (2)	Soil loss ratio (1) * (2)
1	20	0.5	20	0.60	0.5	0.30
2	40	22	20	0.52	1.0	0.52
3	60	42	20	0.38	1.0	0.38
4	80	45	20	0.43	1.0	0.43
5	100	32	40	0.33	1.0	0.33
						Σ=1.96

Average annual C = 1.96/5 = 0.39.

b) Potatoes are planted near Port Elizabeth and emergence date is 1 October. The crop is clean cultivated throughout but prior to planting the soil was cloddy with no residues. After maximum canopy the soil is compact until the potatoes are lifted at the end of April. When the canopy cover reaches 50% ridging reduces soil loss and permits a reduction by half in soil loss ratio. The canopy cover graph is given in Figure D8 and the "C" table as Table D.6.

Table D6 "C" table for potatoes at Port Elizabeth

Period	% of total annual EI_{30} values	Canopy cover (%)	Mulch cover (%)	Soil loss ratio (1)	Soil loss ratio (2)	Soil loss ratio (1) * (2)
1	20	0	0	1.00	0.50	0.50
2	40	20	0	0.90	1.00	0.90
3	60	58	0	0.62	0.25*	0.15
4	80	0	0	0.50	0.25*	0.13
5	100	0	0	1.00	1.00	1.00
						Σ=2.68

* 50% reduction for ridging

Average annual C = 2.68/5 = 0.53.

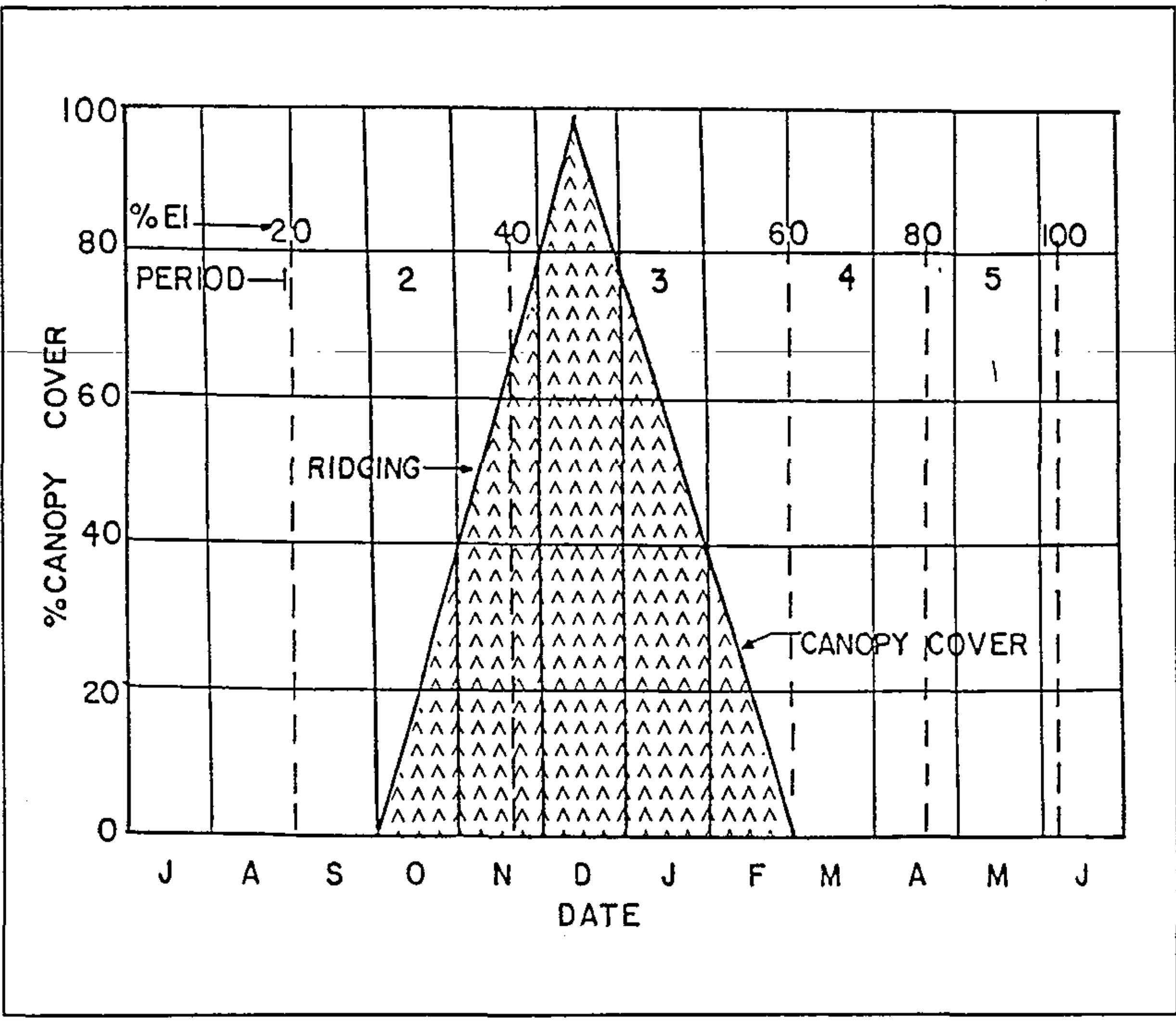

Figure D8 Canopy cover development for potatoes at Port Elizabeth

Quantitative evaluations of the C factor for undisturbed land

The approach in the cases of pasture, veld, bush and forest is rather different. As a general rule the protection afforded to the soil does not vary significantly throughout the year and an annual average C value can be assumed.

In the case of veld, bush and forest, C depends on canopy cover and the cover that contacts the ground surface (basal cover). Table D7 can be used for estimating C values when cover can be estimated.

Table D7 "C" values for veld, bush and forest (after Wischmeier and Smith, 1978)

Vegetative canopy		Cover that contacts the ground surface						
		% ground cover						
Type & height	% cover	Type	0	20	40	60	80	95+
No appreciable canopy		G	.45	.20	.10	.042	.013	.003
		W	.45	.24	.15	.091	.043	.011
Tall weeds or short brush with average drop fall height of 0.5m	25	G	.36	.17	.09	.038	.013	.003
		W	.36	.20	.13	.083	.041	.011
	50	G	.26	.13	.07	.035	.012	.003
		W	.26	.16	.11	.076	.039	.011
	75	G	.17	.10	.06	.032	.011	.003
		W	.17	.12	.09	.068	.038	.011
Appreciable brush or bushes with average drop fall height of 1.95m	25	G	.40	.18	.09	.040	.013	.003
		W	.40	.22	.14	.087	.042	.011
	50	G	.34	.16	.08	.038	.012	.003
		W	.34	.19	.13	.082	.041	.011
	75	G	.28	.14	.08	.036	.012	.003
		W	.28	.17	.12	.078	.040	.011
Trees but no appreciable low brush. Average drop fall height of 3.9m	25	G	.42	.19	.10	.041	.013	.003
		W	.42	.23	.14	.089	.042	.011
	50	G	.39	.18	.09	.040	.013	.003
		W	.39	.21	.14	.087	.042	.011
	75	G	.36	.17	.09	.039	.012	.003
		W	.36	.20	.13	.084	.041	.011

The "C" values listed in Table D7 assume that the vegetation and mulch are randomly distributed over the entire area. Canopy height in column (1) is measured as the average fall height of water drops falling from the canopy to the ground. Canopy effect is inversely proportional to the drop fall height and is negligible if the fall height exceeds 10.4 metres. The percent cover in column (2) is the portion of the total surface area that would be hidden from view by canopy in a vertical projection (bird's eye view). The cover type in column (3) is denoted by "G" if the cover at the surface is grass, grasslike plants, decaying compacted duff, or litter at least 50 mm deep. The cover type is denoted by "W" if the cover at the surface is mostly broadleaf, herbaceous plants such as weeds with little lateral root network near the surface, or undecayed residues, or both.

Established pastures have a low C value and afford almost complete protection to the soil. Approximate "C" values are given in Table D8.

Table D8 Approximate "C" values for established pasture

Pasture type	"C"
Grass and legume mix (3-5 t hay yield)	0.004
Grass and legume mix (2-3 t hay yield)	0.006
Grass and legume mix (1 t hay yield)	0.01
Lucerne (well established)	0.02

Table D9 should be used to estimate cover factors for undisturbed forest land.

Table D9 C factor for undisturbed forest land (after Wischmeier and Smith, 1978)

% of area covered by canopy of trees and undergrowth	% of area covered by litter at least 50 mm deep	C factor
100 - 75	100 - 90	0.0001 - 0.001
70 - 45	85 - 75	0.002 - 0.004
40 - 20	70 - 40	0.003 - 0.009

D3.5 *Support practice factor (P)*

In general, whenever sloping soil is to be cultivated and exposed to erosive rains, the protection offered by sod or close-growing crops in the system needs to be supported by practices that will slow the run-off water and thus reduce the amount of soil it can carry. The most important of these supporting cropland practices are contour tillage, strip-cropping on the contour, and contour bank systems. Stabilized waterways for the disposal of excess rainfall are a necessary part of each of these practices.

By definition, factor P in the USLE is the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down-slope culture. Improved tillage practices, sod-based rotations, fertility treatments, and greater quantities of crop residues left on the field contribute materially to erosion control and frequently provide the major control in a farmer's field. However, these are considered conservation cropping and management practices, and the benefits derived from them are included in C.

D3.5.1 Working on the contour

The practice of tillage and planting on the contour, in general, has been effective in reducing erosion. In limited field studies, the practice provided almost complete protection against erosion from storms of moderate to low intensity, but it provided little or no protection against the occasional severe storms that caused extensive breakovers of the contoured rows. Working on the contour appears to be the most effective on slopes in the 3 to 8 percent range. As land slope decreases, it approaches equality with contour row slope, and the soil loss ratio approaches 1.0. As slope increases, contour row capacity decreases and the soil loss ratio again approaches 1.0.

Effectiveness of contour cultivation is also influenced by the slope length. In heavy storms when rainfall exceeds infiltration and surface detention, breakovers of contour rows often result in concentrations of run-off that tend to become progressively greater with increases in slope length. Therefore on slopes exceeding some critical length the amount of soil moved from a contoured field may approach or exceed that from a field on which each row carries its own run-off water down the slope. At what slope length this could be expected to occur would depend to some extent on gradient, soil properties, management, and storm characteristics.

D3.5.2 Contour banks

Contour banks combined with contour farming and other conservation practices are more effective than those practices without contour banks because they positively divide the slope into segments equal to the horizontal interval.

Values of P for contour cultivated fields with contour banks are given in Table D10.

However, recognize that the erosion control benefits of contour banks are much greater than indicated in the P values. Dividing a field slope into n approximately equal horizontal contour bank intervals divides the average soil loss per unit area by the square root of n. This important erosion control benefit of contour banks is not included in P because it is brought into the USLE computation through a reduced LS factor obtained by using the horizontal interval as the slope length.

D4 Estimating Total Sediment Delivery

Of the several methods now used for estimating sediment yield, the Gross Erosion-Sediment Delivery method uses the USLE. A brief description of this method follows. The equation is :

$$Y = E(DR)/W_s$$

where Y is sediment yield per unit area, E is the gross erosion, (estimated with the help of the USLE), DR is the sediment delivery ratio, and W_s is the area of the catchment above the point for which the sediment yield is being computed.

Table D10 P factor values for contour-farmed lands with contour banks

Land slope (%)	Contour factor	Contour banks with grassed waterways
1 to 2	0.60	0.12
3 to 8	0.50	0.10
9 to 12	0.60	0.12
13 to 16	0.70	0.14
17 to 20	0.80	0.16
21 to 25	0.90	0.18

D4.1 *Gross erosion*

Gross erosion is the summation of erosion from all sources within the watershed. It includes sheet and rill erosion from tilled cropland, meadows, pastures, woodlands, construction sites, abandoned acreages, and surface-mined areas; gully erosion from all sources; and erosion from streambeds and streambanks. The relative importance of each of these sources of gross erosion will vary between watersheds.

The USLE can be used to estimate the sediment generated by sheet and rill erosion that is usually, but not always, the major portion of a catchment's gross erosion. Sediment from gully, streambank and streambed erosion, and from uncontrolled roadsides must be added to the USLE estimates.

Erosion hazards are highly site specific. The parameters that determine the USLE factor values vary within a large catchment, and the variations are often not interrelated. Combining overall averages in the equation does not reflect the particular way in which the factors are actually combined in different parts of the catchment. Neither does it show which portion of the drainage area are contributing most of the sediment.

A more accurate procedure is to divide the heterogeneous drainage area into subareas for which representative soil type, slope length, gradient, cover, and erosion-control practice factors can be defined. The USLE is then used to compute the sheet and rill erosion on each sub-area. For this purpose, eroded soil that is entrapped within the field by contour banks is not soil loss. By this procedure, the sub-area soil loss computations identify the portions of the drainage area that contribute most of the sediment and also show how much of the sediment derives from tracts that receive heavy applications of the agricultural chemicals.

D4.2 *Sediment delivery ratio*

Eroded soil materials often move only a short distance before a decrease in run-off velocity causes their deposition. They may remain in the fields where they originated or may be deposited on more level slopes that are remote from the stream system. The ratio of sediment delivered at a given location in the stream system to the gross erosion from the drainage area above that location is the sediment delivery ratio for that drainage area. A general equation for computing watershed delivery ratios is not yet available.

Available USA catchment data indicate that the delivery ratio varies approximately as the 0.2 power of drainage-area size, with representative values for the ratio of about 0.33 for 1 km^2; 0.18 for 25 km^2 and 0.10 for 250 km^2. There were indications that the exponent in this relationship may be as small as 0.1 for very large areas. But the ratio may vary substantially for any given size of drainage area. Other important factors include soil texture, relief, type of erosion, sediment transport system, and areas of deposition within the catchment. Fine soil texture, high channel density, and high stream gradients generally indicate delivery ratios that are above average for the drainage-area size.

With reference to a field-sized area, the delivery ratio can closely approach 1.0 if the run-off drains directly into a lake or stream system with no intervening obstructions or flattening of the land slope. On the other hand, a substantial width of forest litter or dense vegetation below the eroding area may cause deposition of essentially all the sediment except colloidal material. Anything that reduces run-off velocity (such as reduction in gradient, physical obstructions, vegetation, and ponded water) reduces its capacity to transport sediment. When the sediment load exceeds the transport capacity of the run-off, deposition occurs.

D4.3 *Dealing with slope length in practice*

If a catchment can be realistically divided into sub-elements with overland flow draining into a channel, then the USLE does provide a means for estimating sediment delivery into the channel. In most cases this sheet and rill run-off will be well within the extrapolated L value of 300 m. Deposition and erosion in the channels then becomes a matter of sediment transport mechanics.

Inevitably experience must be a major factor in developing realistic estimates. Additional theories on detachment and deposition mechanisms and the influence of varying slopes are contained in the literature referred to in Handbook No. 537. One of the more useful techniques provides for concave and convex slopes provided no deposition takes place.

Naturally while the LS factor provides an estimate of the average soil loss over the full length of L the soil loss will, in practice, be greater on the lower reaches of the slope. Table D11 below enables an estimate to be made of the soil losses relative to the various segments.

Provided it is assumed that where a change in slope takes place the change in gradient is not sufficient to cause deposition and that irregular slope can be divided into a small number of equal length segments in such a manner that the gradient within each segment can be considered uniform, it is possible to make allowances for irregular slopes.

After dividing the convex, concave or complex slope into equal length segments the procedure is as follows: List the segment gradients in the order in which they occur on the slope, beginning at the upper end. Obtain the LS value from the chart for the full slope length but for the segment gradient and multiply by the factor from Table D11 above and add the products to obtain LS for the entire slope.

Table D11   Example of soil loss relative to slope segments

No. of segments	Sequence no.	Fraction soil loss
2	1 2	0.38 0.62
3	1 2 3	0.22 0.35 0.43
4	1 2 3 4	0.14 0.24 0.29 0.33
5	1 2 3 4 5	0.11 0.17 0.21 0.24 0.27

Compare two slopes divided into five segments with the same average slope of 10%. One is concave starting with a gradient of 20% and ending with 3% while the other is convex starting with a slope of 3% and ending with 20%. The results are given in Table D12.

A uniform 250m slope with a 10% gradient would have had a LS value of 4.0.

D4.4 *Sediment delivery ratios and slope gradients*

It is appreciated that the sediment delivery ratio concept is not universally accepted and that it is dependent on complex factors. Not the least of the problems in short term considerations is the flushing out of 'in transit' sediments by large floods. It is, however, a fact that stream gradient is a function of catchment area, the larger the catchment area, the flatter the valley gradient. In parts of the Karoo and East Cape (Beaufort Series) it has been found that stream gradient is inversely proportional to catchment area to the power of 0.4. Transverse gradients are related to longitudinal gradients. It appears that a close approximation to established sediment delivery ratios can be derived by calculating the LS factor according to the average landscape gradient and making allowance for average distance of overland flow to channels. One example is that for three catchments 1, 25, and 250 km^2 with computed gradients of 3.6%, 1.0% and 0.4% assumed slope lengths of 50 m, 90 m, and 100 m would bring sediment production into line with the USA assumed generalised sediment delivery ratios of 0.33, 0.18 and 0.10.

Table D12 Comparison of the LS factor for a convex and a concave slope

CONCAVE segment	% slope	LS	Value from Table D11	Product
1 (50m)	20	12.0	0.11	1.32
2 (50m)	13	5.7	0.17	0.97
3 (50m)	8	2.8	0.21	0.59
4 (50m)	6	1.9	0.24	0.46
5 (50m)	3	0.6	0.27	0.16
CONVEX segment				= 3.50
1 (50m)	3	0.6	0.11	0.07
2 (50m)	6	1.9	0.17	0.32
3 (50m)	8	2.8	0.21	0.59
4 (50m)	13	5.7	0.24	1.37
5 (50m)	20	12.0	0.27	3.24
				= 5.59

D5 The Practical Relationship between Sediment Production and Land Use

It is recognized that the development of deterministic models capable of predicting erosion processes and sediment deposition and transport is highly desirable. One wonders, however, if the problem of parameter transfer, which arises in hydrology, will prevent the practical application of such models even when they are developed. Possibly we will be well enough served in the immediate future by relying on present and improved sediments gauging and reservoir surveys in conjunction with the application of soil loss equations to help predict the affect of changing land use.

It would seem feasible to divide catchments into "soil loss response units" and to approach the question of deposition rationally in that deposition in contour banks and dense vegetation must receive special treatment. Practically speaking maximum slope lengths shorter than 300 m to drainage channels seem reasonable. In many parts of South Africa the drainage channels (even when these are dongas) are reasonably stable from the soil loss point of view. Similarly it is doubted if channel deposition is a major factor.

The essential element in relating soil loss to land use is the estimation of C and P and we have seen the drastic variations that can come about through changing agricultural patterns. C and P are valuable indicators that can supplement judgement.

It is strongly recommended that positive attempts be made to relate the established delivery of sediment into reservoirs to the erosion situation in catchment areas as estimated by the USLE. A calibration exercise of this nature would help to establish the need for further research. The USLE factors which are currently being estimated do need further refinement but exhaustive in-depth research may not be warranted by the usable results obtained.

Appendix E : Automatic Calibration Procedures

(This excerpt from Görgens (1983))

E1 State-of-the-Art Parameter Optimization

E1.1 *Optimization procedures used in catchment modelling*

Automatic optimization procedures have attracted increasing interest in the field of conceptual catchment modelling since Dawdy and O'Donnell (1965) showed in the mid-sixties that this type of model can be calibrated automatically. Automatic optimization procedures are mathematical search algorithms (computer-coded) which seek to minimize differences between selected features of modelled and observed streamflow by systematic trial alterations in the values of the model parameters. These trial alterations are called 'iterations'. The objective function, i.e. the quantitative measure of the fit of the modelled runoff to the observed runoff, is calculated after each parameter iteration. Successful iterations are those which cause a reduction in the value of the objective function. During the search only the parameter set associated with the current least objective function value is retained, which, at the end of the search, is regarded as the optimal parameter set. The end of a search can be decided by a convergence test of the rate of reduction of the objective function value, by a predetermined number of iterations, or by a computer run-time limitation.

For two-parameter models, the distribution of the objective function values produced by different pairs of parameter values can be plotted on two-dimensional diagrams as contours of equal values, as shown in Figure E1. The distribution of objective function values in the two-parameter plane is known as a **response surface**. For a multi-parameter model the same concepts will hold: if there are N parameters and these are represented by N of the coordinates of an M-dimensional coordinate system (where $M = N + 1$), and the remaining coordinate represents the objective function, then this function forms a surface in the M-dimensional space known as a response surface (Johnston and Pilgrim, 1973). For $N > 2$ this surface obviously cannot be represented visually. The optimum parameter set is defined by the lowest point on the surface in the case of a minimizing objective function. This lowest point is known as the **global** optimum and discovery of the optimum is known as **convergence.** There may be other points on the surface which are lower than all others in their immediate vicinity, but not lower than the global optimum. Such points are known as **local** optima. Figure E1(a) illustrates the aforementioned phenomena.

The response surface is a most useful concept: the optimizing procedure may be portrayed as a search on and across the response surface for its lowest point. Most search algorithms conduct a line-search, i.e. the objective function values at various points along a search **direction** are determined. When the line-optimum in that direction has been found, a new search direction is defined and a new search cycle starts. How the search directions are defined, how each subsequent search step is generated, how each line is searched and which assumptions are made about the form of the responsé surface give rise to the different optimization algorithms reported in the literature.

Outlines of a number of different optimization procedures have been given by Ibbitt and O'Donnell (1971), Clarke (1973a), Wood (1975) and Johnston and Pilgrim (1973), while Pickup (1977) recommended the work by Himmelblau (1972) as a primary source of information. The different procedures can be categorized as either deterministic or stochastic, with the former being more common.

