



Sediment Yield Prediction for South Africa: 2010 Edition

Report to the

WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

Introduction

This is a report of the work on the revision of the sediment yield map of Southern Africa. The current sediment yield determination methodology of Southern Africa was developed in 1992 (Rooseboom et al., 1992). Continual revision of sediment yield prediction methods is necessary in the wake of changing environments, more data, advanced analysis tools, increased experience and current technological advancements in the sedimentation field. This report presents the revised methods for the prediction of sediment yields from ungauged catchments for South Africa and Lesotho.

Aims of the project

The aim of this project was to develop sediment yield prediction methods based on analytical approaches and mathematical modelling. The sediment yield prediction methods can be used in planning and management of water resources particularly in reservoir sedimentation control at a catchment scale. The catchment erosion and sediment yield modelling methods can be applied in temporal and spatial analysis of sediment yields within a catchment from a point scale to a catchment scale where results are essential for the detailed design of water resources, particularly in the identification of critical erosion areas, sediment sources and formulation of catchment management strategies.

Objective

The key objective of the project was to improve the methods for the prediction of sediment yields by revising current procedures and guidelines for the prediction of sediment yields from ungauged catchments.

Methodology

The development of the revised methods involved the following steps: collection of data, refinement and calibration of national erosion hazard potential data, preparation of electronic copies of erosion hazard potential maps, computation of sediment yield values, delineation of homogeneous regions, regional analysis and assessment of data, generation of catchment area erosion hazard potential statistics and development of sediment yield estimation methods. The proposed Polihali Dam in Lesotho was selected as a case study to illustrate the role and application of mathematical modelling in sediment yield prediction within a catchment.

Conclusion

The observed sediment yields were calculated from reservoir sediment deposition data and river sediment sampling. The relationships between sediment yields and the variables that determine sediment yields were investigated. Ten relatively homogeneous sediment yield regions were demarcated across Southern Africa. The sediment yield map of Southern Africa has been revised to incorporate the following sediment yield prediction methods: probabilistic, empirical and mathematical modelling.

The probabilistic method has been developed using statistical analysis of regional data of observed sediment yields and soil erosion hazard based on Rooseboom et al. (1992).

The empirical method is based on the total input stream power and has been developed from regression analysis of variables that control sediment yield with respect to the South African conditions namely floods, soil erosion hazard, river network density, catchment area and river slopes.

The probabilistic and empirical methods were validated on all the ten homogeneous regions. From the results it was possible to determine which method had the best performance and better results in each of the regions. The probabilistic approach is recommended for sediment yield regions 3, 6 and 9. The empirical method is recommended for regions 1, 2, 4, 5, 7 and 8. It is recommended that estimation of sediment

yields in Region 10 (Lesotho Highlands) should be based on direct measurements and locally observed data since no meaningful analysis of sediment yield values was possible due to poor and limited data.

Revised sediment yield confidence bands for both the probabilistic and empirical method have been provided to allow for the prediction of sediment yields at varying preset confidence bands.

An investigation of the application of SHETRAN and ACRU as erosion and sediment yield models has shown that the models can be successfully used to simulate sediment yield in a catchment, but calibration and validation against observed sediment loads are very important.

Systematic sediment monitoring in rivers and dams through sediment sampling and reservoir surveys respectively has been proposed.

Recommendations

The following recommendations for future research are made:

- Additional studies may be required to determine whether possible depleting sediment storage capacity in some catchments would trigger future increases in sediment yields than currently predicted.
- Research studies may be directed towards investigating the climate change impacts on sediment loads and sediment yields in order to determine the future challenges in water resources management in relation to sediment control.

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Nomenclature

A_e	Effective catchment area
Q	Discharge
Q_o	Observed flow discharge
Q_s	Simulated discharge or sediment load
Q	Discharge
$\rho g Q S$	Total input stream power
S_o	Average river slope
SY, S_y	Sediment yield
SY_{obs}	Observed sediment yield
SY_{sim}	Simulated sediment yield
t	Time
V_{50}	Sediment volume after 50 years
V_t	Sediment volume after t years.
V_w	Storage volume of reservoir
w	Settling velocity of sediment
X_i	Discrepancy ratio
Y_C	Estimated catchment sediment yield value
Y_S	Standardised average yield

Abbreviations

ACRU	Agricultural Catchments Research Unit
ANSWERS	Areal Non-point Source Watershed Environmental Response Simulation
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DWA	Department of Water Affairs
EUROSEM	European Soil Erosion Model
GIS	Geographical Information Systems
ICOLD	International Commission on Large Dams
KINEROS	Kinematic runoff and Erosion model
LHWC	Lesotho Highlands Water Commission
MUSLE	Modified Universal Soil Loss Equation
RUSLE	Revised Universal Soil Loss Equation
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project

1.0 INTRODUCTION

1.1 Background

The South Africa (SA) Water Research Commission appointed the Institute for Water and Environmental Engineering (IWESU), Department of Civil Engineering, University of Stellenbosch, to carry out this research project on the revision of the sediment yield maps of South Africa developed in 1992 by Rooseboom et al. The Institute for Soil, Climate and Water of the SA Agricultural Research Council was appointed as part of the project for specialist inputs on soil erosion hazard maps and Geographical Information Systems (GIS). This project was carried out over a three year period from 2007 to 2010.

The problem of elevated sediment concentration in rivers and sediment deposition in reservoirs is currently producing marked effects on land and water resources in southern Africa. The water quality in rivers and reservoirs has been degraded by an increase in suspended sediment. Reservoirs have lost significant proportions of their original storage due to sedimentation. Since reservoirs are beneficial for the provision of storage of water that is required for drinking, irrigation, recreation, hydropower production and flood control, sedimentation has resulted in serious economic losses, and environmental and aesthetic problems. It is therefore not only important but very necessary to consider erosion and sedimentation issues in the planning and detailed design of proposed dams, reservoirs and water resource projects.

According to Morris and Fan (1998), storage loss is not the only problem resulting from sedimentation in reservoirs; sedimentation also affects the normal operation of reservoirs by obstructing intakes, impacting on low level outlets and accelerating the abrasion of hydraulic machinery.

South Africa is one of the countries in the world that has been actively involved in the research and practical aspects of erosion and sedimentation for a long period of time.

Within the last fifty years, a rich knowledge base of erosion and sedimentation has been accumulated through experience and research. It is from this knowledge base that the

problem of reservoir sedimentation has been continuously analysed. New prediction methods have been developed as more data has been collected

The analysis of the reservoir sediment deposit data for South African dams showed that almost 25% of the total number of reservoirs have lost between 10 to 30% of their original storage. Table 1.1.1 shows the results of the assessment of the state of reservoir sedimentation based on reservoir sediment deposit data obtained from the Department of Water Affairs' dam list (DWA, 2006).

Table 1.1.1 State of reservoir sedimentation in South Africa (storage lost as a percentage of the original capacity)

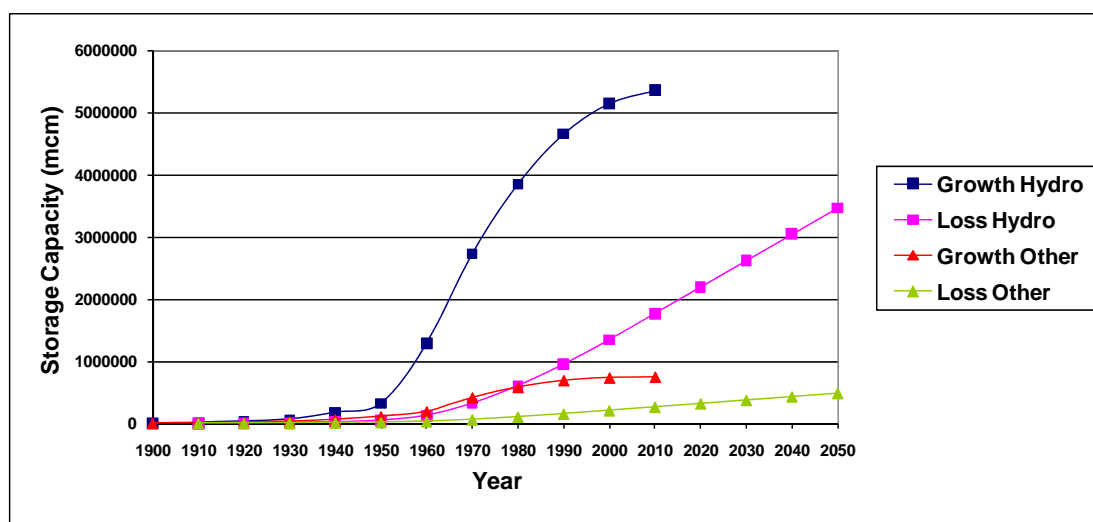
Storage lost (%)	Percentage of dams	Cumulative percentage of dams
0-5	28	28
5-10	18	46
10-20	20	66
20-30	6	72
30-40	5	77
40-50	7	84
50-60	8	92
≥60	8	100

Table 1.1.2 shows the annual storage loss in reservoirs in South Africa due to sediment deposition.

Table 1.1.2 Sedimentation in reservoirs (annual storage loss)

Annual storage loss (%)	Percentage of dams	Cumulative percentage of dams
0-0.1	28	28
0.1-0.2	25	53
0.2-0.5	31	84
0.5-1	8	92
1-1.5	8	100

The estimated global reservoir sedimentation rate is 0.8% per year (ICOLD, 2009). The global storage capacity of water comprises mainly of water that is used for hydro-electric power generation and the rest is for other uses. Over the recent years, there has been very little increase in the storage capacity of water, Nevertheless, reservoir sedimentation rates continue to increase resulting in loss of storage capacity of water for both hydroelectric power generation and other uses (Figure 1.1-1). Reservoir sedimentation rates in South Africa is fortunately on average lower than the global trend and the estimated mean annual loss in storage capacity is 0.4% per year (Figure 1.1-2).

**Figure 1.1-1 Global reservoir sedimentation rates (ICOLD, 2009)**

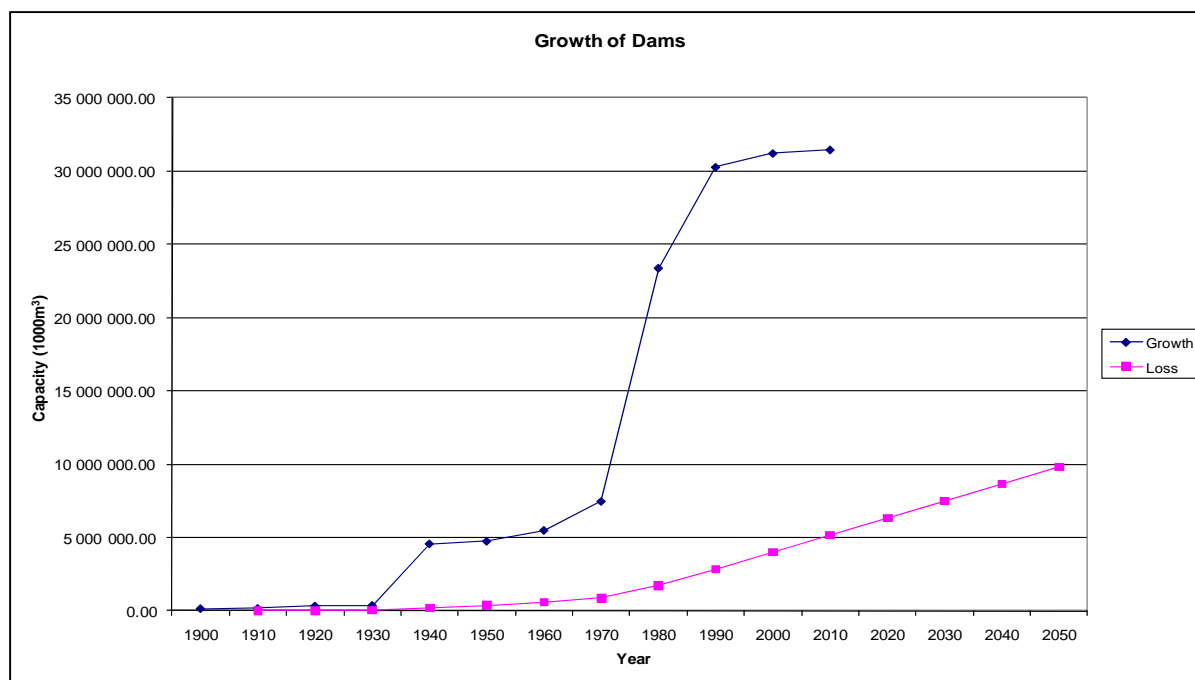


Figure 1.1-2 Predicted reservoir sedimentation in South Africa (ICOLD, 2009)

In order to meaningfully manage sedimentation in rivers and reservoirs, there is a need to understand, define, quantify and/or predict catchment soil erosion and sediment yield. If something cannot be measured, it becomes difficult to manage. While in sedimentation studies, it is not easy to accurately measure the quantities that are involved, reliable predictions of sediment yield can help in the sustainable management of land and water resources.

Worldwide, different erosion and sediment yield prediction methods are in use. No single catchment erosion and sediment yield prediction method can be presumed to be applicable to all possible conditions. All methods have limitations and advantages and the choice of the method to apply should consider a number of influencing factors. These factors include: catchment characteristics, site conditions, ecological considerations, dam engineering requirements, availability of time, economics, data requirements and data availability.

Four major approaches for predicting sediment yields have been applied in South Africa namely: direct measurements from reservoir surveys, river suspended sediment sampling, catchment sediment yield modelling and sediment yield maps (Rooseboom et al., 1992) incorporating the probabilistic approach or statistical analysis of sediment yield data. Notable work in sediment yield prediction methods comprised the development of the sediment yield

map of Southern Africa (Rooseboom et al., 1992). The development of this method was influenced by the availability of sediment yield data, experience and physical analysis of sedimentation and erosion related processes. The approach provided a vital tool in sediment yield prediction in South Africa.

However, continuous improvement of sediment yield prediction methods is necessary in the wake of changing environments, more data, increased experience and current technological advancements in the sedimentation field. Improved sediment yield prediction methods are essential for sound land and water resources management decision making with respect to dam development and environmental management in the wake of current population increases that are putting a strain on the available land and water resources.

The purpose of this study was to provide a better understanding of erosion and sediment yield and present information for efficient decision making in water resources planning for sedimentation control in rivers, existing and future reservoirs, through the development of sediment yield prediction and analysis methods and an illustration of the application of catchment sediment yield models. The study involved the improvement of the approach (tools and methodologies) in the sediment yield map of South Africa (Rooseboom et al., 1992), investigation of potential empirical methods and an illustration of the role of catchment sediment yield modelling in sediment yield prediction.

The catchment sediment yield modelling methods will provide an important decision making tool in the application of relevant catchment soil conservation techniques and formulation of reservoir operation procedures aimed at limiting and controlling sedimentation in reservoirs.

Finally, sediment prediction methods would help in the examination of the extent in which sedimentation could threaten the sustainability of the existing reservoirs.

1.2 Objectives

The key project objectives were:

- To develop methodologies for the prediction of the sediment yields from gauged and ungauged catchments.
- To evaluate mathematical modelling of catchment sediment yield with the main focus of illustrating the aspects of model set up, calibration, validation and simulation and to improve understanding of spatial and temporal changes in sediment yield within a catchment.