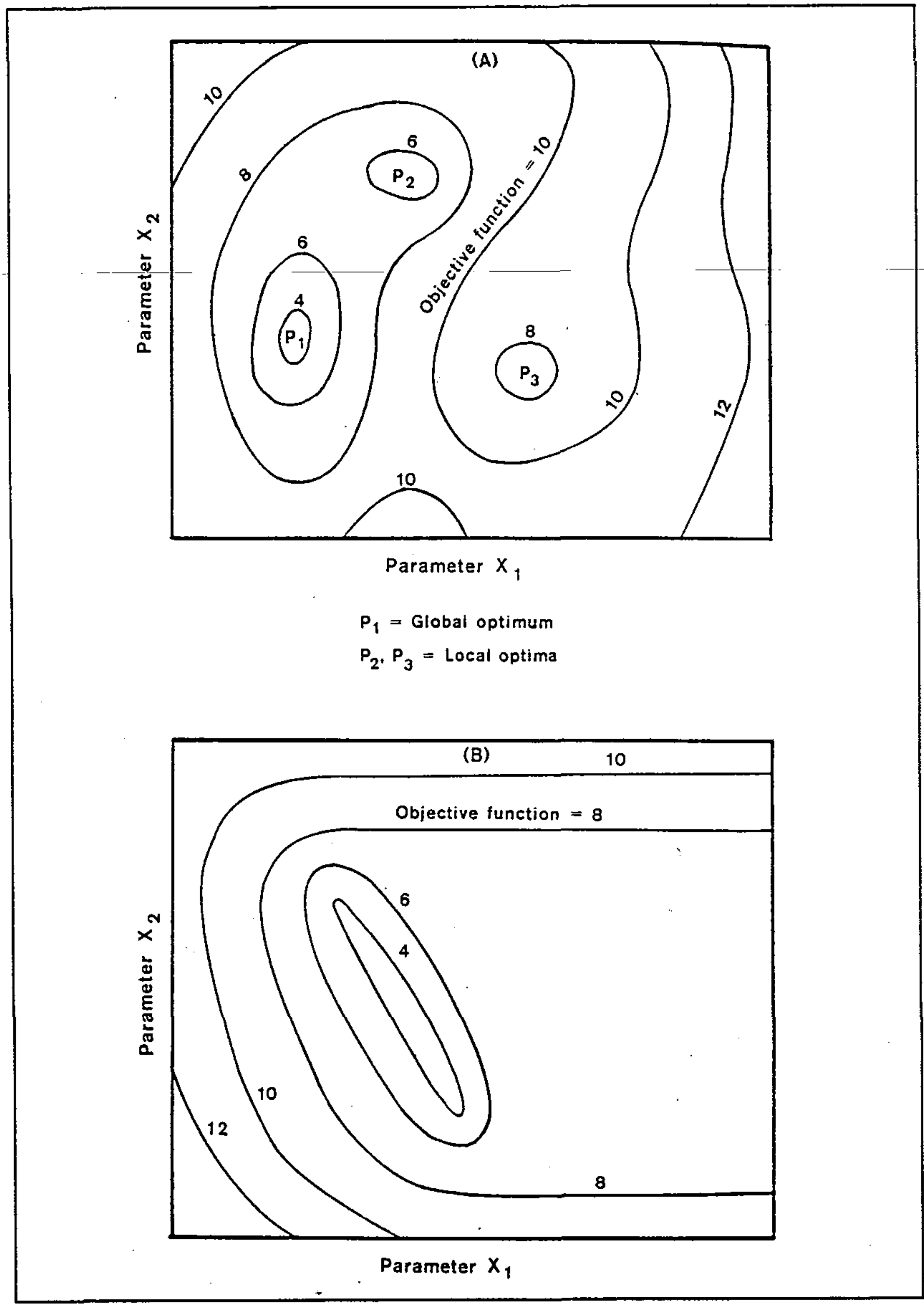

Figure E1 Two-dimensional response surface (hypothetical)

The deterministic category can in turn be subdivided into direct search, steepest descent (also known as 'hill-climbing') and least squares search methods.

a) Direct search procedures: These methods merely require the ability to make simple comparisons of values of the objective function at different points along a directional search, using no information about the shape of the response surface.

b) Steepest descent procedures: In contrast with direct search procedures, the descent methods make use of additional information about the surface being searched. Many of these methods require the slope of the surface in each coordinate direction, i.e. the partial derivative of the objective function with respect to each parameter, at each iteration. Additionally, some methods assume that close to the optimum the surface may be approximated by a positive quadratic shape.

c) Least squares procedures: This approach assumes that the objective function is quadratic for all parameter sets. It finds the optimum by solving analytically for those parameter sets that will define a direction along which the partial derivatives of the objective function will tend to zero.

Comparisons of the fitting ability of different automatic optimization procedures using conceptual rainfall-runoff models have been reported by Ibbitt and O'Donnell (1971) who tested nine different techniques, Johnston and Pilgrim (1973) who investigated four algorithms in depth, Wood (1975) who compared three techniques, Pickup (1977) who tested four different algorithms and Manley (1978) who compared two techniques. From the aforementioned and other studies it can safely be concluded that, in general, direct search procedures perform better than steepest descent in that they are less susceptible to irregularity of the response surface such as local optima and discontinuities and that they converge more rapidly in the earlier stages of optimization. A second conclusion is possible: further progress in the search from a point where convergence seems to cease is often possible by switching to another type of optimization. Ibbitt and O'Donnell (1971) achieved unexpected progress beyond the apparent optimum by switching from a direct search to a stochastic search algorithm, Johnston and Pilgrim (1973) from direct search to steepest descent and Porter and McMahon (1975) also from direct search to steepest descent. A third conclusion stems from the second: a set of parameter values should not be accepted as an optimum until a number of attempts to make further improvements have been made. Apart from employing a different optimization algorithm, the complete optimization should be repeated from different initial parameter sets (spanning the uncertainties in the **a priori** estimates); in other words, starting from different points on the response surface.

E1.2 *Problems common to optimization procedures and catchment modelling*

The effects of the unique problems encountered with optimization methods in conceptual rainfall-runoff modelling have been studied by a number of researchers: O'Connell, Nash and Farrel (1970); Ibbitt and O'Donnell (1971); Plinston (1971); Johnston and Pilgrim (1973, 1976); Pickup (1977); Mein and Brown (1978); Sorooshian and Dracup (1980); Kuczera (1982). These effects are that different sets of 'optimum' values are derived from different sets of initial values of the parameters and that quite different sets of parameter values often give very similar values of the same objective function and of the computed runoff, which also agree with the observed runoffs with acceptable accuracy. Reasons for these difficulties as summarized by Pilgrim (1975) and Moore and Clarke (1981) include the following points:

a) Interdependence between model parameters, by which a large number of combinations of parameter values will give similarly low values of the objective function - a change in one parameter may be compensated by changes in one or more of the other parameters. For a two parameter model, a long flat-bottomed valley results in the response surface, as shown in Figure E1(b). Optimization methods make only slow or no progress along the floor of such a valley towards its lowest point. It could be argued, of course, that this interdependence is not a problem, since any of the pairs of values in the valley is almost an optimum and the resulting output sequence is none the worse for the interdependence. However, if any meaning is to be attached to individual parameter values - if, say, parameter values are to be correlated with catchment characteristics - the values obtained from such an optimization would be meaningless.

b) Indifference of the objective function to parameter values such that appreciable changes in the value of one parameter may cause little or no change in the objective function. Plateau areas will result on the response surface, as shown in Figure E1(b) for high values of X_1, and it may not be possible for search methods to make progress in such areas, leading to a declaration of a false optimum.

c) Discontinuities, or points on the response surface at which the objective function, while still continuous, is non-differentiable.

d) Local optima, as shown in Figure E1(a) - also leading to premature declaration of convergence.

e) Scaling of parameters - the particular scales used for different parameters may result in unfavourable configurations of the response surface for search progress.

Possible solutions to these problems include the following measures. Problem a) can be partially redressed by optimizing interdependent parameters individually in separate searches. Problem b) can be avoided by setting indifferent parameters to constant values or by starting more than one search from different points on the response surface. Problem c) affects only steepest descent algorithms and cannot be solved except by multiple searches from different points on the response surface. Problem d) can often be overcome by direct search methods or by switching optimization algorithms when the search slows down. Point e) is less of a problem in direct search than in steepest descent methods and can be redressed by either scaling parameters to the same order of magnitude or weighting the search step for individual parameters according to parameter scale.

A measure that is often used to cope with more than one of the above difficulties is to constrain the values of certain parameters to a 'likely range' during optimization, i.e. to prevent 'impossible' values from being chosen by the search routine or for the routine to wander into one of the difficulty-prone areas of the response surface. Pilgrim (1975) argues that this procedure is unjustifiable because a parameter value might pass through an impossible region during the search but then return to a realistic level. Imposition of limits also implies that the model structure and the parameters are indeed physically realistic and that the data contain no serious errors. Chapman (1975) argues conversely, i.e. that modellers should consciously strive to make their models more physically-based; then crucial parameters **must** be constrained to known physical limits commensurate with each catchment situation.

The choice and the role of the objective function are aspects of optimization which also offer serious difficulties to the modeller. Because of their importance, these aspects are discussed under a separate heading in the next subsection.

E1.3 *The importance of the objective function*

It is axiomatic that the optimal set of parameters arrived at by optimization is in fact optimal only in the context of the objective function used during the process. A substantially different objective function may converge on a substantially different optimum parameter set, though all other conditions of optimization remain unchanged (Diskin and Simon, 1977; Pilgrim, 1975). Perusal of the scores of modelling studies published since the mid-sixties discloses that in the majority of cases calibration (manual or automatic) occurred, at least partially, by minimization of the sum of the squared deviations between modelled and simulated streamflows, or of a function based on the sum of squared deviations. These least squares-type objective functions can be said to have a general form:

$$Objective function = f\left(\sum_{j=1}^{n} W_j \mid QOBS_j^m - QSIM_j^m \mid^k \right) \qquad \text{Eq. E1}$$

where :

	f(.)	signifies some function of the entity in brackets,
	$QOBS_j$	is the observed streamflow (or some characteristic of the hydrograph such as the peak) in the time period j,
	$QSIM_j$	is the simulated streamflow in the time period j,
	n	is the number of time periods being modelled,
	m	is the power transformation of the streamflows,
	k	is a power to which the deviation for each time period is raised
	w_j	is a weight applicable to each time period (usually related to $QOBS_j$).

By algebraic analysis of two moisture stores typical of those in most explicit-soil-moisture-accounting models, Johnston and Pilgrim (1973) investigated the merits of different configurations of the exponents, m and k, in Equation E1, while keeping the weight w constant at one. This work resulted in five important findings :

a) changing the values of the exponent k did not affect the optimum values of the parameters;

b) leading on from (a) changing exponent k had no effect on the reproduction by the model of small or large events. This finding disproves the traditional assertion that changing the value of k varies the relative weighting given to small and large flow events;

c) the shape of the response surface was altered by changes in exponent k, affecting the ease or difficulty of optimization. The value of k = 2, i.e. the simple least squares function (Clarke, 1973b), was found to produce the most favourable shape - a parabolic shape;

d) changing the values of exponent m, i.e. transforming the streamflows, before calculation of deviations did affect the optimum parameter values considerably;

e) setting m = 2 favoured the reproduction of the large events while m = 0,5 favoured the reproduction of small events.

One suspects that often the main reasons for the popularity of the least squares criterion must be familiarity and computational simplicity, because notably few of the many authors of modelling reports referred to earlier bother to motivate employment of least squares-type objective functions or to explore the implications their use and the use of specific weights and exponents (w, m and k in Equation E1) might have for reliability of parameter estimates. Still, all modellers desire exactly that - estimators of reliable model parameters. This need for reliable parameter estimators is one of the main themes in Clarke's (1973b) benchmark review of the calibration and use of mathematical models in hydrology. Clarke points out that parameters estimated by analysis of the stochastic nature of model residuals through application of maximum likelihood theory must be regarded as the 'most acceptable' parameters, because statistically sound (significance) statements about how 'good' the estimates are may then be possible (also because such estimates are unbiased, have minimal variance and have computable confidence regions that converge as the number of observed data used in the calibration becomes large). A least squares objective function according to Clarke can lead to a maximum likelihood estimate only if four assumptions about the probability distribution of the model residuals, i.e. the deviations $QOBS_j$ - $QSIM_j$, are valid: that the residuals are normally distributed, have a zero mean and constant variance, are uncorrelated and produce a response surface of quadratic form (for all parameters) near the optimum. Clarke then goes on to show the numerous ways in which reported runoff model residuals invalidate one or more of these assumptions. Inevitably, the conclusion must be that more often than not, the parameter estimates achieved by least squares objective functions are not of a maximum likelihood nature, are in fact of unknown statistical significance and may be mere artifacts of the minimization process, thereby complicating attempts to attribute physical or conceptual meaning to them.

Clarke's (1973b) advocacy of the importance of model residual analysis in calibration can now be linked to two of the findings by Johnston and Pilgrim (1973) discussed earlier. Firstly, the finding that k = 2 in Equation E1 produces a parabolic response surface on which it is easiest to find the optimum validates one of Clarke's four assumptions for maximum likelihood estimates by at least squares objective function, i.e. quadracity of the response surface near the optimum. Secondly, awarding values to exponent m in Equation E1 such that $m \neq 1$ changes the statistical characteristics of the model residuals and is analogous to transformation techniques used to try to achieve homogeneity of residual variance in linear regression applications. (Nonhomogeneous residual variance or heteroscedasticity typically arises in conceptual modelling when, due to measurement error, the residual variance increases as discharge increases - a consequence of the concavity of the typical stage/discharge relationship. The result is that higher-stage errors translate into larger deviations in discharge than lower-stage errors; Sorooshian and Dracup, 1980). Choosing a value for $m(m \neq 1, k = 2)$ that stabilizes nonhomogeneous variance will validate another of Clarke's four assumptions. Unfortunately, selecting values for m has in the past been done rather arbitrarily by conceptual modellers and usually there is no certainty of achieving a stabilized residual variance situation.

Computing proper weights, w_j in Equation E1, for individual deviations can be fraught with uncertainty. An example of the rule-of-thumb approach often used is the weighted least squares objective function in the parameter estimation routine of the flood hydrograph package (HEC-1) of the U S Army Corps of Engineers (1973). Here the weights are assigned according to the rule :

$$w_j = \frac{(QOBS_j + \bar{QOBS})}{2\bar{QOBS}} \qquad \text{Eq. E2}$$

where $\bar{QOBS}$ is the average of the historical discharge values. Although this weighting will accentuate peak flows in the minimization process, it is likely that the derived parameters are not transferable in time or space. Sorooshian and Dracup (1980) show that rule-of-thumb weighting is in direct conflict with the principles of maximum likelihood theory and that the only legitimate form of weighting is one in which weights are derived during the optimization process by analysis of residuals.

The inadequacy of least squares-type objective functions ($m = 1, k = 2$ in Equation E1) for parameter estimation in the presence of input data errors is explored by Kuczera (1982) (uncorrelated and homoscedastic errors) and for the case of streamflow data errors by Sorooshian and Dracup (1980) and Sorooshian (1981) (correlated and heteroscedastic errors). All three studies demonstrate that careful attention to the stochastic structure of model residuals during the optimization process can lead to substantial gains in accuracy of parameter estimation in comparison with blind minimization of a simple or a weighted least squares objective function.

Despite increasing recognition in the past ten years that great uncertainty surrounds the physical or conceptual significance of model parameters derived by minimization of one or more objective functions without support by stochastic analysis of model residuals, this practice continues among water resources engineers and consulting hydrologists. In most cases, it is granted, the 'feel' which the modeller has for his model and for the particular catchment he is modelling may dictate the final parameter choice. This 'feel' of the modeller for a catchment, incorporating as it does the intangibles of his/her professional experience, may be a pragmatic way to evade the problems of parameter uncertainty analysis - an undertaking beyond the mathematical and computational resources of the average consulting engineer/hydrologist, as inspection of the attempts by Wood (1976), Douglas, Clarke and Newton (1976), Mein and Brown (1978) and Sorooshian and Dracup (1980) very quickly reveals. It must be expected therefore that model calibration practice comprising this blend of subjective experience and objective optimization, which has gradually developed in engineering-orientated modelling applications, will persist for many years to come - at least until model residual analysis and maximum likelihood estimation techniques can be streamlined, packaged and 'sold' to hydrological practitioners, both as ideas and products.

Recognising the need for pragmatism in water resources engineering practice, hydrologists such as Aitken (1973), Pitman (1977) and Weeks and Hebbert (1980) have continued research into reducing the subjectivity of objective function selection for common modelling applications. Pilgrim (1975) stresses that, without losing sight of the foregoing findings on parameter uncertainty, the choice of an objective function must be related to the **aims of the modelling application**, e.g. catchment yield studies, flood peak estimation for frequency analysis, low flow studies, land use effects on yield or on the whole hydrograph. This theme is echoed by Diskin and Simon (1977) in a comprehensive study of the problem of selection of objective functions in terms of specific engineering modelling applications. They analyzed a configuration consisting of twelve different objective functions and six different engineering applications by optimizing two different models on data from three different catchments. Individual objective functions were not necessarily based on all observed flow data, but often on a specified subset of data. The subset used in any given case was such that the objective function became orientated towards a certain engineering application, e.g. only peaks or only low flows. In some cases the objective functions were calculated not from computed and observed values but from statistical parameters derived from these, such as variance, skewness and kurtosis.

The cental aim of the Diskin and Simon (1977) study was 'to investigate the effects of the objective function selection and to arrive if possible, at some recommendations or guidelines for this selection which will reduce the apparent subjectivity involved'. They demonstrate that a systematic procedure (albeit elaborate) for selection of objective functions is possible, that greatly improved results can be obtained if the objective function is formulated according to the engineering application for which modelling results will be used that it is desirable to use more than one objective function in the optimization procedure for a given model and a given engineering application. It is of interest to note that as an integrated result over the catchments, models and applications considered in this study an objective function based on the sum of absolute deviations proved to be the most robust, with a simple least squares function second best. The worst two performances belonged to functions based on power-transformed observed and simulated values.

E1.4 *Summary of perspectives on optimization/objective function difficulties*

Perspectives on the role of objective functions in parameter estimation are currently still separable into two groups. On the one hand there are the practising engineers/hydrologists who are often hard-pressed to operate against a background of non-existent, inadequate or incomplete hydrometeorological records and having financial constraints and limited time to produce reasonable 'answers'. In this context the operation of conceptual rainfall-runoff models is regarded as completely deterministic and, consequently, model residual analysis is largely ignored in parameter estimation. However, uncertainty in derived model parameters is often indirectly acknowledged by steering model calibration towards simultaneous optimization of a **group of objective functions**, each measuring a different aspect of the goodness-of-fit (Aitken, 1973; Hydrological Research Unit, 1981-1982; Cundy and Brooks, 1981). Subjective but conservative judgement tempered by experience usually completes the optimization process.

The other group of perspectives is exemplified by the ideas of Clarke (1973b), namely that the operation of a conceptual model should be regarded as a stochastic process. Due to model structure inadequacies and data errors the true parameters of a model can be merely estimated and this parameter uncertainty must be defined via the stochastic structure of the model residuals. In other words, the objective function should be of a type that integrates the information in the statistical properties of model residuals to ensure appropriate minimization of uncertainty in model parameters and to make possible confidence statements about simulated streamflows. Although other workers are also making progress in this field, as shown above, Clarke has been developing his approach fairly consistently during the past ten years: Clarke (1973b); Douglas, Clarke and Newton (1976); O'Connell and Clarke (1981); Moore and Clarke (1981).

Perspectives on the general complexities of the calibration process, cited in subsection E1.2, and the possible solutions that are at hand vary from cautiously hopeful (Manley, 1978; Mein and Brown, 1978) to almost pessimistic (Moore and Clarke, 1981). There does seem to be consensus that the available measures by which the typical optimization problems of E1.2 can be redressed still do not guarantee convergence on the global optimum, so that the spectre of 'false' optimum parameter sets or dubiously subjective parameter choices often cannot be escaped. A good example is the long and detailed searches for optimum parameters of the Boughton (1966) model conducted in three different instances by Johnston and Pilgrim (1976), Moore and Mein (1975), Mein and Brown (1978) and Pickup (1977) (in the case of Johnston and Pilgrim over two years of full-time work concentrated on one watershed). In none of these instances could the modellers claim to have found a truly optimum parameter set for the 13-parameter Boughton model, which is a typical example of the class of models under discussion. Indeed, the aforecited complexities are so fundamental that they have led a prominent hydrologist such as R.T. Clarke to remark that 'difficulties of the kind encountered by Johnston and Pilgrim (1973) and Pickup (1977), ... appear to have led to a decreasing emphasis on the use of conceptual models where it is necessary to forecast future runoff in real time ..... instead, forecasters have turned to more empirical models in which there has been little or no attempt to use the principle of continuity that is embodied in all ESMA (explicit-soil-moisture-accounting) models' (Tucci and Clarke, 1980).

Undoubtedly much research on the difficulties of optimizing conceptual models by objective functions can still be expected. However, it may be that the root cause of these difficulties should be sought in the **complexity** of the rainfall-runoff models containing anything from 6 to 30 parameters to be optimized and not in the objective functions or the optimization methods - whether they be automatic or trial-and-error. Moore and Clarke (1981) deliver a powerful verdict on existing rainfall-runoff models saying that because of model complexity 'the objective function cannot in practice be written down explicitly; even if it could be written, it would contain points in the parameter space at which derivatives were undefined. The result is that the existence of multiple optima cannot be satisfactorily explored in a systematic manner, and we are forced to use relatively slow direct search methods for the calculation of optima instead of a method using gradients, such as Newton-Raphson with quadratic convergence. Because the objective function cannot be written down, the hydrologist must have blind faith in the computer that he is using and in the program that he has written; his attention is so much occupied by the problems of optimization that he rarely gets to a full study of the residuals given by the model, which will indicate how it is unsatisfactory. He can acquire no feel for the statistical properties of these residuals, and therefore he cannot use existing statistical methods for testing hypotheses about the model, for making confidence statements about estimated streamflows, for making use of prior information about parameters, and for using additional measurements recorded within the basin that he is modelling.'

Against the background of this rather destructive criticism, Moore and Clarke propose a new conceptual rainfall-runoff modelling approach in which the traditional few moisture stores are replaced by a statistical population of stores, while "bearing in mind that the aim should be the development of models that are parsimonious of parameters (so that rationalization becomes more straightforward), with objective functions that are differentiable everywhere in the parameter space (so that faster optimization procedures may be used) and such that the relation between streamflow, rainfall, and potential evaporation can be written down explicitly (so that standard errors of estimated streamflows can be calculated easily)" (Moore and Clarke, 1981).

The first few preliminary tests of this modelling approach produced promising results, but a general purpose model along the aforesaid lines is still only a remote possibility.

E2. Selection of an Optimization Algorithm

Among the optimization algorithms that have been tested for catchment modelling purposes (discussed in the previous section), the direct search methods of Rosenbrock (1960) and Nelder and Mead (1965) (simplex method) and the steepest descent method known as the Davidon method (Fletcher and Powell, 1963) feature prominently. In general, it seems as if the former two algorithms may be better than the Davidon method (Ibbitt and O'Donnell, 1971; Wood, 1975; Pickup, 1977) but that there is little to choose between the Rosenbrock and Nelder/Mead algorithms (Pickup, 1977; Manley, 1978). Computer programs of all three algorithms are available in various published sources, e.g. Rosenbrock in Kuester and Mize (1973) and Douglas (1974), and the other two in Himmelblau (1972).

Appendix F : Listing and Operation of the PEM Program

The computer program listing is provided at the end of this appendix. A source code listing together with sample data sets is also available on diskette from the Water Research Commission. The program was written in Turbo Pascal® version 5.0 developed by Borland International (1988).

F1 Setting up Data Files

The program requires a flow file and a parameter file as input. If calibration of the model is to be undertaken then an observed P load data file must also be supplied.