1.3 Methodology

The methodology that was followed in order to achieve the objectives included the following:

- Literature review of the general concepts and theories in erosion and sedimentation. Various books, scientific journals, reports and guidelines were reviewed in order to acquire relevant theoretical grounding.
- Review of current sediment yield estimation methods in Southern Africa.
- Development of new analytical methods for the prediction of sediment yield. Relevant data was collected, analysed and correlated in order to derive the empirical and probabilistic relationships.
- Review of mathematical modelling techniques for catchment sediment yield.
- Identification of a case study for the application of catchment sediment yield modelling techniques. Aspects of sediment yield modelling that are applicable to different catchments were evaluated and applied. These aspects include: model set up, calibration, validation and analysis of simulations.

1.4 Layout of the Report

Chapter One of this report introduces the project, the key objective and the methodology that was adopted.

Chapter Two presents the development of a newly improved probabilistic method based on Rooseboom et al. (1992) and an empirical approach for sediment yield prediction. The acquisition and processing of all relevant data and information that was needed for the development of the methods has been explained. The derivation procedure for the regression equations has been discussed. Worked examples for both the empirical and probabilistic methods have been presented to illustrate the practical implementation of the two methods.

Chapter Three presents an approach to catchment sediment yield mathematical modelling. The reasons behind choosing SHETRAN as the model to be adopted for possible application in catchment sediment yield modelling are given. The chapter also provides an overview of the study area and how the model was set up. A detailed procedure of flow calibration and validation, and sediment load calibration and validation is provided. The results of the evaluation of numerical modelling have focused on the ability of the numerical models to identify sources of high sediment yields within the catchment.

Chapter Four deals with the aspects of monitoring sediment loads in rivers. The key aspects are reservoir surveys, sampling techniques and processing of samples.

Chapters Five and Six give a summary of the findings and recommendations for further research respectively.

2.0 REVISED PROBABILISTIC AND A NEW EMPIRICAL APPROACH FOR SEDIMENT YIELD PREDICTION

2.1 Introduction

The previous sediment yield prediction methods have been applied with success. However, there was a need to improve the previous sediment yield map methodology. This was justified by the fact that there had been an increased availability of additional sediment yield data since the previous report (Rooseboom et al., 1992) was prepared and the need to incorporate current technological advancements in sediment yield methods.

An empirical method was investigated to predict the sediment yield based on the unit stream power theory. The probabilistic approach was based on the analysis of newly calculated sediment yield data and revised erosion hazard classes. The empirical approach was based on the relationships established from the observed sediment yields and the selected variables that have a marked effect on the expected sediment yield in a given homogeneous region.

2.2 Sources of Information

The observed sediment yields were obtained from two types of data sources. These sources are reservoir survey data and river suspended sediment sampling data. Reservoir survey data provided information on reservoir deposit sediment volumes.

The sediment yield calculation method that makes use of reservoir deposit data is based on the general concept that any reduction in storage volume of a reservoir that is observed through reservoir surveys is directly related to the amount of sediment being accumulated in the reservoir. The sediment yields had to be recalculated in order to incorporate added data since the preparation of the 1992 sediment yield maps (Rooseboom et al., 1992).

The reservoir survey data was obtained from the Department of Water Affairs (DWA) dam list of 2006 and individual reservoir survey reports. The DWA dam list provided most of the historical information on surveyed and re-surveyed reservoirs and dams such as: the name of the dam, height at full supply level, survey dates and the period (in years) between the surveys and re-surveys with their corresponding storage volumes at the time of surveying.

2.3 Quality of data, analysis and validation

The criteria for the analysis of the validity of the data in order to ensure its integrity were based on the following considerations:

- Records or period between surveys to be longer than ten (10) years
- Reliable high reservoir sediment trap efficiency (at least 97%)
- Raised or lowered dams

In order to determine reliable sediment yields, the raw data for individual dams was analysed based on these considerations. This resulted in the reduction in the number of suitable dams.

Raised and lowered dams for which sediment volumes could not be reliably determined from the net cumulative sediment curves were also discarded. The reservoir storage volume during the original and/or preceding surveys was supposed to be reliable and not significantly affected by possible raising and lowering of a dam.

2.3.1 Mean Annual Runoff and Trap Efficiency

The Mean Annual Runoff (MAR) was applied in the determination of the trap efficiency. The trap efficiency of a reservoir is defined as the ratio of the quantity of sediment deposited with respect to the total sediment inflow (ICOLD, 1989). Not all sediment passing through a reservoir is trapped. The quantification of the amount of sediment trapped with respect to what passes into the reservoir is termed 'the trap efficiency'. In order to ascertain the 'trap efficiency' for each of the dams under consideration, the MAR had to be determined. The trap efficiency is determined as the ratio of the storage volume (V_w) to the MAR of the reservoir. The MAR was acquired from maps and appendices obtained from the Surface Water Resources of South Africa 1990 (WR90) (Midgley et al., 1994).

The MAR of any catchment area was calculated from the summation of individual MARs of each of the quaternary sub-catchments forming the whole catchment area under consideration based on the MAR value given for uniquely coded quaternary sub-catchment as illustrated in Figure 2.3-1 extracted from WR90 (Midgley et al., 1994).



Figure 2.3-1 Sub-quaternary and quaternary sub-catchments for MAR computation (Midgley et al., 1994)

2.3.2 Effective Catchment Area

The effective catchment areas were generated by GIS. The effective catchment area (A_e) represents the significant area for a reservoir or a dam as regards to the computation of the sediment yield particularly where there is another dam falling within its gross catchment area. The effective catchment area is therefore that part of the total drainage area upstream of a dam that contributes to the sediment being deposited in a reservoir.

The MAR is directly related to the total catchment area above a point of reference for a dam, while the sediment yield is computed using the effective catchment area. The general approach is based on the assumption that the sediments that accumulate in a reservoir are produced from the effective catchment in particular cases where there is another dam upstream which is relatively large and has a reliable high reservoir sediment trap efficiency since all sediment resulting from the upstream drainage area is trapped by the upstream dam, while the water inflow into a reservoir comes from the total drainage area upstream.

In the sediment yield computation, the area to be used also depends on the period during which the dams upstream (if any) became operational. In other words; where there was a dam upstream which came into operation at a later stage outside the survey data period, the total area during the period of no dam upstream was used instead of the effective catchment area.

2.4 Determination of sediment yields from reservoir sediment deposit data

The detailed information that was needed in the estimation of the sediment yield from reservoir sediment deposit data included the following:

- Name and reference code of the dam
- The heights at full supply level during recorded surveys.
- The storage volumes.
- The year in which the dam became operational
- The mean annual runoff
- The catchment area and the average sediment density in reservoirs.

It was possible to calculate the sediment yield from reservoir sediment deposition data. The reservoir survey data was used to determine the quantity of sediment deposited in the reservoir by way of comparing the water storage capacity changes between two or more successive surveys. In semi-arid regions that have high rainfall intensity, the storage capacity of a reservoir is usually in the order of the mean annual runoff and the reservoirs therefore trap approximately 97% of the sediment yield (Basson, 2008). Therefore the loss in storage is taken as a true reflection of sediment accumulation. The procedure that was followed was as detailed below.

An empirical equation proposed by Rooseboom (1992) below was used to compute the equivalent fifty (50) year sediment volume, based on the sediment volume after a known period, preferably after 10 or more years.

$$\frac{V_t}{V_{50}} = 0.376 \ln \frac{t}{3.5} \quad 2.4.1$$

Where

V_t = sediment volume after t years.

V_{50} = sediment volume after 50 years.

t = time (years).

The sediment yield S_y was then computed using equation 2.4.2.

$$S_y = \frac{1.35 \times V_{50}}{50 \times A_e} \quad 2.4.2$$

Where

S_y = Sediment yield in tonnes per annum per square kilometre

A_e = Effective Catchment Area

After 50 years of deposition, the sediment density is taken as 1.35 t/m³.

Graphical analysis was applied when the available data were sufficient to predict the volume of sediment in the dam after or at fifty (50) years from a graph as illustrated in Figure 2.4-1. Further graphs are attached in **Appendix A**. A logarithmic trend line was fitted through the data points because of the assumption that a logarithmic relationship exists between sediment deposit volume and time (Rooseboom et al., 1992) and the use of an average density of sediment after fifty years. This is due to the consolidation characteristics of fine sediment (clay and silt). In the case of Olifantsnek Dam the volume at fifty years can be read from the graph as shown by arrows in Figure 2.4-1 or by calculating it using the trend line equation.

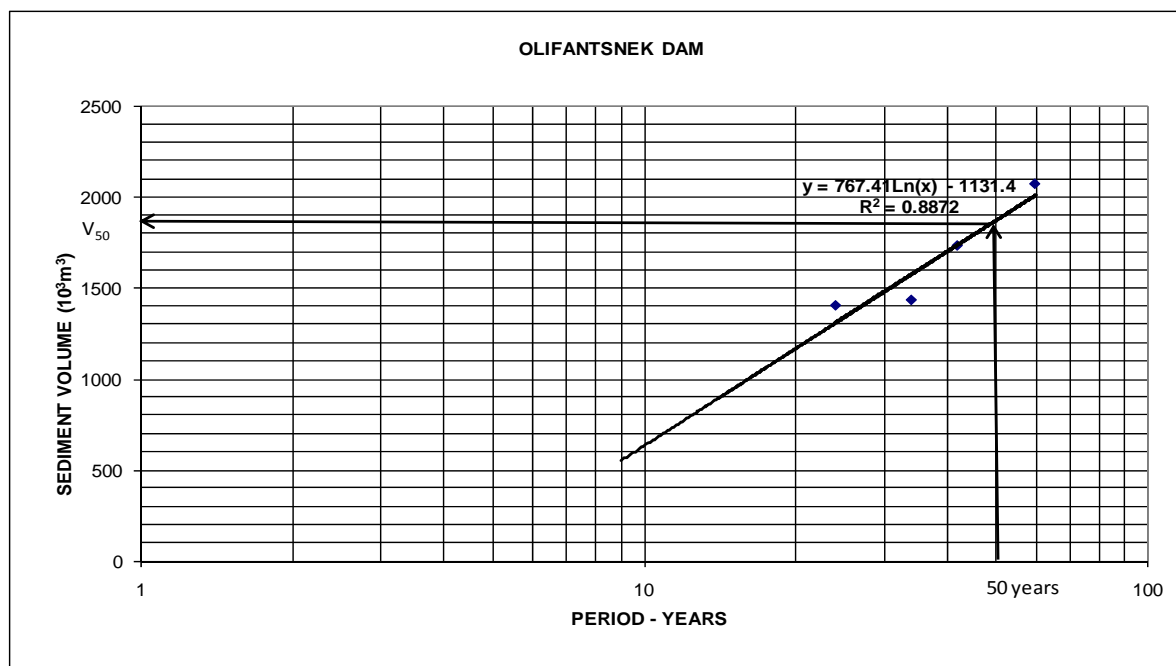


Figure 2.4-1 Graphical analysis of the sediment volume after fifty years

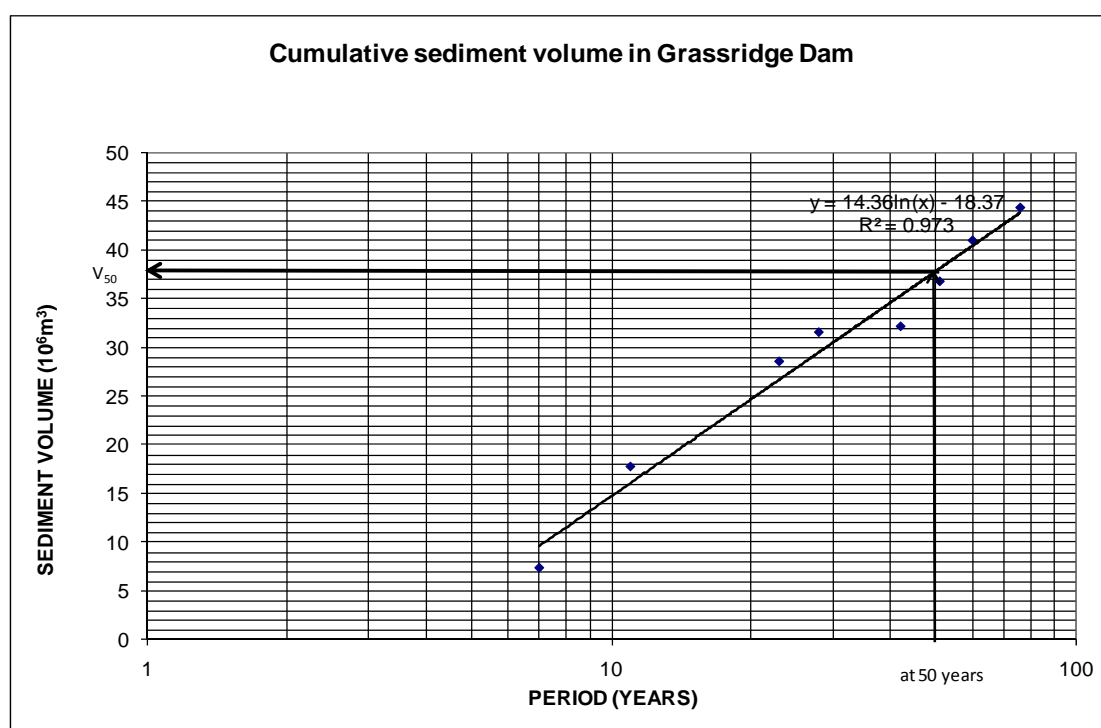
A number of dams that have been raised or lowered have had their sediment yield converted from sediment deposit data. The detailed calculations of the sediment volume at fifty (50) years for raised and lowered dams did not follow the normal summation method of sediment volume in a dam, but rather a cumulative sediment volume was plotted from the dam's data where possible.

This is illustrated by an example of the Grassridge Dam (a case of a raised dam) whose tabular presentation of sediment deposit data is shown in Table 2.4.1. Table 2.4.1 shows that there was a change in the height at full supply level from 1948. However, a plot of the cumulative sediment volume with time gives a consistent trend line.

Table 2.4.1 Grassridge Reservoir deposit data

Year	Vol (10^6 m^3)	Height at FSL (m)	Gauge Plate (m)
1924	77.55	1056.93	14.05
1931	70.20	1056.93	14.05
1935	59.80	1056.93	14.05
1946	51.90	1056.93	14.05
1948	60.86	1057.84	14.96
1952	59.00	1057.84	14.96
1966	58.40	1057.84	14.96
1975	53.78	1057.84	14.96
1984	49.58	1057.84	14.96
2000	46.20	1057.84	14.96

This resultant graphical plot of the cumulative sediment yield in the reservoir is shown in Figure 2.4-2. This graph was used to calculate the sediment volume at fifty years.

**Figure 2.4-2 Cumulative sediment volume in Grassridge Reservoir**

In the event that this approach could not be followed with reliability, raised or lowered dams were discarded. A reliable cumulative sediment volume graph was taken as the one that gave the required sediment volume at fifty years depending on its observed regular pattern and number of data points.