The flow data file can be in one of two formats. If the Pitman or other hydrological rainfall-runoff model has been used to simulate streamflow, or if observed data are used, the format is a line of 12 blank-separated monthly streamflow values (million m^3) preceded by the year. In this case the variable PIT in the parameter file must be set to 0. Note that hydrological years, which begin in October and end in September are used. A sample flow data file is shown below :

```
1985  0.09  0.61  0.07  0.02  0.03  0.03  0.05  0.03  0.05  0.05  0.05  0.05
1986  0.08  0.19  0.62  1.26  0.56  1.94  0.51  0.30  0.10  0.10  0.15  1.58
1987  0.65  0.52  1.07  0.27  0.51  3.70  0.88  0.44  0.24  0.28  0.21  0.23
1988  0.16  0.09  0.52  0.48  6.30  1.20  0.38  0.97  1.34  0.79  0.51  0.17
```

If a hydrological rainfall-runoff model which can separate streamflow into surface and groundwater (or base flow) contributions is used, the format of the flow data file is a line of 24 blank-separated flow values (million m^3) preceded by the year. The first value in each pair of values is the simulated surface flow while the second value is the groundwater flow contribution. The sum of each pair of values is equal to the total monthly streamflow. Again hydrological years are used and in this case the variable PIT is set to 1. A sample data set of this type is shown below :

```
1985 0.08 0.01 0.55 0.06 0.06 0.01 0.02 0.00 0.03 0.00 0.03 0.00 0.04 0.01 0.03 0.00 0.04 0.01 0.04 0.01 0.04 0.01 0.04 0.01
1986 0.07 0.01 0.17 0.02 0.56 0.06 1.13 0.13 0.50 0.06 1.75 0.19 0.46 0.05 0.27 0.03 0.09 0.01 0.09 0.01 0.13 0.02 1.42 0.16
1987 0.59 0.06 0.47 0.05 0.96 0.11 0.24 0.03 0.46 0.05 3.33 0.37 0.79 0.09 0.40 0.04 0.22 0.02 0.25 0.03 0.19 0.02 0.21 0.02
1988 0.14 0.02 0.08 0.01 0.47 0.05 0.43 0.05 5.67 0.63 1.08 0.12 0.34 0.04 0.87 0.10 1.21 0.13 0.71 0.08 0.46 0.05 0.15 0.02
```

The observed P load data file is set up as was the first flow file described. The format is a set of 12 blank-separated P load (tons) values for each month preceded by the year. As before, hydrological years are used. If observed data do exist, the variable POB in the parameter file must given the value 1 or else 0. A sample data file is shown below :

```
1985  0.0056  0.0752  0.0039  0.0014  0.0016  0.0015  0.0030  0.0017  0.0027  0.0027  0.0027  0.0028
1986  0.0045  0.0131  0.0542  0.0965  0.0657  0.2486  0.0289  0.0169  0.0057  0.0056  0.0081  0.2133
1987  0.0446  0.0338  0.0731  0.0152  0.0537  0.4583  0.0535  0.0243  0.0133  0.0158  0.0118  0.0130
1988  0.0090  0.0050  0.0464  0.0288  0.9161  0.1054  0.0220  0.0648  0.1032  0.0440  0.0285  0.0094
```

A sample parameter input file is listed below :

INPUT MENU FOR PHOSPHORUS EXPORT MODEL

Gauge	Area	Iys	Iye	PIT	POBS	QGMax	Pg	Decay	Cgo
CCCCCC	RRRRR.R	IIII	IIII	I	I	RRR.R	RR.R	R.RR	RRR.R
A2M13	1171.0	1985	1988	0	1	0.0	0.0	0.00	100.0

USLEdiv	Region	Dratio	Spar	Ppar
I	I	R.RR	RRRR.RRRR	RRRR.RRRR
2	1	0.00	1.30	0.02

Uarea	EI	Erode	Lengt	Slope	Cover	Support	Rivlen	StoreI	r0
RRRRR.R	RRR.R	R.RR	RRR.R	RR.R	R.RR	R.RR	RRRR.R	RR.RRR	R.RRR
1000.0	200.0	0.40	300.0	5.0	0.40	0.50	60.0	0.600	0.003
171.0	200.0	0.35	100.0	9.0	0.60	0.50	10.0	0.600	0.003

Pop
RRR.RR
1.00
1.00
1.00
1.00

INPUT AND OUTPUT FILES

```
         Output file : A:B1H005.OUT
 Pitman surf/gnd flow : A:B1H005.SEP
   Observed flow data : A:B1H005.FLW
      Observed P data : A:B1H005.POB
```

The function, source and value range of each variable and parameter in the parameter input file is explained below.

Gauge : is the Department of Water Affairs streamflow gauging weir designation at the outlet of the catchment concerned. A six character (letter or number) name must be input.

Area : is the total catchment area obtained from relevant literature of measured off a topographical map.

Iys : is the starting year of simulation. The flow and observed P data files must start with this year.

Iye : is the ending year of simulation. The flow and observed P data files must end with this year.

PIT : is the flow data file source parameter. If the flow consists of 12 pairs of monthly flow values, for each year, separated into surface and groundwater flows then PIT = 1. If the flow data consists of 12 total flow values for each year then PIT = 0.

POBS : is the observed P load data parameter. If no P data is available then POBS = 0, otherwise POBS = 1.

QGMax : is the maximum assumed groundwater flow rate (million m^3 $month^{-1}$). QGMax determines the amount of the total flow which is attributed to groundwater flow and must be estimated by the user. QGMax should be set significantly lower than the mean monthly flow. If PIT = 1 then QGMax can be set equal to 0.0.

Pg : is the percentage (0 - 100%) of the current months total flow which is assumed to give rise to groundwater flow in the following month. As with the previous parameter, Pg must be estimated. If PIT = 1 then Pg can = 0.0.

Decay : is the groundwater decay parameter (0 - 1) and determines what ratio of the current months groundwater remains in the system to be considered in the next month. This must be estimated by the user. If PIT = 1 then Decay can = 0.0.

Cgo : is the assumed groundwater P concentration (mg l^{-1}) and must be estimated by the user.

USLEdiv : is the number of USLE land-use divisions in catchment (1 - 20). If the PEM model is to used as a lumped-parameter model then only one area, encompassing the entire catchment, is defined. However the PEM can be used as a distributed-parameter model by defining a number of homogeneous areas within the catchment. The number of divisions are user defined and demarcated usually by homogeneous areas of land-use. Other features such as homogeneous soil types can also be used to demarcate areas.

Region : is the southern African region in which the catchment lies. Values of the variable Region = 1 for Transvaal and the Highveld, = 2 for the O.F.S. and the Northern Cape, = 3 for the Karoo and the North-Western Cape, and = 4 for the Cape winter rainfall region.

DRatio : is the sediment delivery ratio (0 - 1) which determines what proportion of the total soil eroded from the catchment is actually delivered to the streams. If Dratio = 0.0 is input, then a value for Dratio will be calculated in the program.

Spar : is the soluble P washoff rate ($m^3 * 10^{-6}$). This parameter can be set initially to 1 and then altered during the calibration process.

Ppar : is the particulate P washoff rate ($m^3 * 10^{-6}$). This parameter can be set initially to 1 and then altered during the calibration process.

For EACH of the USLE area divisions :

Uarea : is the area of the current USLE segment (km^2). If a number of segments are demarcated then the sum of the areas of all the segments must equal the total area of the catchment.

EI : is the USLE rainfall erosivity (EI_{30}) parameter with values in the range 0 to 500. Values can be read from Figure D1 in Appendix D.

Erode : is the USLE soil erodibility parameter with values in the range 0 to 1. Values can be read off Figure D2 in Appendix D if laboratory analysis of the dominant soil is available or from Tables D2 and D3 in Appendix D. In order to use these tables the soil form and series of the dominant soils in the catchment need to be known. This can be accomplished by one of two methods. Either a soil survey of the catchment can be undertaken or the 1:250000 soil type series maps produced by the Department of Agricultural Technical Services of the Soil and Irrigation Research Institute can be used. This method, however, requires access to the so-called memoirs (McPhee, 1991) used in compiling the soil type maps and can produce results of questionable accuracy.

Lengt : is the USLE slope length with values in the range 0 to 300 metres. If this parameter is set equal to 0 then it is automatically calculated by the program using the equation relating slope length and gradient given in section D3.3 in Appendix D.

Slope : is the USLE slope gradient parameter with values in the range 0 to 99%. This can be measured off topographical maps but improved accuracy can be expected from a survey of the catchment.

Cover : is the USLE cover and management parameter with values in the range 0 to 1. This parameter is described in section D3.4 of Appendix D. Land-use within the catchment is required for the calculation of this parameter. Land-use can be obtained by survey, air photography or satellite imagery of the catchment, however accuracy can only be improved by the depth of study.

Support : is the USLE support practice parameter with values in the range 0 to 1. As with the cover parameter this parameter is often difficult to quantify without expensive in-depth catchment surveys.

Rivlen : is the total length of perennial rivers (km) which can be measured off topographical maps.

StoreI : is the initial catchment surface P storage (tons km^{-2}). Unfortunately, values for this parameter do not exist in southern Africa and an educated guess must suffice with possible changes during the calibration process.

R0 : is the initial P replenishment rate (tons km^{-2} $month^{-1}$). Values for this parameter are scarce and consist mainly of atmospheric loading rates onto research areas as reported in Chapter 2.

Pop : P storage replenishment rate growth index. This parameter has one value for each year and is used to adjust P export annually for any growth in P loading due to growth in population and/or industry in or near to the catchment in question. If no growth is observed the values of this parameter can be set equal to 1.0. Note that there must be one value of Pop for each year of record.

The INPUT AND OUTPUT FILES section of the parameter file should be filed in with the appropriate file names or else left blank, to be entered during the program execution.

F2 Operation of the PEM

The first screen presented to the user asks for the parameter file name as shown below.

```
Enter name of Parameter file :


           Enter Q to Quit
```

Type in the full path of the file and press ENTER. If a run-time error is experienced at this stage, there is a fault in the parameter file. Correct the file and rerun the program. The program will then ask for the output file name. If the file name was included in the parameter file under the INPUT AND OUTPUT FILES section, it will appear on screen. If it is correct press ENTER, otherwise enter the full path of the required output file and press ENTER. If the output file exists the user will be asked whether it is okay to overwrite it as shown below.

```
Enter name of Parameter file : A:B1H005.PAR

  Enter name of Output file : A:B1H005.OUT




This file exists : IS IT OKAY TO OVERWRITE IT <Y/N> ? =>


           Enter Q to Quit
```

If the user inputs N signifying that the file should not be overwritten the program will prompt for a new file name. The program will then ask for the flow file and, if the variable POBS = 1, the program will ask for the observed P load file. In both cases the file name input via the parameter file will appear. Press ENTER to accept this default file name or type in a new file name and press ENTER if the default is incorrect. If the file name input does not exist then the user will be informed and the option to perform a directory listing is provided. The user is prompted for an existent file before proceeding. At any stage of the process the user can input Q to terminate the program.

The next screen prompts for one of three options as shown below.

```
Do you want to (1) Generate P export values,
               (2) Calibrate the model and then generate or
               (Q) Quit ?

=>
```

The user can input a 1 if output is required without calibration of the model. The program generates output, writes it to the specified output file and then terminates. If a 2 is input the program enters the interactive calibration process. If Q is entered the program terminates.

The third screen asks the user if they would like to see a plot of the observed versus simulated P loads. An input of Y enters this phase in which the next screen asks the user if they would like to see the plot of the averages over the entire simulation period or the plot for a specific year. Input A for the average plot or the specific year required. The plot will be displayed on the following screen as shown below, and the user is prompted whether they would like to see another plot or proceed to the calibration phase.

```
 SEASONAL DISTRIBUTION OF AVERAGE MONTHLY P LOADS  + OBSERVED  * SIMULATED
                              B1H005 (1986-1988)

   0.00      1.91      3.82      5.73      7.64      9.55     11.46     13.37
    +---------+---------+---------+---------+---------+---------+---------+
Oct |           *       +                                                 |
Nov |                                           *                         +
Dec |                                                        +            *
Jan |           +               *                                         |
Feb |  +   *                                                              |
Mar |         *+                                                          |
Apr |+                                                                    |
May +                                                                     |
Jun +                                                                     |
Jul +                                                                     |
Aug +                                                                     |
Sep |+                                                                    |
    +---------+---------+---------+---------+---------+---------+---------+
   0.00      1.91      3.82      5.73      7.64      9.55     11.46     13.37

Plot another year ? <y/n> :
```

If another plot is required enter Y. The program then prompts whether scaling, proximity, both or neither is required. If a large discrepancy exists between observed and simulated P loads, scaling adjusts one of them so that they are closer together on the plot and trends can be seen more easily. If 1 is entered the plot is displayed and the scaling factor, if any, is written above the plot. Proximity describes the "nearness" of monthly simulated and observed P loads. If proximity is required, the user must enter 2 and is then asked for the proximity required. The valid range is from 0 to 10 000 %. The plot will be displayed and any simulated monthly P loads which are greater or less than the percentage proximity requested, flash. The percentage proximity is displayed on the screen. If both options are required the user must enter 3 and the percentage proximity is requested. If neither option is wanted the user must input 4. The plotting process is repeated until the user inputs N to signify that they do not want to see any more plots. The calibration process is then entered.

The calibration screen, shown below, presents the user with three options. If Q is entered the program will terminate with the output written to the output file. If N is entered the edit screen of parameters/variables changes to the other of the two screens available. Parameters/variables may be altered by entering the number/letter of the parameter to be altered and then inputting the new value at the prompt and pressing ENTER. Note that if more than one USLE segment is defined, the number of the segment must be entered prior to changing any of the USLE parameters. The new value of the changed parameter will appear in place of the old value. Pressing ENTER causes the program to simulate new P loads based on the new parameter values input. These new simulated values will be written to the output file.

The calibration screen also provides the user with an index of goodness-of-fit via display of the simulated and observed means and standard deviations, sum of squared residuals value and the coefficient of determination for which a value of 1.0 indicates a perfect fit.

```
a)  Area[1] :   3256.00   (km*km)
    Area of specific land-use              B1H005   SIM. P      OBS. P
b)    EI(30) :  250.00
    Storm Energy param.
c)     Erode :   0.250                     Mean :      2.7512       2.7642
    Soil erodibility param.
d)  S-length :   300.00    (m)             S.D. :      6.1474       7.3871
    Slope length  ≤ 300 m
e)     Slope :    1.50     (%)             Sum of Errors  =    378.8806
    Slope gradient                         Coeff. of Det. =      0.8071
f)     Cover :    0.25
    Veg. cover and land management param.     Sed.   =   155.445008 (Tons)
g)  Practice :    0.30                        Sol. P =    47.464243 (Tons)
    Support Practices                        Part. P =    51.577284 (Tons)
h)    StoreI :  0.60000 (t/[km*km])
    Initial surface P storage
i)        Ro :  0.00300 (t/[km*km]/month)    j)   Rivlen :   621.0 (km)
    P surface replenishment rate                 Perrenial river length

Parameter letter/no. to change :


| <ENTER> TO CALCULATE | N for next parameter screen | Q to QUIT |
```

Figure F1   Calibration parameter edit screen 1

```
1)  Area :  3256.00 (km*km)                 B1H005   SIM. P     OBS. P
    Catchment area
2)  Spar :  0.800000
    Sol. P surface washoff param.
3)   CGO :   100.00 (mg/l)                  Mean :     2.7512     2.7642
    Groundwater P concentration
4)   Pop :                                  S.D. :     6.1474     7.3871
    P replenishment growth rate
5) Divs. :     1      (1-20)                Sum of Errors  =   378.8806
    Land-use divisions in catchment         Coeff. of Det. =     0.8071
6)  Ppar :  5.000000
    Part. P washoff parameter                 Sed.    =  155.445008 (Tons)
7) Qgmax :  0.00 (mill. cubic m/month)        Sol. P =    47.464243 (Tons)
    Groundwater flow rate                    Part. P =    51.577284 (Tons)
8)    PG :  0.00 (%)
    Pot. groundwater flow
9) Decay :  0.00
    Groundwater decay param.

Parameter letter/no. to change :


  | <ENTER> TO CALCULATE | N for next parameter screen | Q to QUIT |
```