There were notable differences in the newly calculated sediment yields for some dams in comparison with those of the 1992 sediment yield map (Rooseboom et al., 1992). This was expected and could be accounted to the following factors:

- Normal changes in sediment transport trends and behaviour with time especially due to large floods that might occur in a drainage area that were not captured by previous surveys.
- Increased dam survey data for the dams from additional bathymetric re-surveys

Some of the newly calculated sediment yields were higher for similar dams when compared with those of the 1992 sediment yield map (Rooseboom et al., 1992) and vice versa. Analysis of the overall trend in the sediment yields showed that the newly calculated sediment yields are comparatively higher. It was concluded that total sediment production is not reducing in South Africa.

2.5 Calculation of sediment yields from river suspended solids data

Where possible, the sediment load at a gauging station could be determined from river suspended solids data. The Department of Water Affairs' historical flow records were obtained. The major problem was that the sediment data sets were for short periods and not representative enough to be considered as reliable. The sediment load was computed from the relationship between the suspended solid concentration and the discharge.

The mean annual sediment load was found by applying a factor of 1.25 to cater for bed load and non uniformity in suspended sediment concentrations (Rooseboom et al., 1992). The sediment yields from river suspended solids data are included in the final adopted sediment yield values in Appendix C.

2.6 Probabilistic sediment yield prediction methodology

The probabilistic approach was based on the previous report's fundamental assumptions of Rooseboom et al. (1992).

The main underlying assumption is that sediment transport is influenced by sediment availability and in turn sediment availability is influenced by the soil erosion hazard. This was rather a crude assumption considering the dominant role of other significant sediment controlling factors that could also affect the sediment yield. The probabilistic analysis approach used the following data: dam and river catchment areas, erosion hazard classes and observed sediment yields per region (from reservoir sediment deposit data and river suspended sediment data) whose acquisition and processing has been explained in detail in the preceding paragraphs.

2.6.1 Demarcation of new regions

The current identification and demarcation of the new regional boundaries was based on the latest calculated sediment yields and soil erosion hazard classes that are based on the original erosion map by Morgenthal et al. (2006) and Le Roux et al. (2008), hydrological parameters such as watershed quaternary boundaries and flood regions. The water erosion prediction map of Le Roux et al. (2008) was a modified and improved version of the original erosion map by means of applying new C-factor- and LS-factor maps. A detailed procedure on the determination of the erosion hazard classes is given in Appendix J (A and B). The regional demarcation was necessitated by the need to have relatively homogeneous regions. Geographical considerations and the availability of data played a major role in determining the boundaries of the homogeneous regions.

The availability of adequate sediment yield data for analysis was based on the number of observed sediment yields within a proposed sediment yield region. A map showing observed sediment yield by catchment for the whole of Southern Africa was created in GIS. The soil erosion data were prepared in GIS on a map of Southern Africa showing ten erosion hazard classes based on the water erosion prediction map of Le Roux et al. (2008) which was

modified and improved by means of new C-factor- and LS-factor maps that were applied in the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1994) as explained in Appendix J. The flood regions were based on the homogeneous flood regions in the Drainage Manual (SANRAL, 2006).

The new boundaries for sediment yield regions were traced manually on a map showing observed sediment yields for river gauge and dam catchments, rivers and drainage regions. Manual overlay of the Predicted Water Erosion Map (Le Roux *et al.*, 2008) and the homogeneous flood regions map (SANRAL, 2006) was done using transparent paper to capture homogeneous flood regions and erosion hazard areas. The availability of adequate data for analysis was done by manual computation of the number of observed sediment yields falling in a proposed sediment yield region. The manually demarcated sediment yield regions were electronically delineated using GIS.

A total of ten new homogeneous sediment yield regions were identified. Figure 2.6-1 shows the previous sediment yield regions (Rooseboom *et al.*, 1992) and the new sediment yield regions. Appendix B shows the erosion hazard classes for each of the new sediment yield regions.

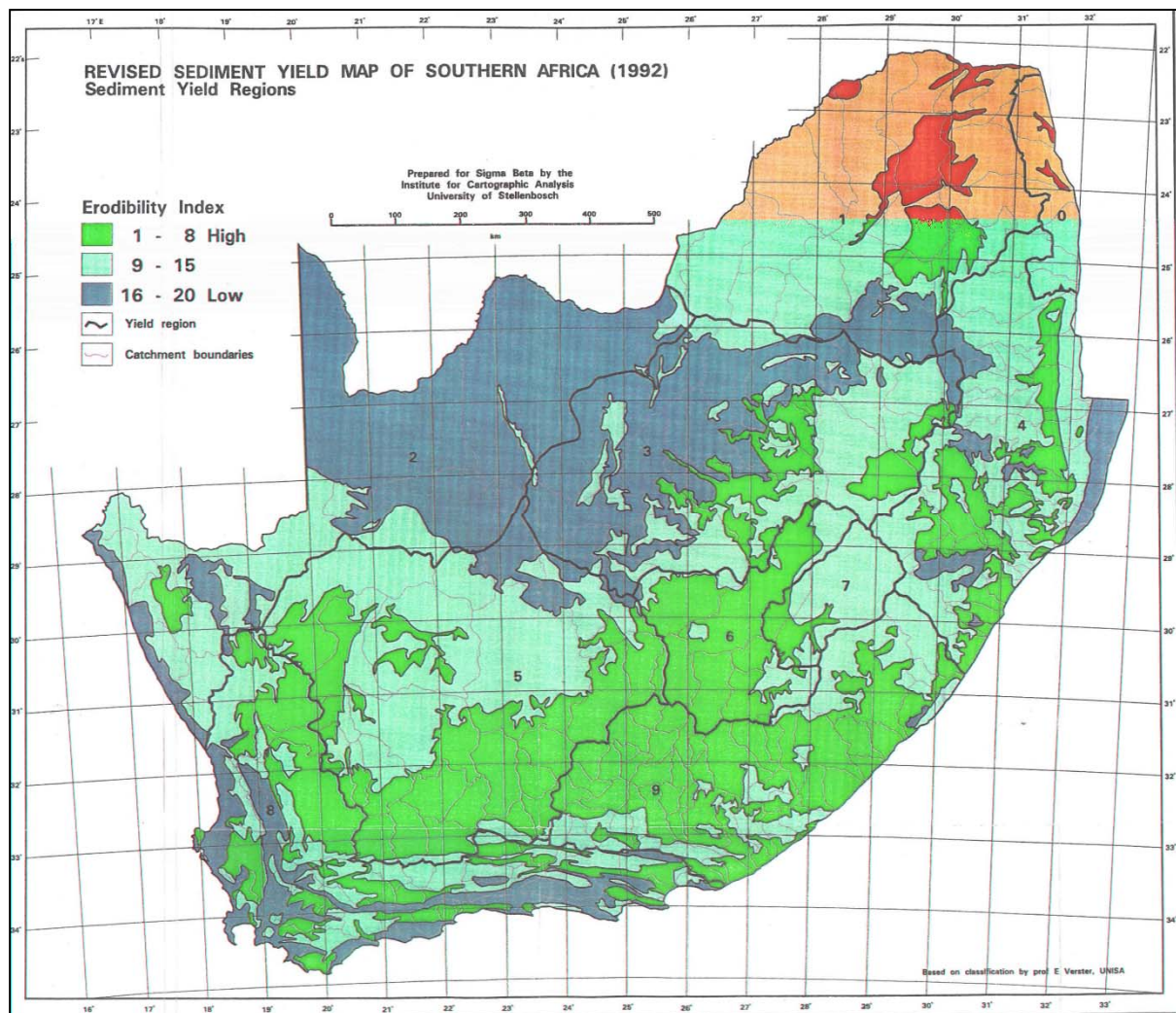


Figure 2.6-1 (a) Previous (Rooseboom et al., 1992) sediment yield regions showing erodibility indices.

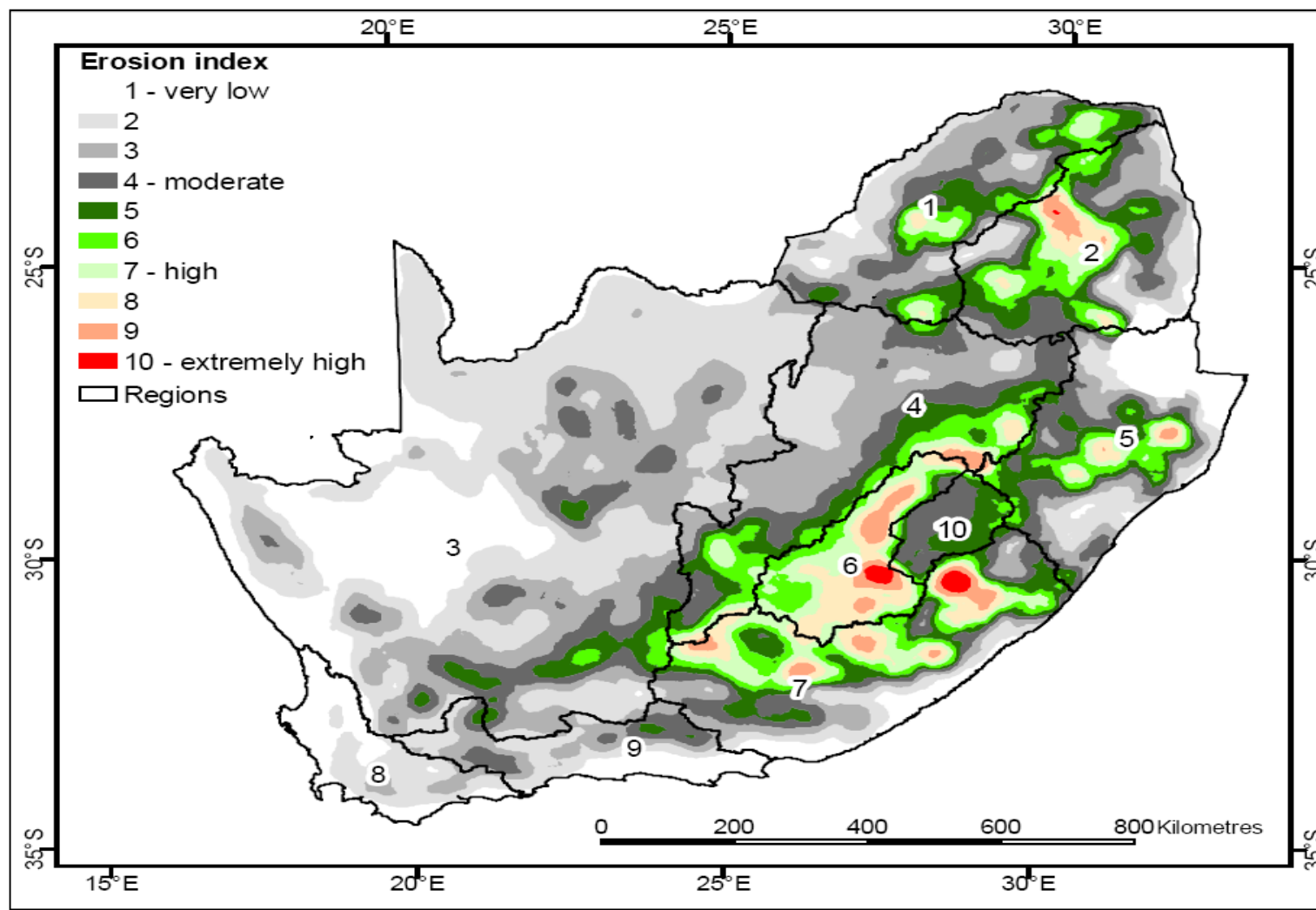


Figure 2.6-1 (b) New sediment yield regions showing erosion indices

Upon demarcating the regions, attention was focused on the determination of the correlation between the calculated sediment yield values and the water erosion prediction map of Le Roux et al. (2008) as explained in Appendix J. This was done to determine the relationship between soil erosion and the observed sediment yields. This relationship was to be used for further prediction of sediment yield in ungauged catchments based on average erosion rates.

Analysis of data (see Figure 2.6-2) was carried out by means of statistic functions in a GIS (Arc Map) and correlation graphs (Refer to Appendix J). For each catchment with an observed sediment yield, the soil erosion based on RUSLE in tonnes/ha/annum was computed using GIS spatial data statistical analysis tools. The observed sediment yields were plotted against the RUSLE simulated sediment yields for each region.

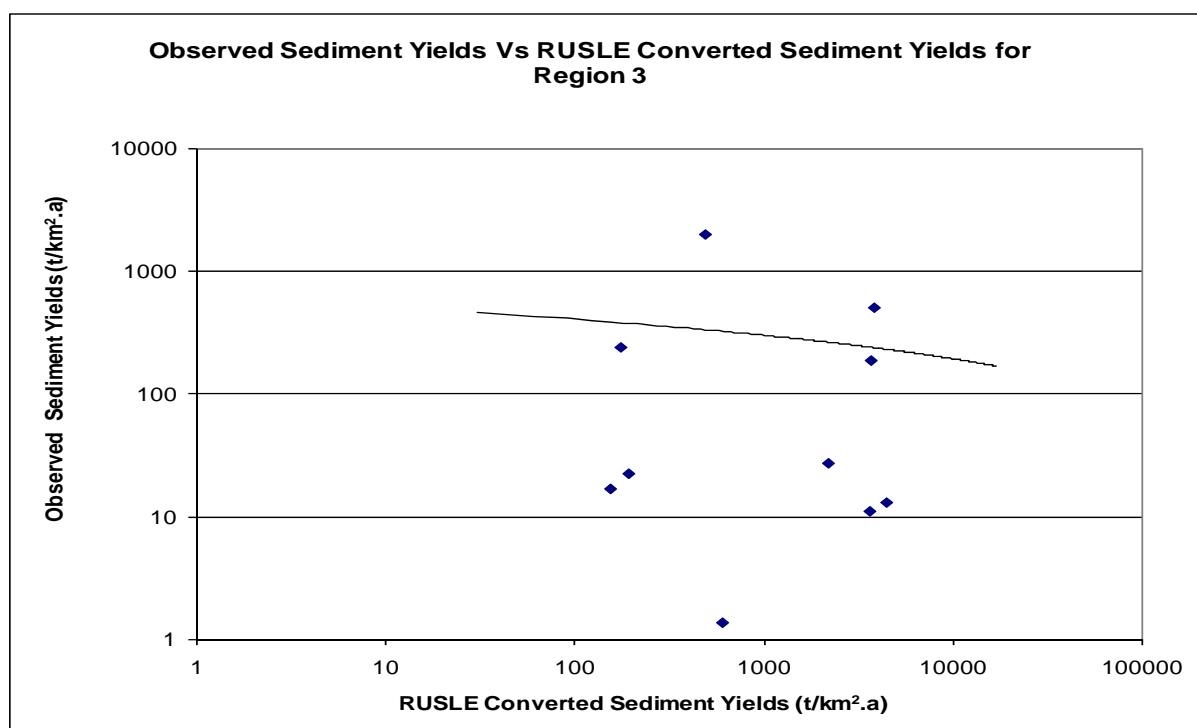


Figure 2.6-2 Observed sediment yields vs. RUSLE simulated sediment yields for Region 3

Analysis of the results for all regions as illustrated in Figure 2.6-2 (for Region 3) indicated very poor correlation between the mean erosion rates and observed sediment yields. The other sediment yield regions gave poor results, which were also characterised by very low r-square values. The main reason is that the mean net soil loss (i.e. the sediment yield at the

outlet) in a catchment differs from the mean total soil erosion (i.e. the total sediment produced in the catchment). Depending on the spatial configuration of topography and land use, a significant part of the eroded soil will deposit again before reaching a river channel or the outlet of the catchment (Van Rompaey et al., 2003). Therefore, erosion cannot be successfully correlated with sediment yield without linking them with a hydrological component (e.g. mean annual runoff and peak runoff). Ideally, the RUSLE erosion map must be hydrologically linked with the sediment data by means of the sediment delivery ratio (SDR). The SDR is the ratio of sediment yield at the outlet over the total volume of produced sediment in the drainage basin. For example, in Europe, Van Rompaey et al. (2003) applied a regional scale model (WaTEM/SEDEM) that requires river and trap efficiency data in order to assess a SDR for each reservoir.