Figure F2 Calibration parameter edit screen 2

The source code listing of the PEM is given below.

```
Program PO4;  { calculates PO4 exported from a catchment to the receiving
                stream }

Uses Crt,Dos;

Const
 reg : array[1..4,1..12] of real =
       ((5.5,12.3,23.05,24.07,18.97,6.12,4.56,1.93,0.0,0.0,1.08,2.42),
        (5.67,8.23,13.48,22.45,35.81,9.89,2.72,0.0,0.0,0.0,0.0,1.75),
        (3.91,3.22,4.17,9.48,33.44,20.13,10.14,3.77,0.0,4.17,3.41,4.16),
        (4.95,0.96,0.61,0.61,3.48,6.99,10.35,14.74,20.35,14.35,12.87,9.74));

Type str50 = string[50];

Var area,store0,storei,spar,ppar,dd,
    ro,ggmax,qgmax,cgo,pg,decay,pgg,
    sqm,stm,sqq,qs,qg,sg,storetot,pob,
    tr,tqg,tqs,tsg,tsdelt,st,r,dratio,
    stt,sq,sx,tav,qav,rx,tpdelt,oll,
    cg,stx,stdq,stdt,sta,sqa,tgmax,ls,
    soutav,pobsav,simean,sll,obsmean,
    sdsim,sdobs,oms,sumerr,cdet,mpow,
    maxsim,maxobs,maxfact,totsed,totsoil : real;
    y,m,ntm,npop,iy,iys,iye,
    n,i,nt,pit,pobs,cal,sumflg,
    pos,nyrs,uslediv,udiv,parflg,
    region,count,drat                    : integer;
                                    simp : array[1..360] of real;
                                     pop : array[1..60] of real;
                        divp,store,soil : array[1..20] of real;
                            sdelt,pdelt : array[1..12,1..20] of real;
                                    usle : array[1..10,1..20] of real;
                                  anfact : array[1..50] of real;
  q,t,sout,tpobs,avsim,avobs,yrsim,
  yrobs,monerode,qqs,qqg                 : array[1..12] of real;
                                   aname : string[6];
                              f,filename : string[50];
      parfile,outfile,flowfile,pobsfile : text;
                                  ch,ans : char;

{=============================================================================}

function power (x,y : real) : real;  { CALCULATES X TO THE POWER Y }

var neg,temp : real;

begin

 if (x < 0.0) and ((abs(x) - trunc(abs(x))) = 0.0) and
                                              ((trunc (x) mod 2) = 1.0)
    then neg := -1
    else neg := 1;
 if (abs(x) < 1.0E-8) then power := 0
                      else
                       if (y < 1.0E-8) then power := 1
                                       else
                                       begin
                                        temp := y*ln(abs(x));
                                        if (temp < -80.0) then
                                           temp := -80.0
                                                          else
                                           if (temp > 80.0) then
                                            temp := 80.0;
                                        power := neg*exp(temp);
                                       end;

 end; {function power}
```

```
{════════════════════════════════════════════════════════════════════}

function exist(fname : str50) : boolean;

var s : searchrec;

begin
 FindFirst(fname,0,s);
 exist := (DOSerror=0);
end;

{════════════════════════════════════════════════════════════════════}

procedure cursor(tipe : integer);  { ALLOWS 6 DIFFERENT CURSOR TYPES }

var xl,yl : integer;
    color : boolean;

procedure setcursor(top,bottom : integer);

var regs : registers;
   color : boolean;

Begin

 regs.AH := 1;
 regs.AL := 0;
 if ((top = 0) and (bottom = 0)) then regs.CH := 32
                                 else
                                  begin
                                   regs.CH := top;
                                   regs.CL := bottom;
                                  end;
 intr(16,regs);

End;

Begin

 color := not (48 and mem[0000:1040]=48);
 if color then yl := 7 else yl := 13;
 case tipe of
  1 : setcursor(0,0);                          {hidden cursor}
  2 : setcursor(0,(yl div 2));                 {upper Half-cell Cursor}
  3 : setcursor((yl div 2),yl);                {lower Half-cell Cursor}
  4 : setcursor((yl-1),yl);                    {normal cursor}
  5 : setcursor(0,1);                          {top cursor}
  6 : setcursor((yl div 2),((yl div 2)+1)); {center cursor}
 end;

End;

{════════════════════════════════════════════════════════════════════}

procedure Box;  { PRODUCES OBJECTIVE FUNCTION BOX ON PARAMETER EDIT SCREEN }

Begin

 textcolor(10);
 gotoxy(42,1);
 write('╔');
 for m := 43 to 76 do
  begin
   gotoxy(m,1);
   write('═');
  end;
 gotoxy(77,1);
```

```
 write('╗');
 for m := 2 to 14 do
  begin
   gotoxy(42,m);
   write('║');
   gotoxy(77,m);
   write('║');
  end;
 gotoxy(42,15);
 write('╚');
 for m := 43 to 76 do
  begin
   gotoxy(m,15);
   write('═');
  end;
 gotoxy(77,15);
 write('╝');

End;

{==================================================================}

procedure par1;  { WRITES SELECTED PARAMETERS TO PARAMETER EDIT SCREEN 1 }

Begin

     gotoxy(1,1);
     write('1)    Area : ',area:9:2,' (km*km)      ');
     gotoxy(1,2);
     textcolor(14);
     write('    Catchment area                    ');
     textcolor(11);
     gotoxy(1,3);
     write('2)    Spar : ',spar:10:6);
     gotoxy(1,4);
     textcolor(14);
     write('    Sol. P surface washoff param.');
     textcolor(11);
     gotoxy(1,5);
     write('3)     CGO : ',cgo:9:2,' (mg/l)       ');
     gotoxy(1,6);
     textcolor(14);
     write('    Groundwater P concentration');
     textcolor(11);
     gotoxy(1,7);
     write('4)     Pop : ');
     gotoxy(1,8);
     textcolor(14);
     write('    P replenishment growth rate');
     textcolor(11);
     gotoxy(1,9);
     write('5)  Divs. : ',uslediv:6,'      (1-20)');
     gotoxy(1,10);
     textcolor(14);
     write('    Land-use divisions in catchment');
     textcolor(11);
     gotoxy(1,11);
     write('6)    Ppar : ',ppar:10:6,'            ');
     gotoxy(1,12);
     textcolor(14);
     write('    Part. P washoff parameter               ');
     textcolor(11);
     gotoxy(1,17);
     ClrEol;
     gotoxy(1,18);
     ClrEol;
     if (pit = 0) then
```

```
        begin
         gotoxy(1,13);
         write('7)  Qgmax : ',qgmax:6:2,' (mill. cubic m/month)');
         textcolor(14);
         gotoxy(1,14);
         write('    Groundwater flow rate                    ');
         textcolor(11);
         gotoxy(1,15);
         write('8)      PG : ',pg:6:2,' (%)                  ');
         textcolor(14);
         gotoxy(1,16);
         write('    Pot. groundwater flow                 ');
         textcolor(11);
         gotoxy(1,17);
         write('9)  Decay : ',decay:6:2,'                              ');
         textcolor(14);
         gotoxy(1,18);
         write('    Groundwater decay param.     ');
         textcolor(11);
        end;

End;

{==========================================================================}

procedure par2;  { WRITES SELECTED PARAMETERS TO PARAMETER EDIT SCREEN 2 }

Begin

     gotoxy(1,1);
     write('a)   Area[',udiv:1,'] : ',usle[1,udiv]:9:2,'   (km*km)');
     gotoxy(1,2);
     textcolor(14);
     write('    Area of specific land-use    ');
     textcolor(11);
     gotoxy(1,3);
     write('b)     EI{30} : ',usle[2,udiv]:7:2,'         ');
     gotoxy(1,4);
     textcolor(14);
     write('    Storm Energy param.                 ');
     textcolor(11);
     gotoxy(1,5);
     write('c)      Erode : ',usle[3,udiv]:7:3,'                   ');
     gotoxy(1,6);
     textcolor(14);
     write('    Soil erodibility param.             ');
     textcolor(11);
     gotoxy(1,7);
     write('d)  S-length : ',usle[4,udiv]:8:2,'    (m)             ');
     gotoxy(1,8);
     textcolor(14);
     write('    Slope length  ≤ 300 m      ');
     textcolor(11);
     gotoxy(1,9);
     write('e)      Slope : ',usle[5,udiv]:7:2,'     (%)');
     gotoxy(1,10);
     textcolor(14);
     write('    Slope gradient                      ');
     textcolor(11);
     gotoxy(1,11);
     write('f)      Cover : ',usle[6,udiv]:7:2,'                   ');
     gotoxy(1,12);
     textcolor(14);
     write('    Veg. cover and land management param.');
     textcolor(11);
     gotoxy(1,13);
     write('g)  Practice : ',usle[7,udiv]:7:2,'                   ');
```

```
     gotoxy(1,14);
     textcolor(14);
     write('    Support Practices                         ');
     textcolor(11);
     gotoxy(1,15);
     write('h)    StoreI : ',usle[9,udiv]:9:5,' (t/[km*km])    ');
     gotoxy(1,16);
     textcolor(14);
     write('    Initial surface P storage');
     textcolor(11);
     gotoxy(1,17);
     write('i)        Ro : ',usle[10,udiv]:9:5,' (t/[km*km]/month)');
     gotoxy(1,18);
     textcolor(14);
     write('    P surface replenishment rate');
     textcolor(11);
     gotoxy(47,17);
     write('j)    Rivlen : ',usle[8,udiv]:7:1,' (km)');
     gotoxy(51,18);
     textcolor(14);
     write('Perrenial river length');
     textcolor(11);

End;

{==================================================================}

procedure Plot(yyr : integer); { CALCULATES AND DISPLAYS ANNUAL & AVERAGE
                                PLOTS OF OBSERVED v SIMULATED P EXPORT LOADS}

var       yy    : array[1..8] of real;
          map   : array[1..71] of char;
          mon   : array[1..12] of string[3];
 scl,ns,no,rat : integer;
       obs,sim : array[1..12] of real;
     schr,chrx : char;
      so,lr,hr : real;

Begin

 mon[1] := 'Oct';
 mon[2] := 'Nov';
 mon[3] := 'Dec';
 mon[4] := 'Jan';
 mon[5] := 'Feb';
 mon[6] := 'Mar';
 mon[7] := 'Apr';
 mon[8] := 'May';
 mon[9] := 'Jun';
 mon[10] := 'Jul';
 mon[11] := 'Aug';
 mon[12] := 'Sep';
 schr := '1';
 rat := 50;
 repeat
  ClrScr;
  lr := 1.0-(rat/100.0);
  hr := 1.0+(rat/100.0);
  for i := 1 to 71 do map[i] := ' ';
  textcolor(10);
  if (yyr = 1) then write(' SEASONAL DISTRIBUTION OF AVERAGE MONTHLY',
                          ' P LOADS  ')
             else
              begin
               write(' SEASONAL DISTRIBUTION OF ');
               textcolor(15);
               write(yyr:4);
```

```
                textcolor(10);
                write(' MONTHLY P LOADS      ');
               end;
textcolor(12);
write('+ OBSERVED');
textcolor(10);
writeln('   * SIMULATED');
gotoxy(31,2);
textcolor(14);
write(aname,' (',iys:4,'-',iye:4,')');
if (schr in ['2','3']) then
 begin
  gotoxy(52,2);
  textcolor(blink+15);
  write('*');
  textcolor(13);
  write(' < or > than ');
  textcolor(15);
  write(rat:4);
  textcolor(13);
  write(' % of Obs.');
  writeln;
 end
 else writeln;
writeln;
textcolor(15);
maxsim := 0.0;
maxobs := 0.0;
for i := 1 to 12 do if (avsim[i] > maxsim) then maxsim := avsim[i];
for i := 1 to 12 do if (avobs[i] > maxobs) then maxobs := avobs[i];
for i := 1 to 12 do sim[i] := avsim[i];
for i := 1 to 12 do obs[i] := avobs[i];
if (yyr > 1) then
 begin
  reset(pobsfile);
  repeat
   read(pobsfile,no);
   for i := 1 to 12 do read(pobsfile,yrobs[i]);
   readln(pobsfile);
  until(no = yyr);
  maxobs := 0.0;
  for i := 1 to 12 do if (yrobs[i] > maxobs) then maxobs := yrobs[i];
  no := ((yyr-iys)*12)+1;
  maxsim := 0.0;
  ns := 1;
  for i := no to (no+11) do
   begin
    yrsim[ns] := simp[i];
    if (yrsim[ns] > maxsim) then maxsim := yrsim[ns];
    ns := ns+1;
   end;
  for i := 1 to 12 do sim[i] := yrsim[i];
  for i := 1 to 12 do obs[i] := yrobs[i];
 end;
scl := 0;
if (schr in ['1','3']) then
 begin
  if (maxsim > maxobs) then
                      begin
                       scl := 1;
                       maxfact := int((maxsim/maxobs)+0.5);
                       maxobs := maxsim;
                       for i := 1 to 12 do obs[i] := obs[i]*maxfact;
                       write('              ');
                       if (maxfact <> 1.0) then writeln('Observed loads',
                                   ' scaledby factor ',maxfact:4:1);
                      end
```

```
                        else
                         begin
                          scl := 2;
                          maxfact := int((maxobs/maxsim)+0.5);
                          for i := 1 to 12 do sim[i] := sim[i]*maxfact;
                          write('                    ');
                          if (maxfact <> 1.0) then writeln('Simulated loads',
                                      ' scaled by factor ',maxfact:4:1);
                         end;
 end;
writeln;
for i := 1 to 8 do yy[i] := (i-1)*(maxobs/7.0);
textcolor(14);
write(yy[1]:7:2);
for i := 2 to 8 do write(yy[i]:10:2);
writeln;
textcolor(11);
writeln('    +---------+---------+---------+---------+---------+',
        '---------+---------+');
for m := 1 to 12 do
 begin
  map[70] := '¦';
  ns := trunc((sim[m]/(maxobs/70.0))+0.5);
  if (ns <> 0) then
   begin
    if (ns > 70) then ns := 71;
    if (obs[m] > 0.0) then so := sim[m]/obs[m]
                      else so := 0.0;
    if (scl = 0) then
    if (((so < lr) or (so > hr)) and (schr in ['2','3'])) then
                                                      map[ns] := '.'
                                                         else
                                                      map[ns] := '*';

    if (scl = 1) then
    if ((((so*maxfact) < lr) or ((so*maxfact) > hr))
                              and (schr in ['2','3'])) then
                                                      map[ns] := '.'
                                                         else
                                                      map[ns] := '*';

    if (scl = 2) then
    if ((((so/maxfact) < lr) or ((so/maxfact) > hr))
                              and (schr in ['2','3'])) then
                                                      map[ns] := '.'
                                                         else
                                                      map[ns] := '*';

   end;
  no := trunc((obs[m]/(maxobs/70.0))+0.5);
  if (no <> 0) then
   begin
    if (no > 70) then no := 71;
    map[no] := '+';
   end;
  textcolor(14);
  write(mon[m]);
  if (no > 0) then
   begin
    textcolor(11);
    write(' ¦');
   end
          else
   begin
    textcolor(12);
    write(' +');
   end;
  textcolor(12);
```

```
  for i := 1 to 69 do
   begin
    if (map[i] = '.') then
     begin
      textcolor(15+blink);
      write('*');
      textcolor(12);
     end
                       else
    if (map[i] = '*') then
                        begin
                         textcolor(10);
                         write(map[i]);
                         textcolor(12);
                        end
                       else write(map[i]);
   end;
  textcolor(11);
  if (map[70] = '¦') then write(map[70])
                      else
                       begin
                        if (map[70] = '.') then textcolor(15+blink)
                                             else
                        if (map[70] = '*') then textcolor(10)
                                             else textcolor(12);
                        if (map[70] = '.') then write('*')
                                             else write(map[70]);
                       end;
  if (map[71] = '.') then textcolor(15+blink)
                      else
  if (map[71] = '*') then textcolor(10)
                      else textcolor(12);
  if (map[71] = '.') then write('*')
                      else write(map[71]);
  writeln;
  if (ns > 0) then map[ns] := ' ';
  if (no > 0) then map[no] := ' ';
 end;
textcolor(11);
writeln('    +---------+---------+---------+---------+---------+',
        '---------+---------+');
textcolor(14);
write(yy[1]:7:2);
for i := 2 to 8 do write(yy[i]:10:2);
writeln;
textcolor(15);
gotoxy(1,23);
write('Plot another year ? <y/n> : ');
gotoxy(29,23);
chrx := UpCase(readkey);
if (chrx = 'Y') then
 begin
  gotoxy(1,23);
  ClrEOL;
  repeat
   gotoxy(1,23);
   write('Year to plot : ');
   textcolor(blink+15);
   write('19');
   textcolor(15);
   write('          [input 1 for average of All years]');
   gotoxy(18,23);
   readln(yyr);
   if (yyr > 1) then yyr := yyr+1900;
  until (((yyr >= iys) and (yyr <= iye)) or (yyr = 1));
  gotoxy(1,23);
  write('                                                              ');
```

```
    repeat
     gotoxy(1,23);
     write('Do you want : (1) scaling (2) proximity (3) both ',
           '(4) neither ? :                              ');
     gotoxy(66,23);
     schr := readkey;
    until (schr in ['1','2','3','4']);
    if (schr in ['2','3']) then
     begin
      repeat
       gotoxy(1,23);
       write('What percentage proximity do you want ? ',
             '(0 - 10000) :                              ');
       gotoxy(55,23);
       readln(rat);
      until ((rat >= 0) and (rat <= 10000));
     end;
   end;
 until (chrx = 'N');
End;

{=======================================================================}

procedure Clearhalf;

var  i : integer;

begin
 for i := 10 to 22 do
  begin
   gotoxy(1,i);
   writeln('                                              ',
           '                                              ');
  end;
 gotoxy(1,12);
end; {procedure Clearhalf}

{=======================================================================}

procedure getDTA(var DTAsegment,DTAoffset : integer);

var regs : registers;

Begin

 regs.AH := 47;
 regs.AL := 00;
 MSDos(regs);
 DTAsegment := regs.ES;
 DTAoffset := regs.BX;

End;

{=======================================================================}

procedure setDTA(DTAseg,DTAofs : integer);

var regs : registers;

Begin

 regs.AH := 26;
 regs.AL := 00;
 regs.DS := DTAseg;
 regs.DX := DTAofs;
 MSDos(regs);
```

```
End;

{=================================================================}

procedure getdirectory;

var          DTA : array[1..43] of byte;
 i,j,k,sysDTAseg,
 sysDTAofs,error : integer;
      entry,mask : string[65];
               s : searchrec;
             chs : char;
       cont,blnk : boolean;

Begin

 repeat
  Clearhalf;
  cursor(4);
  gotoxy(5,10);
  textcolor(10);
  writeln('File Mask :');
  textcolor(14);
  gotoxy(17,10);
  readln(mask);
  textcolor(10);
  getDTA(sysDTAseg,sysDTAofs);
  setDTA(seg(DTA),ofs(DTA));
  findfirst(mask,0,s);
  if ((DOSerror <> 0) and (mask[length(mask)] = '\')) then
   begin
    mask := mask+'*.*';
    findfirst(mask,0,s);
   end;
  gotoxy(5,22);
  write('Press a key to continue (Esc to Quit)');
  cursor(1);
  blnk := false;
  cont := false;
  if (DOSerror=0) then
   begin
    cont := true;
    gotoxy(5,12);
    textcolor(10);
    write('Directory of : ');
    textcolor(14);
    write(mask);
    textcolor(12);
    gotoxy(5,14);
    write(s.name);
    j := 15;
    repeat
     for k := 1 to 2 do
      begin
       for i := 1 to (21-j) do
        begin
         if (k = 1) then gotoxy(5,j+i-1);
         if (k = 2) then gotoxy(25,j+i-1);
         findnext(s);
         if (DOSerror=0) then write(s.name)
                         else if ((k = 1) and (i = 1)) then blnk := true;
        end;
       j := 14;
      end;
     if (blnk = false) then chs := readkey;
     for j := 14 to 21 do
      begin
```

```
      gotoxy(1,j);
      write('                                                                        ');
     end;
    j := 14;
   until (DOSerror<>0);
   textcolor(11);
  end
  else
  begin
   gotoxy(5,12);
   write('File mask > ');
   textcolor(14);
   write(mask);
   textcolor(10);
   write(' <');
   if (DOSerror = 18) then write(' NOT FOUND or HAS NO ENTRIES')
                      else write(' NOT FOUND');
   chs := readkey;
  end;
 until ((cont = true) or (chs = #27));
 cursor(4);
 Clearhalf;

End;

{=========================================================================}

Procedure calibrate;

begin

 repeat
  ls := 0.0;
  for i := 1 to uslediv do ls := ls+usle[1,i];
  if (ls <> area) then
   begin
    clrscr;
    gotoxy(8,8);
    write('WARNING : Sum of USLE segment areas does not equal total area!');
    gotoxy(1,24);
    textbackground(9);
    textcolor(15);
    write(' ║        <ENTER> to continue           ║          <Esc> ',
          'to quit        ║ ');
    ans := readkey;
    textbackground(0);
    clrscr;
    if (ans = #27) then halt;
    gotoxy(74,1);
    textbackground(12);
    textcolor(blink+15);
    write(' WAIT ');
    cursor(1);
    textbackground(0);
    textcolor(11);
   end;

{ CALCULATE THE USLE "LS" FACTOR AND RESULTANT EROSION FROM EACH SEGMENT }

  for i := 1 to 20 do soil[i] := 0.0;
  for i := 1 to uslediv do
   begin
    if (usle[4,i] = 0.0) then  { USE AUTOMATIC CALCULATION OF SLOPE LENGTH }
     begin
      if (usle[5,i] >= 25.0) then usle[4,i] := 25.0
                             else usle[4,i] := 100.0 - (30.0 * usle[5,i]);
     end;
```

```
    if (usle[5,i] < 1.0) then mpow := 0.2;
    if (usle[5,i] >= 5.0) then mpow := 0.5;
    if ((usle[5,i] <= 3.0) and (usle[5,i] >= 1.0)) then mpow := 0.3;
    if ((usle[5,i] < 5.0) and (usle[5,i] > 3.0)) then mpow := 0.4;
    ls := power((usle[4,i]/22.1),mpow) * (((0.043*usle[5,i]*usle[5,i])+
                 (0.3*usle[5,i])+0.43)/6.613);

    soil[i] := (usle[1,i]*usle[2,i]*usle[3,i]*ls*usle[6,i]*usle[7,i])*100.0;

 { SOIL[I] CONTAINS GROSS EROSION IN TONS FOR USLE SEGMENT I }

   end;

  for i := 1 to 360 do simp[i] := 0.0;
  if (pobs = 1) then reset(pobsfile);
  reset(flowfile);
  rewrite(outfile);
  writeln(outfile,'Phosphorus export from catchment ',aname,' for the period',
                 ' 10/',iys:4,' to 9/',(iye+1):4);
  for m := 1 to 71 do write(outfile,'■');
  writeln(outfile);
  writeln(outfile,'For each year the rows contain :');
  writeln(outfile,'         1. Observed flow (million m**3)');
  writeln(outfile,'         2. P Concentration (mg/l)');
  writeln(outfile,'        3. P load leaving catchment in streamflow (T)');
  writeln(outfile,'        4. Observed P load [when supplied by user] (T)',
                 '   { -0.001 indicates missing value }');
  writeln(outfile);
  writeln(outfile,'Year   Oct     Nov     Dec     Jan     Feb     Mar     ',
                 'Apr     May     Jun     Jul     Aug     Sep   Average');
  for i := 1 to 77 do write(outfile,'-');
  writeln(outfile);

 { INITIALISE VARIABLES }

  sumflg := 0;
  nt := 0;          { number of months with P > 0 }
  sq := 0.0;        { sum of flow, q[m], over entire period }
  sx := 0.0;        { total P for entire period }
  sqq := 0.0;       { sum of (q[m]*q[m]) over entire period }
  tr := 0.0;        { total P surface recharge (replenishment) }
  tqg := 0.0;       { total groundwater flow over entire period }
  tqs := 0.0;       { total surface flow over entire period }
  tsg := 0.0;       { total P leaving in groundwater over entire period }
  tsdelt := 0.0;   { total sol. P leaving via surface flow over entire period}
  tpdelt := 0.0;   { total part. P leaving via surface flow over entire period}
  totsed := 0.0;    { total sediment delivered to streams }
  totsoil := 0.0;  { total soil eroded in catchment }
  st := 0.0;        { sum of P conc. over entire period }
  stt := 0.0;       { sum of P conc. squared over entire period }
  simean := 0.0;    { mean of simulated P over entire period }
  sll := 0.0;       { sum of (sim. P - mean sim. P) squared for std. dev. }
  oms := 0.0;       { sum of (obs. P - sim. P) squared for Coeff. of Det. }
  sumerr := 0.0;    { sum of square errors : objective function for fit }
  for i := 1 to 12 do avsim[i] := 0.0;
  pgg := pg*0.01; { convert to % }
  ggmax := qgmax;
  store0 := 0.0;
  cg := cgo;
  tgmax := ggmax;
  for i := 1 to 20 do divp[i] := 0.0;

 { START ANNUAL LOOP }

  for y := iys to iye do
   begin
    if (pit = 0) then  { READ FLOW AND OBS. P VALUES FOR 12 MONTHS }
```

```
      begin
       read(flowfile,iy);
       for i := 1 to 12 do read(flowfile,q[i]);
       readln(flowfile);
      end
      else
       begin
        read(flowfile,iy);
        for i := 1 to 12 do read(flowfile,qqs[i],qqg[i]);
        readln(flowfile);
       end;
     if (pobs = 1) then
      begin
       read(pobsfile,iy);
       for i := 1 to 12 do read(pobsfile,tpobs[i]);
       readln(pobsfile);
      end;
     ntm := 0;        { number of months in current year for which P > 0 }
     sqm := 0.0;      { sum of q[m] for current year }
     stm := 0.0;      { total P for current year }
     for m := 1 to 12 do sout[m] := 0.0;

{ START USLE LAND-USE SEGMENTS LOOP }

     for count := 1 to uslediv do
      begin
       totsoil := totsoil+(soil[count]*anfact[(y-iys+1)]);
       pos := (y-iys)*12;
       ggmax := tgmax;
       rx := usle[10,count];
       if (y = iys) then
        begin
         store[count] := usle[9,count]*usle[1,count]; { calc. init. storage (t)
                                                        for current segment }
         store0 := store0+store[count]; { calc. initial catchment P storage }
        end;
       npop := y-iys+1;
       rx := usle[10,count]*(pop[npop]/pop[1]); { increase by growth index }
       cg := cgo*(pop[npop]/pop[1]);
       r := rx*usle[1,count]; { calc. replenishment (t) for current segment }

{ START MONTH LOOP }

       for m := 1 to 12 do
        begin
         store[count] := store[count]+r*0.5; { increase segment storage by half
                                                 the replen. for current month}
         if (pit = 0) then
          begin            { if PITMAN hasn't been used to produce flows then
                               use this to seperate surface and ground flows }
           qs := 0.0;
           if (ggmax > qgmax) then qg := ggmax
                              else qg := qgmax;
           if (q[m] > qg) then qs := q[m] - qg;
           qg := q[m]-qs;
          end
                 else
          begin
           qs := qqs[m];
           qg := qqg[m];
           q[m] := qs+qg;
          end;
         if (count = 1) then
          begin
           sqm := sqm+q[m];
           sqq := sqq+(q[m]*q[m]);
          end;
```

```
        sdelt[m,count] := 0.0;
        pdelt[m,count] := 0.0;

{ CALCULATE SEDIMENT DELIVERY RATIO AND SEDIMENT DELIVERED }

        dd := usle[8,count]/usle[1,count];      { drainage density }
        if (drat = 0) then dratio := (dd*qs)/10.0;
        if (dratio > 1.0) then dratio := 1.0;
        monerode[m] := (soil[count]*anfact[(y-iys+1)])*
                       (reg[region,m]/100.0)*dratio;
        totsed := totsed+monerode[m];
        if (qs > 0.0) then
         begin          { calculate soluble P load }
          sdelt[m,count] := (1.0 - exp((-1.0)*(spar/10000.0)*qs));
          sdelt[m,count] := store[count]*sdelt[m,count];
         end;

        sg := (cg*qg)*(usle[1,count]/area);    { calc. groundwater P load }

        if (qs > 0.0) then
         begin          { calculate particulate P load }
          pdelt[m,count] := (1.0 - exp((-1.0)*(ppar/10000.0)*
                                          (monerode[m])/10000.0));
          pdelt[m,count] := store[count]*pdelt[m,count];
         end;

        store[count] := store[count]+r*0.5-sdelt[m,count]-pdelt[m,count]-sg;
        sout[m] := sout[m]+sdelt[m,count]+pdelt[m,count]+sg;
        avsim[m] := avsim[m]+sout[m];
        tr := tr+r;
        if (count = 1) then
         begin
          tqg := tqg+qg;
          tqs := tqs+qs;
         end;
        tsg := tsg+sg;
        tsdelt := tsdelt+sdelt[m,count];
        tpdelt := tpdelt+pdelt[m,count];
        divp[count] := divp[count]+pdelt[m,count]+sdelt[m,count];
        stm := stm+sout[m];
        ggmax := decay*ggmax+qs*pgg;
        pos := pos+1;
        simp[pos] := simp[pos]+sout[m];

       end;  { END MONTH LOOP }

     end;    { END USLE LAND-USE SEGMENTS LOOP }

    for m := 1 to 12 do
     begin
      t[m] := 0.0;
      if (q[m] > 0.0) then
       begin
        t[m] := sout[m]/q[m];
        st := st+t[m];
        stt := stt+(t[m]*t[m]);
        sumerr := sumerr+((tpobs[m]-sout[m])*(tpobs[m]-sout[m]));
        ntm := ntm+1;
       end;
     end;
    qav := sqm/12.0;
    sx := sx+stm;
    sq := sq+sqm;
    nt := nt+ntm;
    write(outfile,y:4);
    for m := 1 to 12 do write(outfile,q[m]:8:4);
    writeln(outfile,qav:8:4);
```

```
  tav := 0.0;
  for m := 1 to 12 do tav := tav+t[m];
  tav := tav/12.0;
  write(outfile,'    ');
  for m := 1 to 12 do write(outfile,t[m]:8:4);
  writeln(outfile,tav:8:4);
  soutav := 0.0;
  for m := 1 to 12 do soutav := soutav+sout[m];
  soutav := soutav/12.0;
  write(outfile,'    ');
  for m := 1 to 12 do write(outfile,sout[m]:8:4);
  writeln(outfile,soutav:8:4);
  if (pobs = 1) then
   begin
    pobsav := 0.0;
    for m := 1 to 12 do pobsav := pobsav+tpobs[m];
    pobsav := pobsav/12.0;
    write(outfile,'    ');
    for m := 1 to 12 do write(outfile,tpobs[m]:8:4);
    writeln(outfile,pobsav:8:4);
   end;
  tgmax := ggmax;
 end;   { END YEAR LOOP }

for m := 1 to 12 do avsim[m] := avsim[m]/nyrs;
for m := 1 to pos do simean := simean+simp[m];
simean := simean/pos;
for m := 1 to pos do sll := sll+((simp[m]-simean)*(simp[m]-simean));
sdsim := sqrt(sll/pos);
reset(pobsfile);
oms := 0.0;
if (pobs = 1) then
 begin
  iy := 1;
  for i := iys to iye do
   begin
    read(pobsfile,m);
    for m := 1 to 12 do
     begin
      read(pobsfile,pob);
      oms := oms+((pob-simp[iy])*(pob-simp[iy]));
      iy := iy+1;
     end;
    readln(pobsfile);
   end;
 end;
if (pobs = 1) then cdet := 1-(sumerr/oll)
              else cdet := -99.9;
ClrScr;
if (cal = 2) then
 begin
  ClrScr;
  cursor(4);
  gotoxy(6,6);
  write('Do you want to see the Observed versus Simulated plot ? <y/n> :');
  gotoxy(70,6);
  ch := UpCase(readkey);
  if (ch = 'Y') then
   begin
    gotoxy(1,6);
    ClrEOL;
    gotoxy(10,6);
    write('Plot Average of All years (A) or a specific year (S) ? :');
    gotoxy(67,6);
    ch := upcase(readkey);
    gotoxy(67,6);
    write(ch);
```

```
  if (ch = 'A') then Plot(1)
                else
                 begin
                  repeat
                   gotoxy(10,8);
                   write('Year : 19  ');
                   gotoxy(19,8);
                   readln(n);
                   n := n+1900;
                  until ((n >= iys) and (n <= iye));
                  Plot(n);
                 end;
 end;
ClrScr;
Box;
textcolor(15);
gotoxy(45,2);
write(aname);
textcolor(14);
gotoxy(54,2);
write(' SIM. P      OBS. P');
textcolor(10);
gotoxy(54,3);
write('[redacted]');
textcolor(14);
gotoxy(45,5);
write('Mean : ',simean:11:4,obsmean:12:4);
gotoxy(45,7);
write('S.D. : ',sdsim:11:4,sdobs:12:4);
gotoxy(44,9);
write(' Sum of Errors  = ',sumerr:11:4);
gotoxy(45,11);
if (cdet <> -99.9) then write('Coeff. of Det. = ',cdet:11:4)
                   else write('                              ');
textcolor(11);
gotoxy(47,13);
write(' Sol. P = ',tsdelt:12:6,' (Tons)');
gotoxy(47,14);
write('Part. P = ',tpdelt:12:6,' (Tons)');
udiv := 1;

repeat
 if (parflg = 1) then par1
                 else par2;
 gotoxy(1,24);
 textbackground(9);
 textcolor(15);
 write(' ║  <');
 textcolor(14);
 write('ENTER');
 textcolor(15);
 write('> TO CALCULATE  ║   ');
 textcolor(14);
 write('N');
 textcolor(15);
 write(' for next parameter screen   ║   ');
 textcolor(14);
 write('Q');
 textcolor(15);
 write(' to QUIT   ║ ');
 textbackground(0);
 textcolor(11);
 gotoxy(1,22);
 ClrEOL;
 gotoxy(1,20);
 write('Parameter letter/no. to change :        ');
 gotoxy(34,20);
```

```
ch := readkey;
gotoxy(34,20);
write(ch);
gotoxy(1,22);
ch := UpCase(ch);
if (ch <> 'Q') then
 begin
  gotoxy(1,22);
  case ch of
     '1' : begin
            write('Area = ');
            gotoxy(8,22);
            readln(area);
           end;
     '2' : begin
            write('Spar = ');
            gotoxy(8,22);
            readln(spar);
           end;
     '3' : begin
            write('CGO = ');
            gotoxy(7,22);
            readln(cgo);
           end;
     '4' : begin
            n := 1;
            for iy := iys to iye do
             begin
              gotoxy(1,22);
              write('Pop (',iy:4,') =          (Old = ',pop[n]:6:2,')');
              gotoxy(14,22);
              readln(pop[n]);
              n := n+1;
             end;
           end;
     '5' : begin
            write('USLE Div. =                                       ');
            repeat
             gotoxy(13,22);
             readln(uslediv);
             if ((uslediv < 1) or (uslediv > 20)) then
              begin
               gotoxy(13,22);
               ClrEol;
               write(#7);
               gotoxy(35,22);
               textcolor(blink+15);
               write('(1 - 20)');
               textcolor(11);
              end;
            until ((uslediv > 0) and (uslediv < 21));
           end;
     '6' : begin
            write('Ppar = ');
            gotoxy(8,22);
            readln(ppar);
           end;
     '7' : begin
            write('QgMax = ');
            gotoxy(9,22);
            readln(qgmax);
           end;
     '8' : begin
            write('PG =                                              ');
            repeat
             gotoxy(6,22);
             readln(pg);
```

```
          if ((pg < 0) or (pg > 100)) then
           begin
            gotoxy(6,22);
            ClrEol;
            write(#7);
            gotoxy(35,22);
            textcolor(blink+15);
            write('(0 - 100)');
            textcolor(11);
           end;
         until ((pg >= 0) and (pg <= 100));
        end;
'9' : begin
         write('Decay =                                              ');
         repeat
          gotoxy(9,22);
          readln(decay);
          if ((decay < 0) or (decay > 1)) then
           begin
            gotoxy(9,22);
            ClrEol;
            write(#7);
            gotoxy(35,22);
            textcolor(blink+15);
            write('(0 - 1)');
            textcolor(11);
           end;
         until ((decay >= 0) and (decay <= 1));
        end;
'N' : begin
         if (parflg = 1) then
          begin
           parflg := 2;
           par2;
          end
          else
           begin
            parflg := 1;
            par1;
           end;
        end;
'A' : begin
         if (uslediv > 1) then
          begin
           write('Which section ? :        (1-20)');
           gotoxy(19,22);
           readln(udiv);
          end else udiv := 1;
         gotoxy(1,22);
         write('Area =                                               ');
         repeat
          gotoxy(8,22);
          readln(usle[1,udiv]);
          if ((usle[1,udiv] < 0.0) or (usle[1,udiv] > area)) then
           begin
            gotoxy(8,22);
            ClrEol;
            write(#7);
            gotoxy(35,22);
            textcolor(blink+15);
            write('(0 - ',area:8:2,')');
            textcolor(11);
           end;
         until ((usle[1,udiv] > 0.0) and (usle[1,udiv] <= area));
        end;
'B' : begin
         if (uslediv > 1) then
```

```
          begin
           write('Which section ? :        (1-20)');
           gotoxy(19,22);
           readln(udiv);
          end else udiv := 1;
         gotoxy(1,22);
         write('EI{30} =                                       ');
         repeat
          gotoxy(10,22);
          readln(usle[2,udiv]);
          if ((usle[2,udiv] < 0) or (usle[2,udiv] > 500)) then
           begin
            gotoxy(10,22);
            ClrEol;
            write(#7);
            gotoxy(35,22);
            textcolor(blink+15);
            write('(0 - 500)');
            textcolor(11);
           end;
         until ((usle[2,udiv] >= 0) and (usle[2,udiv] <= 500));
        end;
'C' : begin
         if (uslediv > 1) then
          begin
           write('Which section ? :        (1-20)');
           gotoxy(19,22);
           readln(udiv);
          end else udiv := 1;
         gotoxy(1,22);
         write('Erode =                                        ');
         repeat
          gotoxy(9,22);
          readln(usle[3,udiv]);
          if ((usle[3,udiv] < 0.0) or (usle[3,udiv] > 1.0)) then
           begin
            gotoxy(9,22);
            ClrEol;
            write(#7);
            gotoxy(35,22);
            textcolor(blink+15);
            write('(0 - 1)');
            textcolor(11);
           end;
         until ((usle[3,udiv] >= 0.0) and (usle[3,udiv] <= 1.0));
        end;
'D' : begin
         if (uslediv > 1) then
          begin
           write('Which section ? :        (1-20)');
           gotoxy(19,22);
           readln(udiv);
          end else udiv := 1;
         gotoxy(1,22);
         write('S-length =                                     ');
         repeat
          gotoxy(12,22);
          readln(usle[4,udiv]);
          if ((usle[4,udiv] < 0.0) or (usle[4,udiv] > 300.0)) then
           begin
            gotoxy(12,22);
            ClrEol;
            write(#7);
            gotoxy(35,22);
            textcolor(blink+15);
            write('(0 - 300)');
            textcolor(11);
```

```
        end;
       until ((usle[4,udiv] >= 0.0) and (usle[4,udiv] <= 300.0));
      end;
'E' : begin
       if (uslediv > 1) then
        begin
         write('Which section ? :        (1-20)');
         gotoxy(19,22);
         readln(udiv);
        end else udiv := 1;
       gotoxy(1,22);
       write('Slope =                                              ');
       repeat
        gotoxy(9,22);
        readln(usle[5,udiv]);
        if ((usle[5,udiv] < 0.0) or (usle[5,udiv] > 100.0)) then
         begin
          gotoxy(9,22);
          ClrEol;
          write(#7);
          gotoxy(35,22);
          textcolor(blink+15);
          write('(0 - 100)');
          textcolor(11);
         end;
       until ((usle[5,udiv] >= 0.0) and (usle[5,udiv] <= 100.0));
      end;
'F' : begin
       if (uslediv > 1) then
        begin
         write('Which section ? :        (1-20)');
         gotoxy(19,22);
         readln(udiv);
        end else udiv := 1;
       gotoxy(1,22);
       write('Cover =                                              ');
       repeat
        gotoxy(9,22);
        readln(usle[6,udiv]);
        if ((usle[6,udiv] < 0.0) or (usle[6,udiv] > 1.0)) then
         begin
          gotoxy(9,22);
          ClrEol;
          write(#7);
          gotoxy(35,22);
          textcolor(blink+15);
          write('(0 - 1)');
          textcolor(11);
         end;
       until ((usle[6,udiv] >= 0.0) and (usle[6,udiv] <= 1.0));
      end;
'G' : begin
       if (uslediv > 1) then
        begin
         write('Which section ? :        (1-20)');
         gotoxy(19,22);
         readln(udiv);
        end else udiv := 1;
       gotoxy(1,22);
       write('Practice =                                           ');
       repeat
        gotoxy(12,22);
        readln(usle[7,udiv]);
        if ((usle[7,udiv] < 0.0) or (usle[7,udiv] > 1.0)) then
         begin
          gotoxy(12,22);
          ClrEol;
```

```
                  write(#7);
                  gotoxy(35,22);
                  textcolor(blink+15);
                  write('(0 - 1)');
                  textcolor(11);
                 end;
               until ((usle[7,udiv] >= 0.0) and (usle[7,udiv] <= 1.0));
              end;
        'H' : begin
               if (uslediv > 1) then
                begin
                 write('Which section ? :        (1-20)');
                 gotoxy(19,22);
                 readln(udiv);
                end else udiv := 1;
               gotoxy(1,22);
               write('StoreI =                                    ');
               gotoxy(10,22);
               readln(usle[9,udiv]);
              end;
        'I' : begin
               if (uslediv > 1) then
                begin
                 write('Which section ? :        (1-20)');
                 gotoxy(19,22);
                 readln(udiv);
                end else udiv := 1;
               gotoxy(1,22);
               write('Ro =                                        ');
               gotoxy(6,22);
               readln(usle[10,udiv]);
              end;
        'J' : begin
               if (uslediv > 1) then
                begin
                 write('Which section ? :        (1-20)');
                 gotoxy(19,22);
                 readln(udiv);
                end else udiv := 1;
               gotoxy(1,22);
               write('Rivlen =                                    ');
               gotoxy(10,22);
               readln(usle[8,udiv]);
              end;
    end;
   end;
  until (ch in ['0','Q',#13]);
  if (ch = 'Q') then cal := 1;
  ClrScr;
  gotoxy(74,1);
  textbackground(12);
  textcolor(blink+15);
  write(' WAIT ');
  cursor(1);
  textbackground(0);
  textcolor(11);
 end;           { END (if cal = 2) LOOP }
until (cal = 1);

End;

{==================================================================}

Begin { Main Program }

 cursor(4);
 ClrScr;
```

```
{ READ PARAMETER FILENAME & PARAMETERS }

 repeat
  gotoxy(1,24);
  textbackground(1);
  textcolor(14);
  write('                                 Enter Q to Quit',
        '                                 ');
  textbackground(0);
  textcolor(11);
  gotoxy(12,1);
  writeln('Enter name of Parameter file : ');
  gotoxy(43,1);
  clreol;
  gotoxy(43,1);
  readln(filename);
  if ((filename = 'q') or (filename = 'Q')) then
   begin
    clrscr;
    halt;
   end;
  if NOT(exist(filename)) then
   begin
    gotoxy(25,20);
    textcolor(blink+14);
    write(#7);
    write('ERROR : FILE DOES NOT EXIST');
    textcolor(15);
    gotoxy(25,22);
    write('Enter R to retry or D for directory listing =>');
    gotoxy(72,22);
    ans := upcase(readkey);
    if (ans = 'D') then getdirectory
                   else Clearhalf;
    textcolor(11);
   end;
 until (exist(filename));
 gotoxy(1,20);
 ClrEol;
 assign(parfile,filename);
 reset(parfile);
 writeln;
 for i := 1 to 10 do readln(parfile);
 for i := 1 to 2 do read(parfile,ch);
 readln(parfile,aname,area,iys,iye,pit,pobs,qgmax,pg,decay,cgo);
 for i := 1 to 6 do readln(parfile);
 readln(parfile,uslediv,region,dratio,spar,ppar);
 for i := 1 to 6 do readln(parfile);
 for i := 1 to 20 do for m := 1 to 10 do usle[m,i] := 0.0;
 for i := 1 to uslediv do
  begin
   for m := 1 to 10 do read(parfile,usle[m,i]);
   readln(parfile);
  end;
 nyrs := iye-iys+1;

{ READ ANNUAL GROWTH INDEX }

 for i := 1 to 60 do pop[i] := 1.0;
 for i := 1 to 6 do readln(parfile);
 for i := 1 to nyrs do readln(parfile,pop[i]);

{ READ OUTPUT FILENAME }

 for i := 1 to 4 do readln(parfile);
 for i := 1 to 27 do read(parfile,ans);
 readln(parfile,f);
```

```
ans := 'Y';
gotoxy(1,24);
textbackground(1);
textcolor(14);
write('                                    Enter Q to Quit',
       '                                    ');
textbackground(0);
textcolor(11);
repeat
 gotoxy(15,3);
 writeln('Enter name of Output file : ',f);
 if (ans = 'N') then
  begin
   gotoxy(43,3);
   clreol;
  end;
 gotoxy(43,3);
 readln(filename);
 if ((filename = 'q') or (filename = 'Q')) then
  begin
   clrscr;
   halt;
  end;
 if (filename = '') then filename := f;
 if (exist(filename)) then
  begin
   write(#7);
   textcolor(14);
   gotoxy(10,20);
   write('This file exists : IS IT OKAY TO OVERWRITE IT <Y/N> ? => ');
   gotoxy(67,20);
   readln(ans);
   ans := upcase(ans);
   textcolor(11);
  end;
 gotoxy(1,20);
 ClrEol;
until ((ans = 'Y') or (NOT(exist(filename))));
assign(outfile,filename);
rewrite(outfile);
writeln;

{ READ PITMAN SURFACE/GROUNDWATER -FLOW FILENAME IF PITMAN MODEL WAS USED TO
  GENERATE FLOW ; OR TOTAL-FLOW FILENAME IF FLOW WAS GENERATED OTHERWISE }

if (pit = 0) then readln(parfile);
for i := 1 to 27 do read(parfile,ans);
readln(parfile,f);
if (pit = 1) then readln(parfile);
m := 0;
repeat
 gotoxy(1,24);
 textbackground(1);
 textcolor(14);
 write('                                    Enter Q to Quit',
       '                                    ');
 textbackground(0);
 textcolor(11);
 if (pit = 1) then
  begin
   gotoxy(1,5);
   writeln('Enter name of PITMAN Surf/Gnd Flow file : ',f);
   if (m > 0) then
    begin
     gotoxy(43,5);
     clreol;
    end;
```

```
    gotoxy(43,5);
   end
               else
   begin
    gotoxy(17,5);
    writeln('Enter name of Flow file : ',f);
    if (m > 0) then
     begin
      gotoxy(43,5);
      clreol;
     end;
    gotoxy(43,5);
   end;
  readln(filename);
  if ((filename = 'q') or (filename = 'Q')) then
   begin
    clrscr;
    halt;
   end;
  if (filename = '') then filename := f;
  if NOT(exist(filename)) then
   begin
    gotoxy(25,20);
    textcolor(blink+14);
    write(#7);
    write('ERROR : FILE DOES NOT EXIST');
    textcolor(15);
    gotoxy(25,22);
    write('Enter R to retry or D for directory listing =>');
    gotoxy(72,22);
    ans := upcase(readkey);
    if (ans = 'D') then getdirectory
                   else Clearhalf;
    textcolor(11);
   end;
  m := m+1;
 until (exist(filename));
 gotoxy(1,20);
 ClrEol;
 assign(flowfile,filename);
 reset(flowfile);
 readln(flowfile,y);
 if (y <> iys) then
  begin
   gotoxy(10,12);
   textcolor(blink+12);
   write('FLOW FILE DOES NOT BEGIN WITH START YEAR IN PARAMETER FILE');
   halt;
  end;
 if (iye > iys) then
  begin
   repeat
    readln(flowfile,y);
   until EOF(flowfile);
   if (y <> iye) then
    begin
     gotoxy(8,12);
     textcolor(blink+12);
     write('FLOW FILE DOES NOT FINISH WITH END YEAR IN PARAMETER FILE');
     halt;
    end;
  end;
 reset(flowfile);

 for i := 1 to 50 do anfact[i] := 0.0;
 for i := 1 to nyrs do
  begin
```

```
  read(flowfile,y);
  if (pit = 1) then for y := 1 to 24 do
                    begin
                     read(flowfile,qs);
                     anfact[i] := anfact[i]+qs;
                    end;
  if (pit = 0) then for y := 1 to 12 do
                    begin
                     read(flowfile,qs);
                     anfact[i] := anfact[i]+qs;
                    end;
  readln(flowfile);
 end;
reset(flowfile);
qg := 0.0;
for i := 1 to nyrs do qg := qg+anfact[i];
qg := qg/nyrs;  { QG NOW = MEAN ANNUAL RUNOFF (mar) }
for i := 1 to nyrs do anfact[i] := anfact[i]/qg;

{ ANFACT NOW CONTAINS THE RATIOS OF ANNUAL FLOW TO MAR FOR EACH YEAR FOR USE
  IN GIVING THE USLE EROSION VALUES A DISTRIBUTION SIMILAR TO ANNUAL FLOWS}

{ READ OBSERVED P LOADS FILENAME AND CALCULATE STATISTICS OF THE OBS. LOADS}

if (pobs = 1) then
 begin
  for i := 1 to 27 do read(parfile,ans);
  readln(parfile,f);
  m := 0;
  repeat
   gotoxy(1,24);
   textbackground(1);
   textcolor(14);
   write('                                 Enter Q to Quit',
         '                                 ');
   textbackground(0);
   textcolor(11);
   gotoxy(11,7);
   writeln('Enter name of Observed P file : ',f);
   if (m > 0) then
    begin
     gotoxy(43,7);
     clreol;
    end;
   gotoxy(43,7);
   readln(filename);
   if ((filename = 'q') or (filename = 'Q')) then
    begin
     clrscr;
     halt;
    end;
   if (filename = '') then filename := f;
   if NOT(exist(filename)) then
    begin
     gotoxy(25,20);
     textcolor(blink+14);
     write(#7);
     write('ERROR : FILE DOES NOT EXIST');
     textcolor(15);
     gotoxy(25,22);
     write('Enter R to retry or D for directory listing =>');
     gotoxy(72,22);
     ans := upcase(readkey);
     if (ans = 'D') then getdirectory
                    else Clearhalf;
     textcolor(11);
    end;
```

```
  m := m+1;
 until (exist(filename));
 gotoxy(1,20);
 ClrEol;
 assign(pobsfile,filename);
 reset(pobsfile);
 readln(pobsfile,y);
 if (y <> iys) then
  begin
   gotoxy(5,12);
   textcolor(blink+12);
   write('OBSERVED P FILE DOES NOT BEGIN WITH START YEAR IN ',
         'PARAMETER FILE');
   halt;
  end;
 if (iye > iys) then
  begin
   repeat
    readln(pobsfile,y);
   until EOF(pobsfile);
   if (y <> iye) then
    begin
     gotoxy(5,12);
     textcolor(blink+12);
     write('OBSERVED P FILE DOES NOT FINISH WITH END YEAR IN ',
           'PARAMETER FILE');
     halt;
    end;
  end;
 reset(pobsfile);
 obsmean := 0.0;
 oll := 0.0;
 for i := 1 to 12 do avobs[i] := 0.0;
 repeat
  read(pobsfile,y);
  if not(EOF(pobsfile)) then
   begin
    for i := 1 to 12 do
     begin
      read(pobsfile,tpobs[i]);
      avobs[i] := avobs[i]+tpobs[i];
      obsmean := obsmean+tpobs[i];
     end;
    readln(pobsfile);
   end;
 until (EOF(pobsfile));
 obsmean := obsmean/(nyrs*12); { OBSMEAN = A SINGLE MEAN MONTHLY P OVER
                                 ENTIRE PERIOD }
 for i := 1 to 12 do avobs[i] := avobs[i]/nyrs; { MONTHLY MEAN P FOR EACH
                                                  MONTH (12 VALUES) }
 reset(pobsfile);
 repeat
  read(pobsfile,y);
  if not(EOF(pobsfile)) then
   begin
    for i := 1 to 12 do
     begin
      read(pobsfile,tpobs[i]);
      oll := oll+((tpobs[i]-obsmean)*(tpobs[i]-obsmean));
     end;
    readln(pobsfile);
   end;
 until (EOF(pobsfile));
 sdobs := sqrt(oll/(nyrs*12)); { SDOBS = STD. DEV. OF OBSERVED P LOADS }
end;

ClrScr;
```

```
drat := 1;
if (dratio = 0.0) then drat := 0;
if (pobs = 1) then
 begin
  writeln('Do you want to (1) Generate P export values,');
  writeln('                (2) Calibrate model and then generate or');
  writeln('                (Q) Quit ?');
  writeln;
  repeat
   gotoxy(1,5);
   writeln('=> ');
   gotoxy(4,5);
   ch := readkey;
   gotoxy(4,5);
   write(ch);
  until (ch in ['1','2','q','Q']);
  if ((ch = 'q') or (ch = 'Q')) then
   begin
    clrscr;
    halt;
   end;
  cal := ord(ch)-48; { SET VAR. CAL }
  ClrScr;
  gotoxy(74,1);
  textbackground(12);
  textcolor(blink+15);
  write(' WAIT ');
  cursor(1);
  textbackground(0);
  textcolor(11);
 end
 else cal := 1;
parflg := 1;

{ START CALIBRATION LOOP }

calibrate;

{ END CALIBRATION LOOP }

storetot := 0.0;
for i := 1 to uslediv do storetot := storetot+store[i];
stx := sx/sq;   { total P/total flow over entire period }
stdq := sqrt((sqq-sq*sq/(nyrs*12))/((nyrs*12)-1));
stdt := sqrt((stt-st*st/nt)/(nt-1));
sqa := sq/(nyrs*12);
sta := st/(nyrs*12);
writeln(outfile);
write(outfile,'                                            ');
writeln(outfile,' Mean    Std. Dev.    N');
write(outfile,'                                            ');
writeln(outfile,'[redacted]');
writeln(outfile,'    Monthly Flow (mill. cubic m)',sqa:10:2,stdq:10:2,
                                                        (nyrs*12):9);
writeln(outfile,'    Average monthly PO4 (mg/l)',sta:12:2,stdt:10:2,nt:9);
writeln(outfile);
writeln(outfile,'    Total modelled surface runoff       = ',tqs:10:2,
                ' (million m**3)');
writeln(outfile,'    Total modelled groundwaterflow      = ',tqg:10:2,
                ' (million m**3)');
writeln(outfile);
writeln(outfile,'    Initial catchment P storage         = ',store0:10:2,
                ' (Tons)');
writeln(outfile,'    Final catchment surface P storage   = ',storetot:10:2,
                ' (Tons)');
writeln(outfile,'    Total surface P recharge            = ',tr:10:2,
                ' (Tons)');
```

```
writeln(outfile,'    Total surface soluble P washoff      = ',tsdelt:10:2,
                ' (Tons)');
writeln(outfile,'    Total surface particulate P washoff = ',tpdelt:10:2,
                ' (Tons)');
writeln(outfile,'    Total P leaving groundwater          = ',tsg:10:2,
                ' (Tons)');
writeln(outfile,'    Flow weighted average P              = ',stx:10:2,
                ' (mg/l)');
writeln(outfile);
totsoil := totsoil/area;
totsed := totsed/area;
writeln(outfile,'    Total soil eroded from catchment    =',totsoil:10:2,
                ' (Tons/[km*km]/year)');
writeln(outfile,'    Total sediment delivered to streams =',totsed:10:2,
                ' (Tons/[km*km]/year)');
writeln(outfile);
writeln(outfile,'Simulation Statistics :   Sum of Error Squared =',
                sumerr:11:4);
writeln(outfile,'[redacted]     Coef. of Determination =',
               cdet:11:4);
writeln(outfile);
writeln(outfile);
writeln(outfile,' P losses from each USLE division');
writeln(outfile,'[redacted] ');
writeln(outfile);
write(outfile,'      1');
for i := 2 to uslediv do write(outfile,i:10);
writeln(outfile);
for i := 1 to uslediv do write(outfile,'==========');
writeln(outfile);
for i := 1 to uslediv do write(outfile,divp[i]:10:4);
writeln(outfile);
writeln(outfile);
writeln(outfile);
writeln(outfile,' PEM Parameters');
writeln(outfile,'[redacted] ');
writeln(outfile);
writeln(outfile,' Area     Spar     Ppar     QGMax     cgo       PG     ',
                ' Decay');
writeln(outfile,'==============================================================',
                '========');
writeln(outfile,area:6:1,spar:8:2,ppar:9:2,qgmax:9:1,cgo:10:1,pg:9:1,
                decay:9:1);
writeln(outfile);
writeln(outfile,' Pit   Pobs   Region   Dratio');
writeln(outfile,'==============================');
writeln(outfile,pit:3,pobs:6,region:8,dratio:11:1);
writeln(outfile);
writeln(outfile,' Uarea    EI   Erode  Length  Slope  Cover  Supp.',
                '    Rivl    StorI       Ro');
writeln(outfile,'==============================================================',
                '=========================');
for i := 1 to uslediv do
 begin
  write(outfile,usle[1,i]:7:1);
  write(outfile,usle[2,i]:8:1);
  write(outfile,usle[3,i]:7:2);
  write(outfile,usle[4,i]:8:2);
  write(outfile,usle[5,i]:7:2);
  write(outfile,usle[6,i]:7:2);
  write(outfile,usle[7,i]:7:2);
  write(outfile,usle[8,i]:9:2);
  write(outfile,usle[9,i]:8:2);
  write(outfile,usle[10,i]:10:4);
  writeln(outfile);
 end;
close(outfile);
```