Consequently, an attempt to correlate the average erosion loss rates and sediment yield was discontinued. The development of an erosion risk database at national scale for South Africa in the form of erosion hazard classes was pursued. This was used in the development of the probabilistic method which was based on the previous report's fundamental assumptions of Rooseboom et al. (1992). The revised probabilistic method has used erosion hazard classes which were generated after a re-assessment of soil erosion risk at the national scale. The procedure for the determination of the erosion hazard classes is given in paragraph 2.6.2 and a detailed account of the determination of the erosion hazard classes by Le Roux et al. (2008) is given in Appendix J.

2.6.2 Soil erosion hazard classes

The soil erosion hazard depends on the combined and interactive effects of climate, soil profile, relief, land use and vegetation, and cultivation system, also known as the soil erosion factors, namely rainfall erosivity, soil erodibility, slope steepness and slope length, crop management, and support practice factor (Wischmeier and Smith, 1978). Appendix J gives a detailed account on the derivation of the soil erosion hazard classes taking into account the influence of soil erosion factors.

Ten erosion hazard classes were identified using GIS spatial data analysis based on the RUSLE. The Predicted Water Erosion Map (PWEM) of Le roux et al. (2008) was generated from a combination of the effect of cover and crop management factor “C” and physical soil erosion contributing factors of rainfall erosivity, soil erodibility, topography and vegetation cover. According to Le Roux et al. (2008), RUSLE groups the many influences on the erosion process into five categories comprising climate, soil profile, relief, vegetation and land use and land management practices. The categories are known as erosion factors indicated by R, K, LS, C and P respectively. The RUSLE model is expressed by equation 2.6.1 (Renard et al., 1994):

$$A = R.K.L.S.C.P \quad 2.6.1$$

Where

- A = Expected annual soil loss ($\text{tonnes ha}^{-1} \text{ yr}^{-1}$)
 R = Rainfall erosivity in ($\text{MJ mm ha}^{-1} \text{ h}^{-1} \text{ yr}^{-1}$)
 L and S = Topographic factors that describe hill slope length and hill slope steepness (dimensionless) respectively
 K = Soil erodibility in ($\text{Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$)
 C and P = cover-management practices and support practices’ factors that describe land use respectively

The four major factors of rainfall erosivity, topography, soil erodibility and land cover were calculated from new maps generated in GIS framework using improved input data.

These erosion hazard classes were classified in terms of an index scale of one to ten for the whole of southern Africa whereby Class 1 is very low erosion hazard and Class 10 represents extremely high erosion hazard. The proportion of area covered by specified hazard classes per catchment was calculated for all the dam and river catchments using GIS-based spatial analysis tools.

For example, the total effective catchment area of Albasini Dam in Region 1 was computed as 501 km^2 . Out of this total area; 145 km^2 falls under erosion hazard class 4, 352 km^2 falls under erosion hazard class 5 and 4 km^2 is covered by erosion hazard class 5. A weighted

average was calculated to provide a single dominant erosion hazard class per catchment based on the proportionate areas. The computation of a single dominant erosion hazard class was done for all river and dam catchments which had an observed sediment yield. For the purpose of the probabilistic analysis, each observed sediment yield was associated with its corresponding dominant erosion hazard class. The weighted average erosion hazard class was converted to the nearest integer in the range of 1 to 10 to provide a single hazard class per catchment.

2.6.3 Probabilistic analysis of observed sediment yield data

The probabilistic analysis was done using the following types of data:

- (i) Dam and river catchment area sizes and proportionate areas covered by each soil erosion hazard class.
- (ii) Observed sediment yields per region.

The final data set for the observed sediment yields per region is attached in Appendix C. Each observed sediment yield value had a corresponding dominant erosion hazard class. The dominant erosion hazard class was then linked to its sediment yield value for further probabilistic analysis. The previous probabilistic approach (Rooseboom et al., 1992) had three soil erosion hazard classes. The probabilistic approach in this study has applied ten indices (referred to as erosion hazard classes) in order to improve the classification. For each dam and river catchment, the dominant erosion hazard class was recorded. Appendix D gives the data for the computation of the dominant erosion hazard class per catchment and the determination of potential factors for Region 9 which has been used for illustrative purposes.

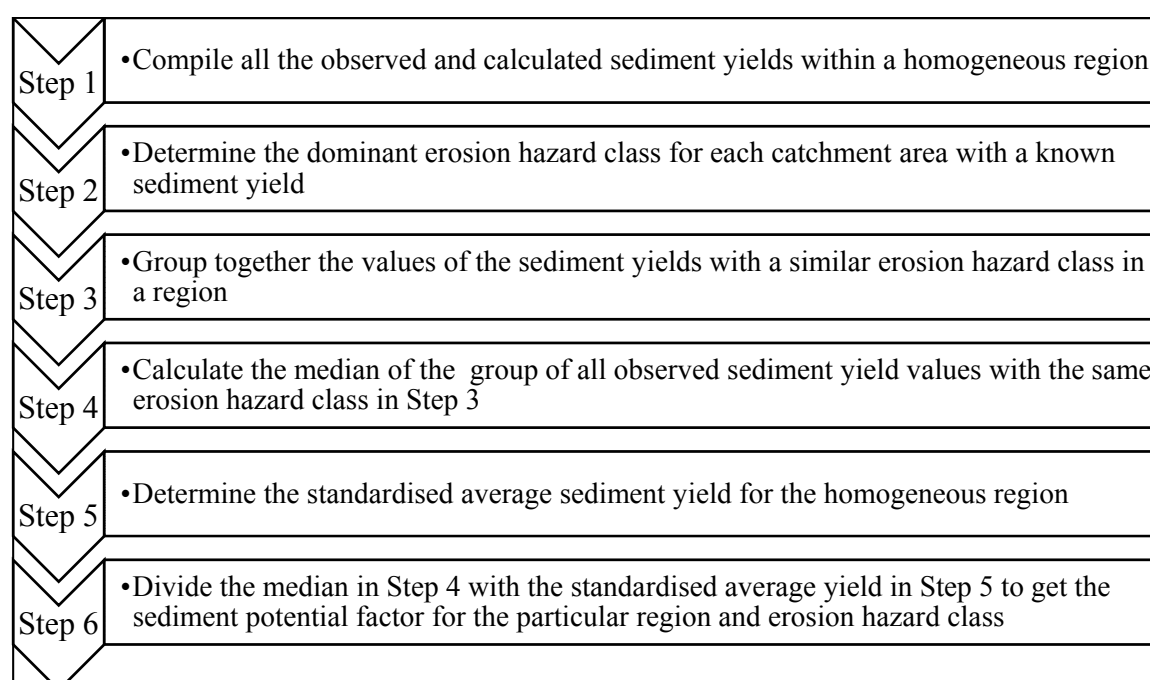
A summary of the results in Appendix D is given in Table 2.6.1. The sediment yield values for dam and river catchments with similar erosion hazard class were grouped together.