The Pitman monthly rainfall-runoff model described in this report was obtained from 1989. The computer program was converted from the original FORTRAN to the PASCAL computer language. The modifications described in Chapter 3 are included in the copy of the source code and compiled executable version of the program submitted with this report and available on 360kB diskette from the Water Research Commission.

The user friendliness of the model has been improved and use of the model should present no problem. Recorded rainfall, recorded runoff and the parameters must be input in the same format of the sample data files included with the program.

Due to the great length of the computer program, a listing will not be included with this report but a description of the input files follows.

The recorded rainfall file is shown below. The first line contains the raingauge name followed by the first and last year in the entire data set. The second line contains the South African Weather Bureau gauge location number, followed by the first and last year of record and the Mean Annual Precipitation for the current gauge. The third line contains the location number and year followed by 12 monthly rainfall totals (mm) at the gauge in question. Note that hydrological years, which start in October and end in September, are used. A number of blocks of data can be input, using one block for each raingauge in the catchment. In the example below, 2 raingauges have been used. The last line consists of 73 zeros used for program control purposes.

```
R2H006      1967      1988
    079       316       1970      1988      703.1
 079 316 1970  814  411 2584  998 1169  478 1069  554   35  815 1880  130
 079 316 1971  740  678    0  975 2020  819  162  180  360   40  155  475
 079 316 1972  405 1210  170  426 1411  785    0  440    0   55  731  237
 079 316 1973  506 1237  966 1941 1275 1632  413 1380  515    0 1136  290
 079 316 1974  349 1146  512  408  685  753   85    0  535  300  220 1575
 079 316 1975    0  625 1725  790 1650 2610   85  355  105  580  125  290
 079 316 1976 1435  387   15   55  110   50   70   95  180    0  300 1235
 079 316 1977  610 1085 1375  880  245  305 1337  372  165   90  240  180
 079 316 1978 1334  835 1145  655  815  605  250  825  210 1680 2385  430
 079 316 1979  620  255  255  595  542  405  210  130  125  240   60  835
 079 316 1980  465  822  705 1691  699 1037  170  955  255    0 1015  170
 079 316 1981  680  525  530  230  530  600  375    0  625  340   50  430
 079 316 1982 1246  234  185   83  200  300  255  170  185 1165   25 1264
 079 316 1983  902  290  350  230  410  840  990  380  170  460   40  355
 079 316 1984  315  750  145  865 1910   90  335  230  165   30    0  320
 079 316 1985 2075 2235 1324  970  800 1050  830    0  240  140  310  740
 079 316 1986  840 1480  305  515  995  361  425  170  330   80  300 1555
 079 316 1987  865  250  507  517  825  870  360  495  200  405  275  540
 079 316 1988  676  685  865  308  725  895 1575  105  145  235    0   65
    079       647       1967      1972      599.6
 079 647 1967   40  810  260   78  120  370  500  155  200   35  220 1220
 079 647 1968  605  255  495  275 1109 1560  510  200   95  115  130  122
 079 647 1969  665  815  315  180 1085  190  355  150  480   22 2986  242
 079 647 1970  692  410 1560  977  755  344  506  480   10  748 1360   31
 079 647 1971  655  610  465  950 1913  605  325   67   85   45  150  285
 079 647 1972  507  754  225  390 1590  880  215   60    0   25  525  225
0000000000000000000000000000000000000000000000000000000000000000000000000
```

The recorded streamflow input data file is shown below. The file consists of lines of data beginning with the year and following with 12 monthly observed streamflow values (million m^3).

1967	0.10	0.28	0.12	0.02	0.00	0.08	0.40	0.08	0.12	0.08	0.03	3.13
1968	0.37	0.23	0.17	0.11	1.05	1.92	0.57	0.12	0.12	0.12	0.14	0.09
1969	0.11	0.61	0.11	0.13	1.13	0.24	0.09	0.07	0.07	0.11	10.98	0.77
1970	1.79	0.46	6.45	2.79	1.70	0.66	1.83	0.26	0.06	0.47	4.26	0.57
1971	0.23	0.34	0.89	0.60	3.96	1.36	0.85	0.01	0.14	0.13	0.12	0.12
1972	0.10	1.07	0.89	0.90	0.64	0.09	0.29	0.21	0.24	0.28	0.79	0.60
1973	0.05	1.07	0.89	0.90	1.09	1.09	0.58	0.37	0.26	0.22	2.23	0.26
1974	0.01	2.17	0.40	0.27	0.63	0.39	0.06	0.00	0.24	0.28	0.79	0.60
~~1975~~	~~0.55~~	~~1.07~~	~~0.89~~	~~0.90~~	~~1.09~~	~~1.36~~	~~0.41~~	~~0.59~~	~~0.09~~	~~0.21~~	~~0.07~~	~~0.06~~
1976	0.76	0.13	0.07	0.10	0.88	0.65	0.32	0.83	0.19	0.14	0.12	0.38
1977	0.27	1.64	1.18	3.15	0.58	0.50	1.51	0.90	0.48	0.27	0.20	0.13
1978	1.14	1.13	0.84	0.70	0.43	0.41	0.20	0.19	0.15	1.95	2.53	0.65
1979	0.53	0.22	0.09	0.15	0.13	0.17	0.06	0.06	0.06	0.07	0.07	0.08
1980	0.12	0.43	0.85	2.42	2.32	0.88	0.29	0.37	0.30	0.17	0.26	0.39
1981	0.24	0.14	0.22	0.32	0.10	0.32	0.19	0.06	0.09	0.09	0.05	0.12
1982	0.20	0.24	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.27	0.05	0.23
1983	0.70	1.83	0.68	0.98	0.33	1.41	0.92	0.17	0.12	0.10	0.08	0.06
1984	0.14	0.57	0.21	1.41	3.43	0.28	0.14	0.14	0.12	0.07	0.01	0.00
1985	0.92	5.91	5.02	1.99	0.58	1.28	0.53	0.28	0.15	0.11	0.14	0.30
1986	1.74	2.14	1.03	1.30	1.26	0.62	0.28	0.15	0.05	0.06	0.06	0.68
1987	0.41	0.39	0.20	0.47	1.48	3.07	0.68	0.36	0.24	0.21	0.20	0.50
1988	0.63	0.47	2.61	1.93	0.22	0.38	1.59	0.47	0.11	0.08	0.14	0.12

The input model parameter file is shown below.

INPUT MENU FOR PITMAN MONTHLY MODEL

Gauge	Area	MAP	Nit	Nusc	Nobs	Ne
CCCCCC	RRRRR.R	RRRR.R	I	I	I	I
R2H006	119.0	651.4	4	0	1	0

POW	SL	ST	FT	GW	AI	ZMIN	ZMAX	PI	TL	GL	R
R.R	R.R	RRR.R	RR.R	R.RR	R.RRR	RRR.R	RRR.R	R.R	R.RR	R.RR	R.RR
3.0	0.0	70.0	40.0	0.00	0.000	1000.0	1000.0	8.0	0.00	0.00	0.50

Airre	Afore	Ff	Piwtr	Growai
RR.R	RR.R	R.RR	R.RR	RR.RR
0.0	0.0	1.00	0.00	0.00

					PIndex						
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
I	I	I	I	I	I	I	I	I	I	I	I
0	0	0	0	0	0	0	0	0	0	0	0

Perm	Prexp	Effp	Cancap	Frmin	Prcan
RR.R	RR.R	R.RR	R.RR	RR.RR	RR.RR
0.0	0.0	0.00	0.00	0.00	0.00

Propfd	Estmar	Pcfd	Capfd	Surfd
RR.R	RR.R	R.RR	R.RR	RR.RR
0.0	0.0	0.00	0.00	0.00

Igt	Gria
IIII	RR.RR
0	0.00

Graf
RR.RR
0.00

Mean monthly Symons Pan evaporations

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R	RRR.R
105.0	152.0	174.0	174.0	145.0	131.0	94.0	80.0	72.0	64.0	82.0	93.0

Ly0	Ly1	Ly2
IIII	IIII	IIII
1957	1957	1988

INPUT AND OUTPUT FILES

```
    Observed flow data : C:R2H006OBS.FLW
Upstream flow data (1) : C:R2H006UP1.FLW
Upstream flow data (2) : C:R2H006UP2.FLW
Upstream flow data (3) : C:R2H006UP3.FLW
   Daily rainfall data : C:R2H006PPT.DAY
Historical Evaporation : C:R2H006HIS.EVP
 Monthly rainfall data : C:R2H006PIT.PPT
   AVRAIN calculations : C:R2H006CAL.AVR
  AVRAIN rainfall data : C:R2H006PPT.AVR
              PO4 data : C:R2H006.PO4
Output (with headings) : C:R2H006.OUT
  Output (no headings) : C:R2H006NON.OUT
```

Where the parameters are :

INPUT PARAMETERS FOR THE PHOSPHATE EXPORT MODEL

Gauge	: *Gauge name [6 Characters]*
Area	: Catchment area (km*km)
MAP	: Mean annual precipitation (mm)
Nit	: Number of iterations [daily = 0 ; monthly = 4]
Nusc	: Number of upstream catchments [=0,1,2 or 3]
Nobs	: Observed runoff record flag [1 = obs. ; 0 = no obs.]
Ne	: Actual evaporation flag [1 = actual evap. ; 0 = ?]
POW	: Power of soil moisture storage-runoff curve [= 1.0,2.0 or 3.0]
SL	: Soil moisture storage below which no runoff occurs (mm)
~~ST~~	: ~~Maximum soil moisture capacity (mm)~~
FT	: Runoff rate from soil moisture storage at maximum capacity (mm/month)
GW	: Maximum groundwater runoff rate (mm/month)
AI	: Impervious proportion of catchment [= 0.0 -> 1.0]
ZMIN	: Minimum catchment absorption rate (mm/month)
ZMAX	: Maximum catchment absorption rate (mm/month)
PI	: Interception storage capacity (mm/day)
TL	: Time lag runoff other than that from soil moisture ≤ GW (months)
GL	: Time lag groundwater ie. lag of runoff from soil moisture ≤ GW (months)
R	: Evaporation-soil moisture storage coefficient
Airre	: Irrigation area in last year of record (km*km) [= 0 -> Area]
Afore	: Forest area in last year of record (km*km) [= 0 -> Area]
Ff	: Forest factor [= forest PE/natural veld PE]
Piwtr	: Proportion of irrigation water that returns to the river
Growai	: Annual growth rate of urban area (Ai)

IRRIGATION (if Airre > 0)

Pindex[12]	: months of irrigation [1 = irrig. ; 0 = no irrig.]
Perm	: Maximum permitted abstraction in a season (million cubic meters)
Prexp	: Proportion of total river flow exploitable
Effp	: Proportion of rainfall assumed effective
Cancap	: *Take-off canal capacity (cumecs) [= 0.0 if no canal]*
Frmin	: Minimum river flow for canal abstractions (million cubic meters)
Prcan	: Propotion of river flow passing through canal
Propfd	: Propotion of total irrigation from farm dams
Estmar	: Estimated catchment MAR (million cubic meters) [used if Propfd > 0 AND if no estimate of Pcfd,Capfd & Surfd available]
Pcfd	: Proportion of catchment commanded by farm dams
Capfd	: Final capacity of farm dams (million cubic meters)
Surfd	: Final surface area of farm dams (km*km)
Gria	: Growth of irrigation area
Igt	: Units of growth [0 = (km*km)/year ; 1 = % per annum)

FOREST (if Afore > 0)

Graf	: Growth of forest area ((km*km)/year)

PE[12]	: Mean monthly Symons Pan evaporations (mm)
Ly0	: First year of rainfall in record
Ly1	: First year of simulation
Ly2	: Last year of simulation

Testing the adequacy of a simple linear regression fit :

$$\hat{y}_k = a_0 + a_1 x_k$$

1. Choose f, the degree of smoothing $0.33<f<0.67$, say $f=½$
2. Sort the (x_i,y_i) in ascending order of x_i, $i=1,2,..n$
3. For each point (x_k,y_k), perform a weighted least squares simple linear regression fit using the $f*n$ closest values to x_k. Use the following tricube weighting function to obtain appropriate weights:

$$w(i,k) = (1-\left|\frac{x_i - x_k}{\max|x_i - x_k|}\right|^3)^3$$

4. Define residuals for each (x_k,y_k) point by :

$$r_k = y_k - \hat{y}_k$$

5. Define robustness weights for each (x_k,y_k) point by :

$$b_k = (1 - \left[\frac{r_k}{6\eta}\right]^2)^2$$

where η is equal to the median of the r_k.

6. Redefine smoothing weights as :

$$w(i,k) = w(i,k)\ b(k)$$

7. Repeat steps 3, 4, 5 and 6 using the new w(i,k) weights.
8. Repeat step 3 using the latest w(i,k) weights.
9. LOWESS smoothed values are the predicted values for y_k obtained from the final weighted least squares simple linear regression fits.

Appendix I : Durbin-Watson Test for Residual Independence

I1

Durbin-Watson Test Critical Values

	Level of Significance $\alpha = 0.05$									
	$p = 1$		$p = 2$		$p = 3$		$p = 4$		$p = 5$	
n	d_L	d_U	d_L	d_U	d_L	d_U	d_L	d_U	d_L	d_U
15	1.08	1.36	0.95	1.54	0.82	1.75	0.69	1.97	0.56	2.21
16	1.10	1.37	0.98	1.54	0.86	1.73	0.74	1.93	0.62	2.15
17	1.13	1.38	1.02	1.54	0.90	1.71	0.78	1.90	0.67	2.10
18	1.16	1.39	1.05	1.53	0.93	1.69	0.82	1.87	0.71	2.06
19	1.18	1.40	1.08	1.53	0.97	1.68	0.86	1.85	0.75	2.02
20	1.20	1.41	1.10	1.54	1.00	1.68	0.90	1.83	0.79	1.99
21	1.22	1.42	1.13	1.54	1.03	1.67	0.93	1.81	0.83	1.96
22	1.24	1.43	1.15	1.54	1.05	1.66	0.96	1.80	0.86	1.94
23	1.26	1.44	1.17	1.54	1.08	1.66	0.99	1.79	0.90	1.92
24	1.27	1.45	1.19	1.55	1.10	1.66	1.01	1.78	0.93	1.90
25	1.29	1.45	1.21	1.55	1.12	1.66	1.04	1.77	0.95	1.89
26	1.30	1.46	1.22	1.55	1.14	1.65	1.06	1.76	0.98	1.88
27	1.32	1.47	1.24	1.56	1.16	1.65	1.08	1.76	1.01	1.86
28	1.33	1.48	1.26	1.56	1.18	1.65	1.10	1.75	1.03	1.85
29	1.34	1.48	1.27	1.56	1.20	1.65	1.12	1.74	1.05	1.84
30	1.35	1.49	1.28	1.57	1.21	1.65	1.14	1.74	1.07	1.83
31	1.36	1.50	1.30	1.57	1.23	1.65	1.16	1.74	1.09	1.83
32	1.37	1.50	1.31	1.57	1.24	1.65	1.18	1.73	1.11	1.82
33	1.38	1.51	1.32	1.58	1.26	1.65	1.19	1.73	1.13	1.81
34	1.39	1.51	1.33	1.58	1.27	1.65	1.21	1.73	1.15	1.81
35	1.40	1.52	1.34	1.58	1.28	1.65	1.22	1.73	1.16	1.80
36	1.41	1.52	1.35	1.59	1.29	1.65	1.24	1.73	1.18	1.80
37	1.42	1.53	1.36	1.59	1.31	1.66	1.25	1.72	1.19	1.80
38	1.43	1.54	1.37	1.59	1.32	1.66	1.26	1.72	1.21	1.79
39	1.43	1.54	1.38	1.60	1.33	1.66	1.27	1.72	1.22	1.79
40	1.44	1.54	1.39	1.60	1.34	1.66	1.29	1.72	1.23	1.79
45	1.48	1.57	1.43	1.62	1.38	1.67	1.34	1.72	1.29	1.78
50	1.50	1.59	1.46	1.63	1.42	1.67	1.38	1.72	1.34	1.77
55	1.53	1.60	1.49	1.64	1.45	1.68	1.41	1.72	1.38	1.77
60	1.55	1.62	1.51	1.65	1.48	1.69	1.44	1.73	1.41	1.77
65	1.57	1.63	1.54	1.66	1.50	1.70	1.47	1.73	1.44	1.77
70	1.58	1.64	1.55	1.67	1.52	1.70	1.49	1.74	1.46	1.77
75	1.60	1.65	1.57	1.68	1.54	1.71	1.51	1.74	1.49	1.77
80	1.61	1.66	1.59	1.69	1.56	1.72	1.53	1.74	1.51	1.77
85	1.62	1.67	1.60	1.70	1.57	1.72	1.55	1.75	1.52	1.77
90	1.63	1.68	1.61	1.70	1.59	1.73	1.57	1.75	1.54	1.78
95	1.64	1.69	1.62	1.71	1.60	1.73	1.58	1.75	1.56	1.78
100	1.65	1.69	1.63	1.72	1.61	1.74	1.59	1.76	1.57	1.78

Transfer model identification and fitting:
Tindall Example: Phosphorus-Runoff Relationship.

1. Using the Time Series : Box & Jenkins procedure in Statgraphics (1989), fit a suitable model for the logged runoff ($\ln X_t = x_t$) data.
Examine the serial (auto)correlation function (ACF). This function consists of the correlations between the x_t series at time lags of 0,1,2,3,.... periods. For the Tindall River (USA) this plot suggests an autoregressive one (AR-1) model :

$$x_t = cx_{t-1} + a_t$$

2. Prewhiten the corresponding phosphorus export data, $y_t = \ln Y_t$, using the above model. The prewhitened phosphorus export data for the Tindall River is given by :

$$n_t = y_t - cy_{t-1}$$

3. Calculate the cross-correlation between the a_t and n_t time series. This is the correlation function between the two series at various lags. Any correlation with absolute value in excess of $3/\sqrt{n}$ is considered to be significant. In the case of the Tindall River a significant cross-correlation is observed only at a lag of zero.

4. Estimate and identify the form of the error process e_t. In the case of the Tindall River the error process is defined as :

$$e_t = y_t - c(0)\,\frac{s_n}{s_a}\,x_t$$

where c(0) denotes the cross-correlation at a lag of zero periods, s_n denotes the standard deviation for n_t and s_a denotes the standard deviation for a_t. For the Tindall River the appropriate form for the error model is again an autoregressive one (AR-1) model :

$$(1 - cB)\,e_t = m_t$$

where $Be_t = e_{t-1}$ and the m_t are distributed $N(\mu,\sigma^2)$ with no serial correlation.

5. Estimate the complete transfer model. For the Tindall River the complete transfer model is derived as follows :

$$y_t = bx_t + \frac{m_t}{(1-cB)}$$
$$\text{ie. } y_t(1-cB) = bx_t(1-cB) + m_t$$
$$\text{ie. } y_t = cy_{t-1} + bx_t - bcx_{t-1} + m_t$$

where the m_t are distributed $N(\mu,\sigma^2)$ with no serial correlation (ie. independently). This can be done iteratively by minimising the error sum of squares by :

$$S(b,c) = \sum_{t=1}^{n} m_t^2 .$$

K1 Introduction

In this study model evaluation has been conducted using a statistical approach on Statgraphics (1989). After describing the measures used to evaluate the various conventional REM models, it is indicated how Statgraphics (1989) can be used to estimate these measures.

K2 Model Evaluation Measures

In this study models are evaluated according to bias, the coefficient of efficiency denoted as R^2 in this report, and error standard deviation. Bias measures the mean prediction error and is expressed as a percentage of the observed mean. Ideally the bias should be zero. The R^2 values provide a measure of the explanatory power of the model. Ideally the R^2 should be close to unity. Finally the error standard deviation, which is often expressed as a percentage of the observed mean, is used. Ideally this measure should lie close to zero. However, when the errors exhibit significant serial correlation the R^2 and error standard deviation measures are unreliable. The R^2 values tend to be over-estimated and the error standard deviations tend to be under-estimated. This means that the R^2 and error standard deviation measures must be corrected for the presence of significant serial correlation in the errors before they can be given any credence.

K3 Calculation of Model Evaluation Measures

K3.1 *Error Definition*

The first point to consider is the definition of the errors. Errors can be defined as the difference between observed and predicted values or as the ratio of observed to predicted values. Analysis for the latter is much more complicated.

Start by plotting observed y_t values against predicted $\hat{y}_t$ values using a simple X-Y plot with $\hat{y}_t$ on the x-axis and y_t on the y-axis. If the plot suggests a random scatter, with approximately constant range in y_t for all values of $\hat{y}_t$, then errors should be defined as the difference between observed and predicted values :

$$e_t = y_t - \hat{y}_t \qquad \text{Eq. K 1}$$

If, instead, one finds that for high values of $\hat{y}_t$ the range in y_t values is much greater than for low values of $\hat{y}_t$, then the errors should be defined as the ratio of observed to predicted values. This is the case for the Pitman (1973) model predictions of runoff for the Sterk river, illustrated in Figure K1.

However, it is much easier to work with the log of this ratio. So, in this situation it is best to define :

$$e_t = \ln\left(\frac{y_t}{\hat{y}_t}\right) = \ln(y_t) - \ln(\hat{y}_t) \qquad \text{Eq. K 2}$$

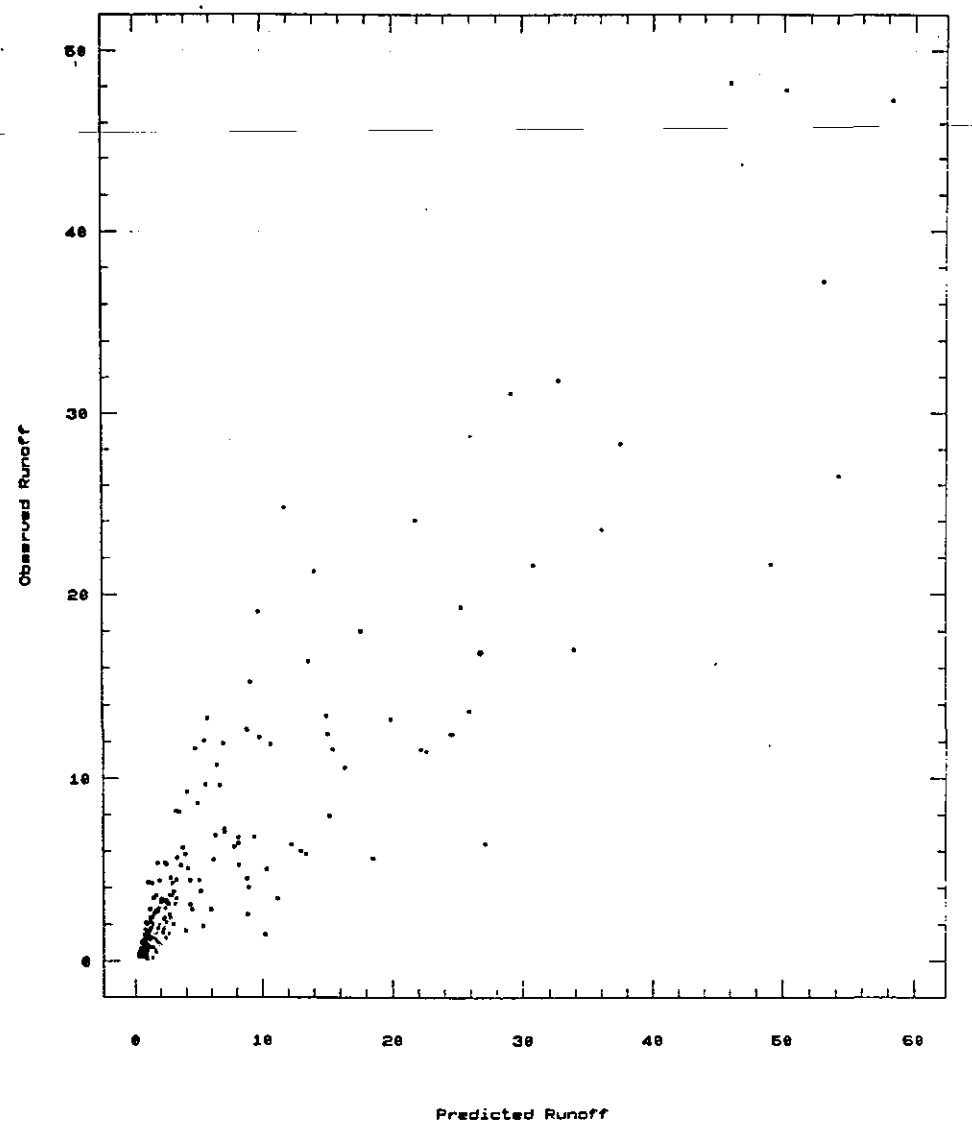

Figure K1 Observed v predicted runoff for the Sterk River : Opening fan

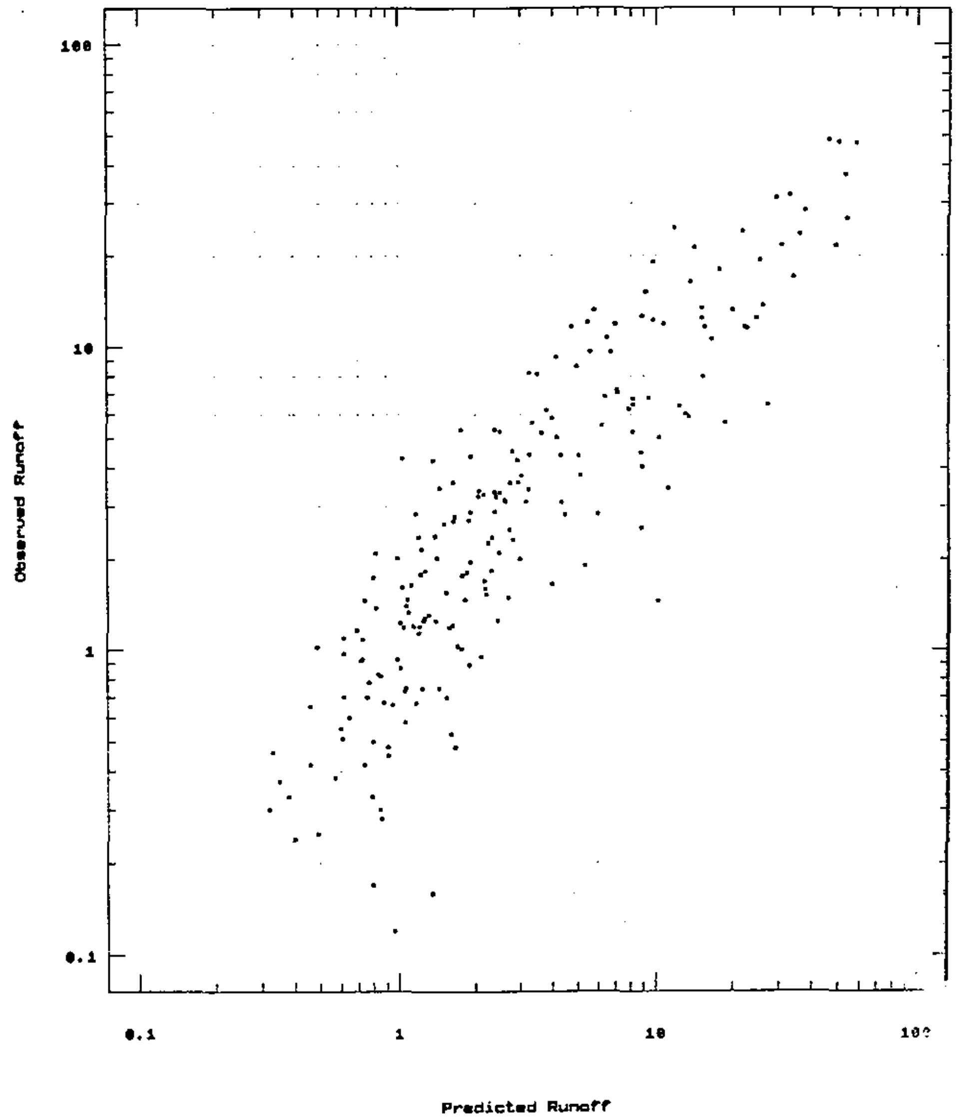

Figure K2 Log-log scale Sterk River : Observed v predicted runoff

As shown in Figure K2, the effect of logging the observed and predicted runoff values for the Sterk river is to produce a figure with approximately constant y_t range for all values of $\hat{y}_t$, the type of pattern for which errors should be defined as in Equation K1.

K3.2 *Percentage Bias*

Bias is easily calculated using the Statgraphics (1989) package. The "Summary Statistics" option under "Descriptive Methods" can be used to calculate the sample means for the observed (y_t) and predicted ($\hat{y}_t$) values. Ensure that the same sample observation numbers, t, are used to calculate both means. The percentage bias is calculated from the formula :

$$Bias\% = 100\frac{\bar{\hat{y}} - \bar{y}}{\bar{y}} \qquad \text{Eq. K 3}$$

When errors are defined as in Equation K1 this bias formula translates to the formula :

$$Bias\% = 100\frac{-\bar{e}}{\bar{y}} \qquad \text{Eq. K 4}$$

However, when the errors are defined as in Equation K2 there is no easy formula for expressing bias in terms of the mean error. In theory if the errors, e_t, are distributed $N(\mu,\sigma^2)$ then the bias % is equal to :

$$\begin{aligned} Bias\% &= 100\frac{\bar{y}\exp(-\mu-\frac{\sigma^2}{2}) - \bar{y}}{\bar{y}} \\ &= 100(\exp(-\mu-\frac{\sigma^2}{2})-1) \end{aligned} \qquad \text{Eq. K 5}$$

However, in practise, μ and σ^2 are unknown, and Equation K5 can only be applied with any success if very accurate estimates for μ and σ^2 are available.

The bias calculation is illustrated using Pitman runoff predictions for the Sterk River. Using Equation K3 and the "Descriptive Statistics:Summary Statistics" shown in Table K1 the bias percentage for these predictions found to be equal to 16%. For this data it was recommended in section K3.1 that the errors be defined as the log of the ratio for observed and predicted values as indicated in Equation K2. Table K1 indicates that the mean and standard deviation for these errors are -0.062 and 0.600 respectively. If these estimates for μ and σ^2 in Equation K5 are used in order to re-estimate the bias a value of -11% is obtained. As expected, in practise Equation K5 does not generally yield reliable estimates of bias.

Before R^2 and error standard deviations can be calculated it must be determined whether the errors show serial correlation.

Table K1 Summary statistics for Sterk River runoff predictions

Variable	RUNOBS	RUNPRED	LOG(RUNOBS/RUNPRED)
Sample size	204	204	204
Average	5.89069	6.82995	-0.0623387
Median	2.745	2.28	-0.0102254
Mode	0.7	0.62	0
Geometric mean	2.74543	2.92202	
Variance	70.5837	117.978	0.360116
Std. dev.	8.40141	10.8618	0.600097
Std. error	0.588217	0.760477	0.0420152

K3.3 *Error analysis*

The easiest way to test for serial correlation for errors defined as indicated in Equations K1 or K2, is to use the "Box-Jenkins *ARIMA Modelling*" *procedure found under* "Time Series Analysis". When the errors are analyzed by this procedure the autocorrelation plot can be used to determine whether the errors are serially correlated. The terms autocorrelation and serial correlation are synonymous and will be used interchangeably in the remainder of this appendix. The autocorrelation for a lag of unity measures the correlation between all errors separated in time by only one time period (a month in this case). Similarly the autocorrelation for a lag of two measures the correlation between all errors separated in time by two time periods (eg. two months). Statgraphics (1989) furnishes a plot of these autocorrelations complete with a zero line, an upper two standard error line and a lower two standard error line. If an autocorrelation departs from the zero line to such an extent that either the upper or the lower two standard error line is crossed, it means that for this lag there is significant (non-zero) autocorrelation. If there is significant autocorrelation at any lag, the errors are said to be serially correlated.

In this study only two forms of serial correlation in the errors were observed. The first form is characterised by an autocorrelation function which oscillates around zero like a gradually dying sine wave. The autocorrelation at a lag of unity is always significantly different from zero. Refer to Figure K3 for an example of such an autocorrelation function (for the Sterk River Pitman predictions of runoff). The errors corresponding to such an autocorrelation function are said to be generated by an autoregressive one (AR-1) process. This means that the errors can be described by the model :

$$e_t = \phi e_{t-1} + a_t \qquad \text{Eq. K 6}$$

where ϕ can be estimated by the ARIMA procedure and a_t represents a series of independent (ie. uncorrelated) identically distributed random variables.

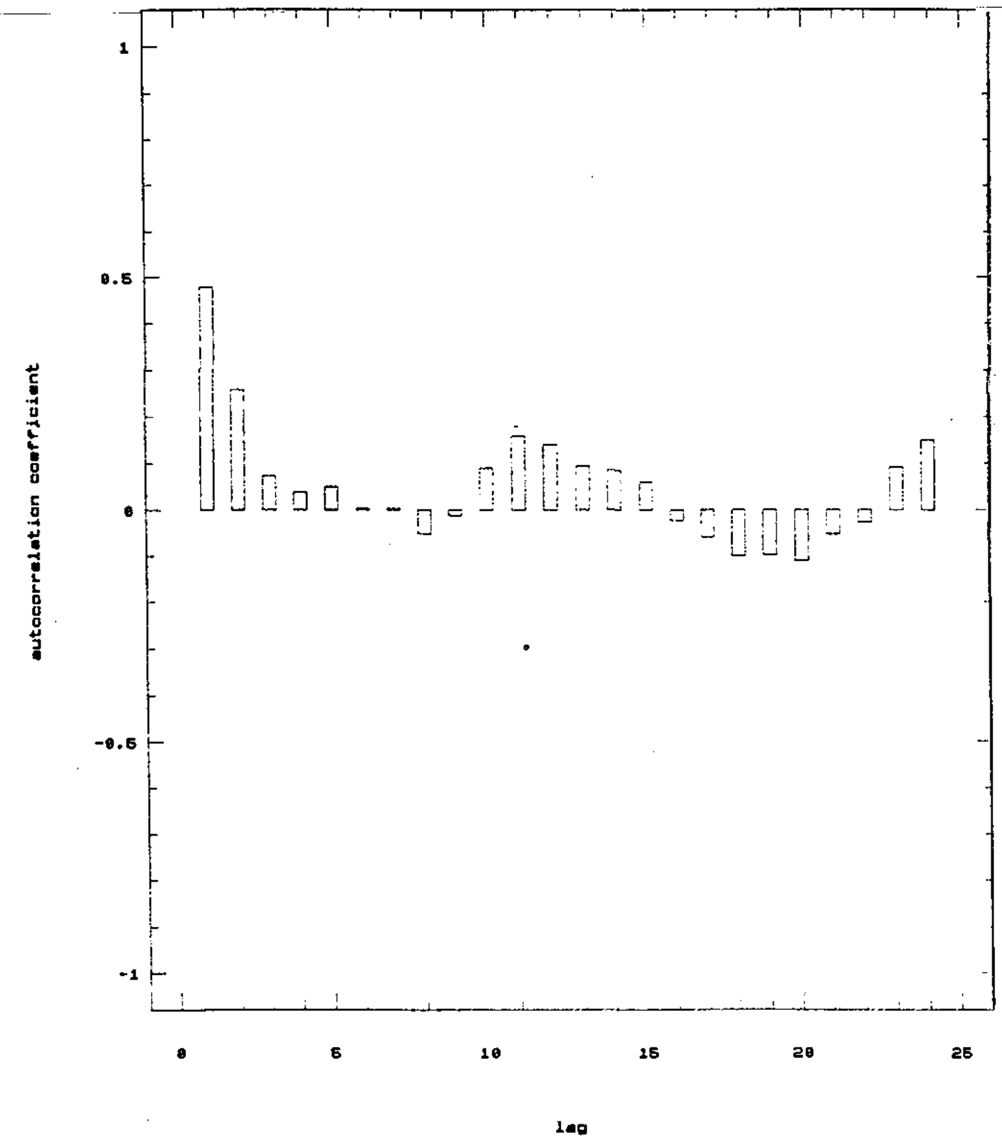

Figure K3 Estimated autocorrelation for log(observed/predicted) : Sterk River

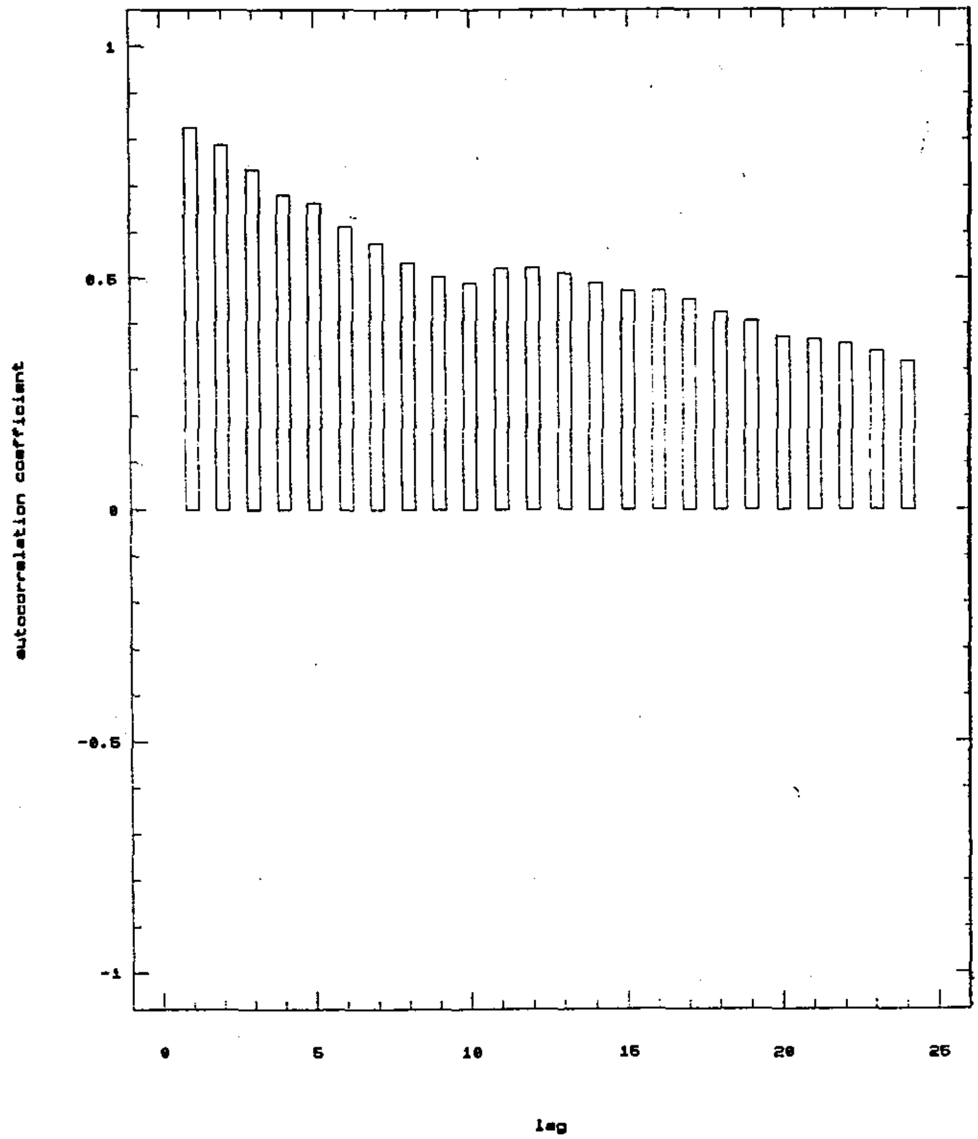

Figure K4 Estimated autocorrelation for log(observed/predicted) : Magalies River

The second form of error serial correlation observed, is characterised by an autocorrelation function which has the form of a decay which tends to remain on only one side of the zero line. Again the autocorrelation at a lag of unity is always significantly different from zero. Refer to Figure K4 for an example of such an autocorrelation function (for the Magalies River Pitman predictions of runoff). The following model can be used to describe the autocorrelation structure of this series.

$$e_t = \phi_1 e_{t-1} + \phi_2 e_{t-2} + a_t \qquad \text{Eq. K 7}$$

with a_t defined as above.

However, when errors are not serially correlated :

$$e_t = a_t \qquad \text{Eq. K 8}$$

In all cases it was found that, for suitably defined e_t (see section K3.1), the a_t can be assumed to be normally distributed with constant variance. This is important because it means that distributions for prediction errors can be easily generated for use in Monte Carlo simulations.

Tests for constant a_t variance are usually performed visually using plots of a_t against $\hat{y}_t$. If this plot has a random appearance with approximately constant range it is reasonable to assume that the a_t have constant variance. Tests for normality are most easily performed using the "Distribution Functions/Distribution Fitting" procedure and the Kolmogoroff-Smirnov test statistics. If the approximate (observed) significance level associated with this test is greater than 0.1 it is not unreasonable to assume that the a_t are normally distributed. The closer the approximate (observed) significance level lies to unity, the more reasonable is this assumption.

The Sterk River Pitman runoff prediction errors are now analyzed using the above methods. As indicated by Figure K3, an autoregressive one (AR-1) model of the form of Equation K6 can be used to describe the autocorrelation structure of the errors. In Table K2 this model has been fitted to the errors, giving rise to an estimate of 0.47958 for ϕ. The mean for the a_t is estimated to be -0.0283 and the variance is estimated to be 0.278691. Having stored the a_t residuals after subtracting their mean, the test is whether or not it is reasonable to assume a normal distribution. Performing the Kolmogoroff-Smirnov test as indicated above, Table K3 was obtained. The approximate (observed) significance level is well above 0.10 indicating that it is reasonable to assume in Monte Carlo simulations that the a_t are normally distributed, with a mean and variance of -0.0283 and 0.278691 respectively.

K3.4 *The R^2 and error std. dev. for independent errors*

In multiple linear regression the R^2 is the proportion of the variability in y, relative to its mean level, which is explained by the predictions. This quantity is automatically calculated by Statgraphics (1989) in its regression model fitting procedures. Actually this can be a disadvantage because when the errors are serially correlated, the R^2 is still calculated (assuming independent errors). Ideally a warning regarding the unreliability of this measure should appear when errors are serially correlated.

Table K2 AR(1) Error model for the Sterk River errors

Estimation begins..... Initial: RSS = 56.3028 b = 0.478888 -0.0623387 Final: RSS = 56.2955 ...stopped on criterion 2				
Summary of Fitted Model for: LOG(U2M06.RUNOBS/U2M06.RUNPRED)				
Parameter	Estimate	Stnd.error	T-value	P-value
AR (1)	.47958	.06181	7.75903	.00000
MEAN	-.05437	.07047	-.77163	.44124
CONSTANT	-.02830			
Estimated white noise variance = 0.278691 with 202 degrees of freedom Estimated white noise standard deviation (std err) = 0.527912 Chi-square test statistic on first 20 residual autocorrelations = 12.2471 with probability of a larger value given white noise = 0.874792 Backforecasting: no Number of iterations performed: 1				

Table K3 Kolmogoroff-Smirnov test for a_t normality

Estimated KOLMOGOROV statistic DPLUS = 0.0331029 Estimated KOLMOGOROV statistic DMINUS = 0.0488503 Estimated overall statistic DN = 0.0488503 Approximate significance level = 0.715025

The formula used to calculate the R^2 is :

$$R^2 = 1 - \frac{\sum_{t=1}^{n} e_t^2}{\sum_{t=1}^{n} (y_t - \bar{y})^2} \qquad \text{Eq. K 9}$$

When this formula is used for measuring the adequacy of fit when predictions have been obtained by non-regression methods, it is possible for negative values to be obtained. Consequently R **squared** is an unfortunate choice of name for this measure of fit. However, negative R^2 values can only occur for an exceedingly poor model calibration. For properly calibrated models a negative R^2 is impossible.

The size of the error has been assessed using a measure which has been called the error standard deviation. The error standard deviation is sometimes expressed as a percentage of the observed mean. This is calculated using the formula :

$$Std.Dev.\% = 100\frac{\sqrt{\frac{\sum_{t=1}^{n}(y_t - \hat{y}_t)^2}{n-p}}}{\bar{y}} \qquad \text{Eq. K10}$$

where p denotes the number of parameters estimated during model calibration.

K3.5 *The R^2 and error std. dev. for serially correlated errors*

The assumption is made that the errors, e_t, are defined as the difference between the observed and predicted values of the response variable, y_t :

$$e_t = y_t - \hat{y}_t$$

Furthermore, assuming that the errors are serially correlated and can be described by the model :

$$e_t - \phi e_{t-1} = a_t$$

with the a_t denoting an independent (noise) series or process, then when the equation :

$$y_t - \phi y_{t-1} = b_0 + b_1 \ (\hat{y}_t - \phi \hat{y}_{t-1})$$

is fitted to the data, using Simple Linear Regression, the R^2 and error standard deviation obtained will approximate the true R^2 and error standard deviation for the model.

K4 Summary

Random error plots are evidence of an adequate model. But the percentage bias, the R^2, and error standard deviation, are also useful measures of model adequacy. The best model has the lowest bias%, the highest R^2 and the lowest error standard deviation.

In this study it has been possible to achieve all three of these goals simultaneously. For simulations carried out ignoring the error distributions a low bias, preferably zero bias, is essential. In this situation bias can result in misleading simulation results. In the Monte Carlo simulations, any model bias is corrected for by means of a non-zero mean for the error distribution.

L1 Introduction

There are usually five stages in model development : conceptualization, formulation, calibration, verification and application. These stages have been used, predominantly, to fit dynamic models to South African time series data. The calibration for each model is specific to an individual water body. In theory, the complexity of these models is limited only by the extent of the available data base. However, in practise it is found that the reliability of prediction deteriorates with increasing complexity. The models have therefore been kept as simple as possible.

L2 Conceptualization

The basic goal of the REM model is to predict the impact of a change in water quality management strategy. This means that it is necessary for the models to be robust to such changes. For example, the parameters of the model should not include phosphorus concentration when changes in phosphorus loading are envisaged. And the models must be causal in nature, relating directly to the processes at work.

It was found that rainfall, and hence runoff, "drove" the system. Once this causal relationship had been correctly modelled it was found that errors were devoid of seasonality. Consequently, at no stage of the analysis was a seasonal decomposition or seasonal model appropriate. This means that all the seasonality in the system was so closely correlated with runoff that, once the runoff effect had been modelled, seasonality no longer existed.

L3 Formalization

Linear regression models have been used to formulate the conceptual models. There are many advantages in these relatively simple models. They are easily calibrated and uncertainty or error analysis is straightforward. In addition regression models are easily extended to introduce more of the realities of southern African water systems.

The first question which must be answered before a linear regression model can be formalized concerns the decision of data transformation by means of logs. A linear regression model assumes linearity in the regression coefficients. This means that a model of the form:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \varepsilon \qquad \text{Eq. L 1}$$

must be appropriate. The variables X_1, X_2 ... can be defined in any way, for example as variable products or variable squares. In this model it is assumed that the errors, ε, are independently distributed $N(0,\sigma^2)$.

A model of the form :

$$Y = \alpha_0 \, X^{\alpha_1} \, \epsilon \qquad \text{Eq. L 2}$$

is obviously not a linear regression model. However, it can be linearised by taking log transformations, as indicated below.

$$\ln Y = \ln\alpha_0 + \alpha_1 \ln X + \ln\epsilon$$
$$= \beta_0 + \beta_1 \ln X + \varepsilon \qquad \text{Eq. L 3}$$

Consider the Magalies River phosphorus export-runoff relationship illustrated in Figure L1. It is clear from this plot that the scatter in phosphorus export increases for higher runoffs/phosphorus exports. This suggests a multiplicative error term such as that shown in Equation L2. Plotting this phosphorus-runoff relationship on a log-log scale it is found that the scatter, and hence the error variance, become much more constant suggesting an additive constant variance error term such as that shown in Equations L1 and ~~L3,~~ and illustrated in Figure L2. This means that a linear regression model can only be used to describe the runoff-phosphorus export relationship if both phosphorus export and runoff are initially log transformed.

When Equation L3 is fitted to such data, the mean of the prediction errors, e_t, is zero. It might therefore be assumed that predicted phosphorus values could be obtained by taking the exponential of the ln(phosphorus) predictions. This is not so. Such practise results in seriously biased predictions. As suggested in section K3.2, when errors defined by the equation :

$$e_t = \ln y_t - \ln\hat{y}_t \qquad \text{Eq. L 4}$$

follow a $N(\mu,\sigma^2)$ distribution, predicted values, $\ln\hat{y}_t$, should be bias corrected using the formula :

$$\hat{Y}_t = \exp(\ln\hat{y}_t)\ \exp(\mu + \frac{\sigma^2}{2}) \qquad \text{Eq. L 5}$$

However, in practice μ and σ^2 are unknown, and if the estimated values for μ and σ^2 are used, the bias-corrected predictions for the sampled y-values are still badly biased.

This seems to suggest that it is better to use nonlinear regression to fit an equation to data of the form of Equation L2 rather than to linearise the relationship using Equation L3 and then anti-log the predictions. However, nonlinear regression estimates also tend to be biased. Moreover it is difficult to extend a nonlinear regression formulation to encompass more explanatory variables.

Instead it is suggested that a (log) linearised relationship (Equation L3) be used to obtain predictions for $\ln(y_t)$ and then, after exponentiation, a data dictated correction factor be applied in order to eliminate observed prediction bias. That is :

$$\hat{Y}_t = \exp(k\mu + \frac{1}{2}k^2\sigma^2)\ \exp(\ln\hat{y}_t) \qquad \text{Eq. L 6}$$

where μ and σ^2 are estimated by the error mean and variance and k is chosen so that :

$$\bar{y} = \exp(k\mu + \frac{1}{2}k^2\sigma^2)\ \overline{\exp(\ln\bar{y})} \qquad \text{Eq. L 7}$$

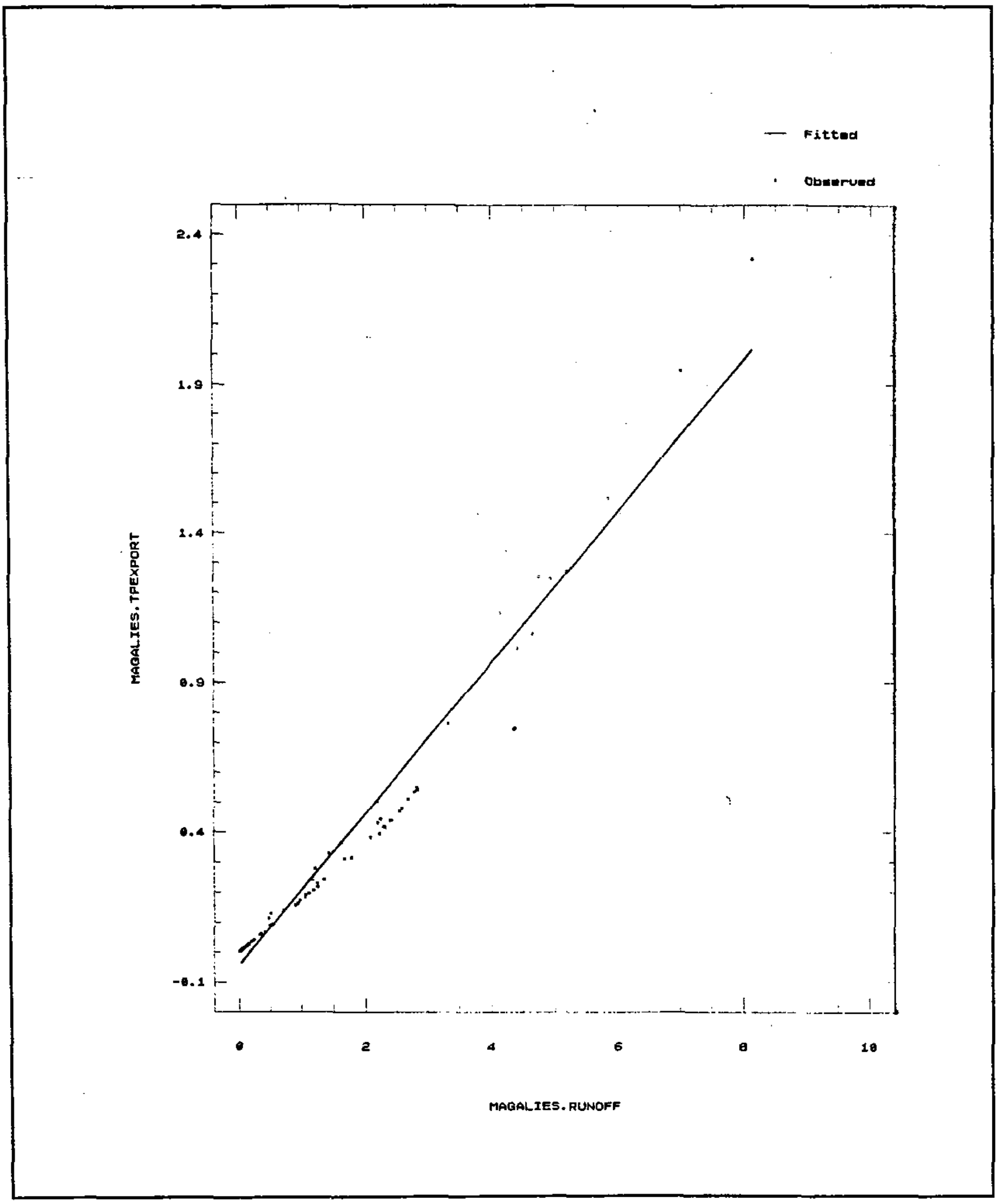

Figure L1 Magalies phosphorus-runoff : Simple linear regression prediction

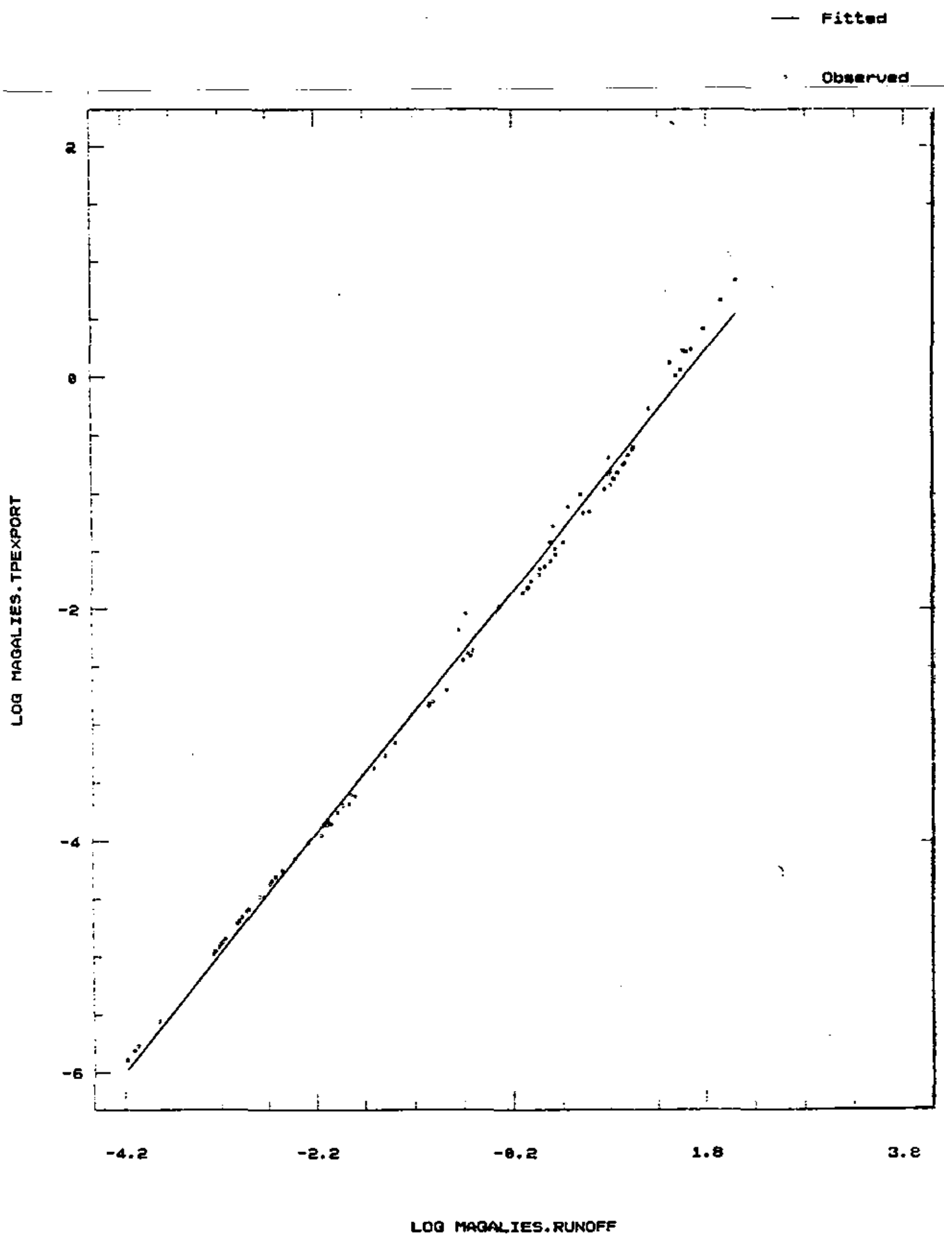

Figure L2 Ln(phosphorus) v Ln(runoff) : Simple linear regression prediction

L4 Calibration

Linear Regression Models are calibrated by minimising the sum of the prediction errors squared. When new chlorophyll models were being developed in this study, the conceptualization and calibration stages of model development were often combined. This was done using the stepwise regression procedure.

When the effect of several related X_i variables on Y are to be examined, stepwise regression chooses the optimum set of X_i variables to explain Y. This set is optimum in the sense that the R^2 is as high as possible while all the β_i coefficients are significantly different from zero. However, there is a danger in this approach. This approach may produce models which do not make conceptual sense. Although such models may produce good predictions for the calibration data set, it is doubtful that these models will produce reasonable simulations when conditions change. It was found that it was useful to apply both a forward and a backward selection of variables in the stepwise regression. Simpler models with fewer parameters tended to be favoured over more complicated models. Although the R^2 (adjusted) does make an adjustment to the R^2 in favour of simpler models, a marginally higher R^2 (adjusted) for a more complicated model will not produce more accurate predictions than a simpler model when circumstances change.

L5 Verification

Uncertainty or error analysis has been used as the verification tool. If the errors obtained from a calibrated model do not satisfy the assumptions of the linear regression model this means that the model is not complete, or inappropriate. Regression models assume that the errors are not serially correlated and that both the mean level and variance of the errors is constant, independent of the value of any variable. It was found that when the verification stage identified problems in the nature of the errors, model changes were automatically suggested. So model reconceptualization was automatically triggered as a result of model verification problems. To start with consider the problem of errors for which the mean and/or variance are not constant.

In this study the problem of non-constant variance occurred often. An opening-fan shaped error plot occurred repeatedly. Such an error pattern indicates that the data should be transformed using logarithms and then refitted.

The problem of non-constant error mean level occurred in the case of the runoff(X)-phosphorus export(Y) relationship. After fitting :

$$\ln Y = \beta_0 + \beta_1 \ln X + \varepsilon \qquad \text{Eq. L 8}$$

it was found that for the South African rivers there was a tendency for errors to follow a U-shape when plotted against ln(Runoff). That is the mean value of the errors tended to be positive for low and high runoffs, but negative in between. This suggested that a quadratic relationship existed between ln(Runoff) and ln(phosphorus) which should be modelled by the equation :

$$\ln Y = \beta_0 + \beta_1 \ln X + \beta_2 (\ln X)^2 + \varepsilon \qquad \text{Eq. L 9}$$

In Figure L3 the errors for model Equation L8 have been plotted against ln(Runoff) for the Magalies River. For this river the strength of the U-shape suggested the model Equation L9. Clearly model verification has resulted in model reconceptualization in this case.

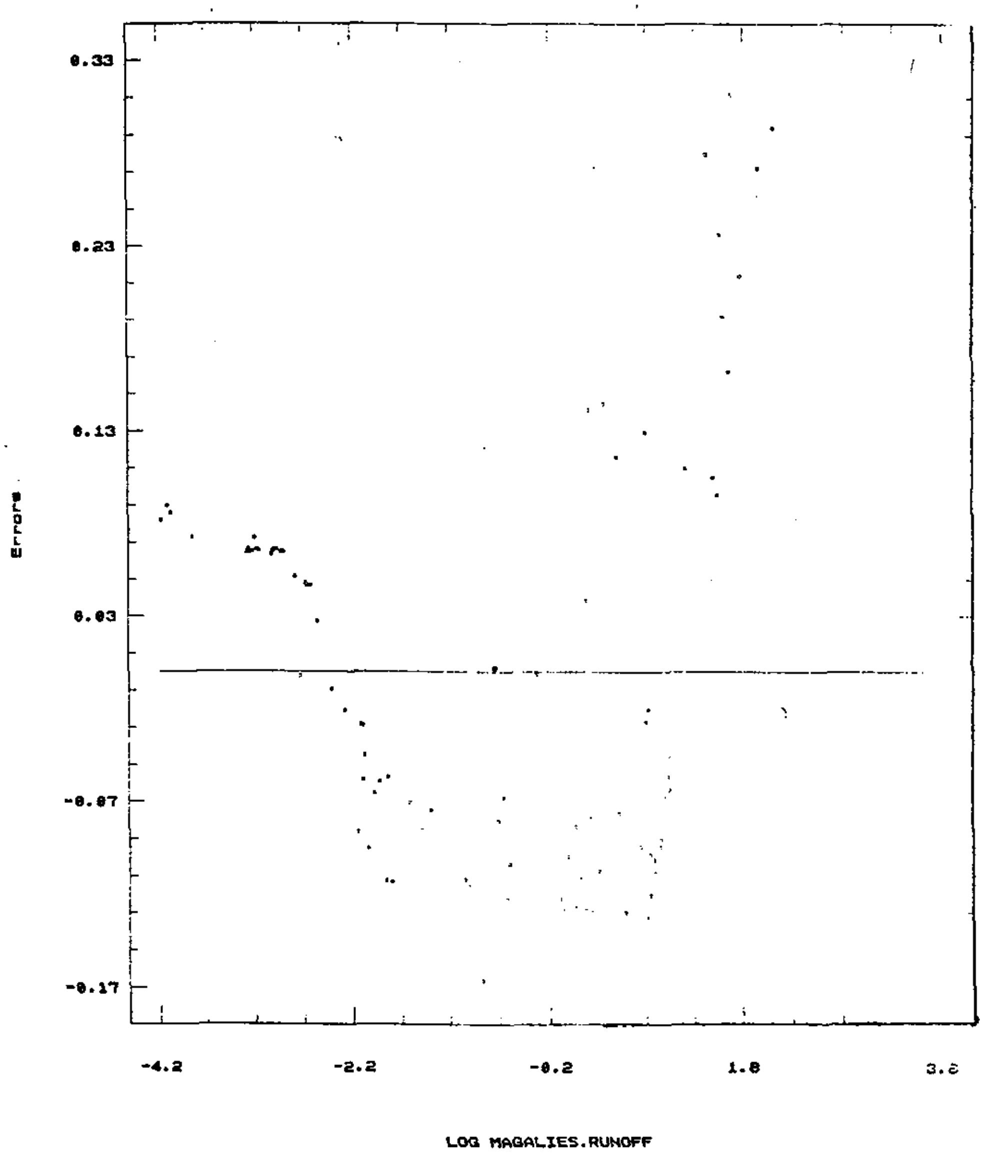

Figure L3 Errors for phosphorus fit : Simple log-log linear regression model

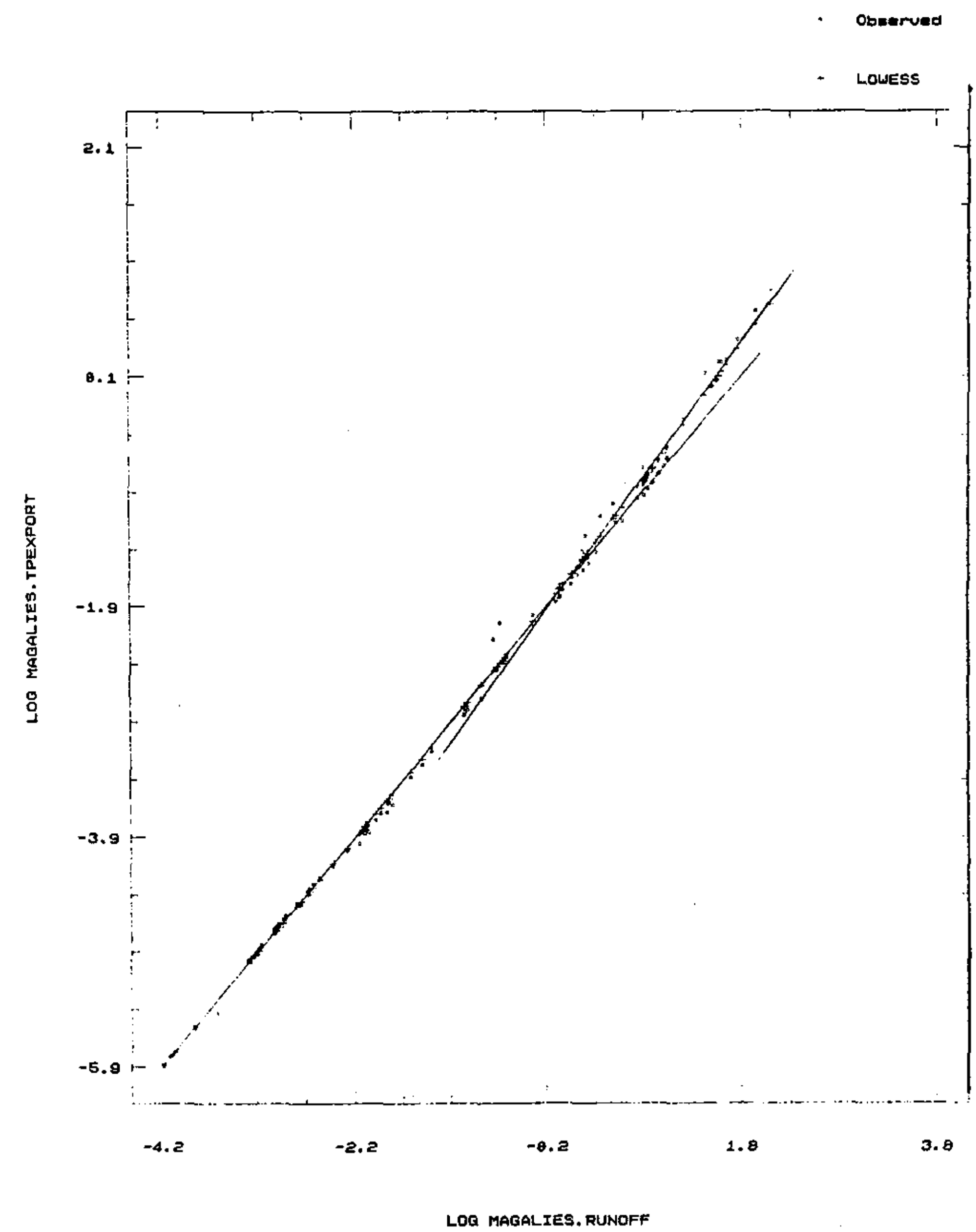

Figure L4 Magalies River : LOWESS smoothing ln(phosphorus export)

LOWESS smoothing is another method for identifying the true form of a relationship. LOWESS smoothed values for ln(Y) for the Magalies River are shown in Figure L4. LOWESS smoothing was developed by Cleveland (1979) and is explained in Appendix H. Each smoothed point is predicted from its own weighted regression line. The weights used in each regression are lower for points which are outliers and for points far-removed from the smoothed point.

Problems involving serially correlated errors are considered next. For time series data the Durbin-Watson statistic is a very useful measure of error independence. For values of this statistic close to two, error independence between successive errors can be assumed. For values of this statistic close to zero successive errors are positively correlated and for values of this statistic close to four successive errors are negatively correlated. Critical values for this statistic are readily available. (Durbin and Watson, 1951 ; refer Appendix I).

When the errors were not independent, in all respects, the conceptualization stage must be returned to in order to reformulate the models. Serial correlation in the errors can be an indication of missing variables in a model or of autocorrelation in the input series or both.

Missing variables can be identified by means of error plots as indicated above. In the case of the runoff-phosphorus export relationship, the input runoff figures are autocorrelated. This is certainly, partly a seasonal effect. In the summer rainfall regions of South Africa low runoff recordings tend to be obtained in consecutive months during winter while high runoff recordings tend to be obtained during consecutive summer months. So even when the quadratic ln(Runoff) model Equation L9 had been fitted, it was found that errors were still serially correlated.

When an input series exhibits autocorrelation a time series transfer model should be fitted using the approach described in Appendix J (Box and Jenkins, 1970). An example of such a model is the form :

$$\ln Y_t - c\ln Y_{t-1} = \beta_1(\ln X_t - c\ln X_{t-1}) + \beta_2((\ln X_t)^2 - c(\ln X_{t-1})^2) + \varepsilon \qquad \text{Eq. L10}$$

where the parameter c forces error independence.

When the errors eventually comply with all the regression assumptions no further reconceptualization is warranted. At this stage the distribution of the errors must be established using the "Distribution Function/ Distribution Fitting procedure". Inference for a linear regression model, for example, tests for the significance of the β_i, require that the errors come from a normal distribution. In this study it was found, using the Kolmogoroff-Smirnov test, that the distribution of errors never departed significantly from a normal distribution.

In linear regression independently normally distributed errors with constant variance are assumed. Only when the residuals support all these assumptions can a model be considered adequate.

L6 Applications

As indicated above the distribution of the errors was established for the final models. Assuming independence between the error distributions for the various models, a Monte Carlo simulation was employed to assess the effect of various phosphorus control strategies. By using a Monte Carlo simulation the distributions for the prediction errors of the various models were incorporated into the assessment. Monte Carlo simulations provide not only a simulated mean for the response variable, (chlorophyll concentration in this case), but also an estimate of the standard error associated with this mean.

L7 Summary

Model development is an iterative procedure in more ways than one. Model confirmation from verification studies for individual water bodies should be followed by model comparison for other water bodies. In this study the models for individual water bodies have been verified by ensuring that the prediction errors complied with the linear regression assumptions. In addition models have been developed for more than one time series. When the same form of model was found to be appropriate for all such time series, the model form gained respectability.

Certainly the aim should be to produce a model formulation which can be applied universally in South Africa, if not elsewhere. But, for simulations of the nature required in REM modelling, reservoir specific models are unavoidable in view of the diverse behaviour of South African reservoirs.