Table 2.6.1 Computation of sediment potential factors

	Erosion Hazard Class									
	1	2	3	4	5	6	7	8	9	10
Group of Observed Sediment Yields	10	149	145							
	7	53	75							
	18	129								
		6								
Median of Group of Observed Sediment Yields per Erosion Hazard Class (t/km ² .a)	10	91	110							
Standardised Average Yield (t/km ² .a)	53	53	53	53	53	53	53	53	53	53
Sediment Potential Factor	0.184	1.719	2.076	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The median values for the sediment yield values with similar dominant erosion hazard class were computed as shown in Table 2.6.1.

A summary of the procedure for the determination of the sediment potential factors is given in the flowchart in Figure 2.6-3.

**Figure 2.6-3 Flowchart of the procedure for the computation of potential factors**

The procedure as illustrated in Table 2.6.1 for region 9 was followed for all the sediment yield regions to determine the sediment potential factors given in Table 2.6.2.

The main assumption in the analysis was that the standardised average yield (taken as the sediment yield at 50% exceedance probability) for each region is related to the median of each group of observed sediment yield with similar dominant erosion hazard class in a region. The relationship is indicated by the ratio of the median values and the standardised average yield which is termed “sediment potential factor” (see Table 2.6.1). The sediment potential factors for sediment yield regions 3, 6 and 9 are shown in Table 2.6.2. The data for regions 1, 2, 4, 5, 7 and 8 has not been indicated because the empirical method was more accurate (See section 2.7).

The following procedure was done to determine the standardised average yield for the regions. The observed sediment yield values for each of the ten regions were then plotted on a probability graph to determine their distribution. The following logarithmic distributions were investigated to select the distribution that would best fit the data.

- (i) Log Normal Distribution
- (ii) Log Pearson Type III Distribution
- (iii) General Extreme Value Distribution (Using Mean Moments)
- (iv) General Extreme Value (using Probable Mean Moments)

The logarithmic distributions were chosen because they were found to give good results when fitted to sediment yield data (Rooseboom et al., 1992). The final adopted graphical distribution depended on the distribution that fitted the data well. The observed data was plotted on the electronic probability paper in Microsoft Excel whereby the observed sediment yield values were on the vertical axis and probability values on the horizontal axis. The Cunnane plotting position was used. The Log Pearson Type III Distribution was found to give better results for the data in regions 1 and 8. The Log Normal distribution was found to be best suited to data for regions 2, 3 and 6. In regions 4, 5, 7 and 9, the data was fitted with a distribution line between the Log Normal and Log GEV_{mm} distributions in order to achieve a better fit.

Appendix E shows the various distributions that were plotted using the observed sediment yields for nine sediment yield homogeneous regions (except Region 10). The sediment yield value at 50% probability of exceedance as read from the regional distribution plot was taken as the standardised average yield given in Table 2.6.2 for that region.

Table 2.6.2 Sediment potential factors

REGION	Standardised Average Yield (t/km ² .a)	SEDIMENT POTENTIAL FACTORS									
		F ₁	F ₂	F ₃	F ₄	F ₅	F ₆	F ₇	F ₈	F ₉	F ₁₀
1											
2											
3	33	0.033	0.501	1.445	1.334	0.778	0.000	0.000	0.000	0.000	0.000
4											
5											
6	622	0.000	0.000	0.000	0.000	0.000	1.428	1.042	1.002	0.998	0.000
7											
8											
9	53	0.184	1.719	2.076	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10											

F_n Sediment potential factor for erosion hazard class n (n = 1 to 10) obtained using the procedure outlined in Table 2.6.1

Notes: The data for regions 1, 2, 4, 5, 7 and 8 has not been indicated because the empirical method was more accurate (See section 2.7).

2.6.4 Multiplication factors, confidence intervals and limits

The distribution that fitted the regional observed data well as described in section 2.6.3 was used for the determination of the confidence limits. The confidence limits are required to act as envelope values on the regional standardised average sediment yield. The standardised average yields were obtained from the probability distribution graph at 50% exceedance probability. A 50% exceedance probability indicates that 50% of the predicted values could be lower or 50% of the predicted values could be higher. By default a multiplication factor of 1 is applied at 50% probability of exceedance when equation 2.6.2 is used without considering confidence limits.

The confidence limit graphs were plotted with the multiplication factors as the parameters on the vertical axis and the catchment areas on the horizontal axis. The multiplication factor was obtained from the ratio of the observed sediment yield against the standardised average yield. The multiplication factors describe the relationship between the observed sediment yields and the standardised average yield. Observed sediment yields that were greater than the standardised average yield in a particular region gave factors that were greater than one (1) and vice versa. The multiplication factors indicate the variability in the observed sediment yields with respect to the standardised average yield. The confidence bands' lines were manually fitted along the data points on the graph of the relationship between the multiplication factor and catchment area. The graphs for the sediment yield confidence bands for each region are shown in Appendix F. These confidence bands have been plotted with respect to catchment areas. Just like in the previous methodology (Rooseboom et al., 1992), there were some regions where the effect of the size of catchment area on the confidence limit could not be reliably ascertained. In such cases, a constant factor was adopted for the whole range of catchment sizes.

2.6.5 Steps for the prediction of sediment yields – probabilistic approach

The proposed procedure for the prediction of the sediment yields for an ungauged catchment based on the above statistical analysis of the regional data is as follows:

- (a) Establishment of the sediment yield region in which the specific dam under investigation falls.
- (b) Determination of the boundary of the catchment and tracing of this boundary on an electronic copy or hard copy of the map showing the ten erosion hazard classes.
- (c) Computation of the area covered by each of the erosion hazard classes that are found in the catchment – The area covered by each of the erosion hazard classes within a quaternary catchment will be displayed upon querying the individual quaternaries within the catchment. The querying will be done on an electronic portable document format (PDF) copy of the relevant regional map (per sediment region) when the ‘Model Tree’ viewing tool in Adobe Acrobat Reader is activated. The user has to click a point within any quaternary in order to be able to get quaternary data pertaining to erosion hazard classes and the corresponding areas covered.
- (d) Calculation of the proportion of the area out of the total catchment area (i.e. 100% = 1) that is covered by each of the specific erosion hazard classes – This will be achieved by the summation of the areas covered by each of the erosion hazard classes per quaternary for all the quaternaries within the catchment under consideration.
- (e) The sediment yield for an ungauged catchment is predicted using equation 2.6.2 below whereby the proportion of the area out of the total catchment area that is covered by each of the specific erosion hazard classes is multiplied by the corresponding sediment potential factor for that particular class and the summation of the values across all classes are then multiplied by the standardised average sediment yield value ($t/km^2.a$) for the specific region:

$$SY_{est} = SY_{sty} \left\{ F_1 \frac{A_1}{A_T} + F_2 \frac{A_2}{A_T} + F_3 \frac{A_3}{A_T} + F_4 \frac{A_4}{A_T} + F_5 \frac{A_5}{A_T} + F_6 \frac{A_6}{A_T} + F_7 \frac{A_7}{A_T} + F_8 \frac{A_8}{A_T} + F_9 \frac{A_9}{A_T} + F_{10} \frac{A_{10}}{A_T} \right\} \quad 2.6.2$$

Where

SY_{est} = Estimated median sediment yield value ($t/km^2.a$)

SY_{sty} = Standardised average sediment yield value ($t/km^2.a$) for the specific region.

The standardised average sediment yield is obtained from Table 2.6.2 with respect to the region. $F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9$ and F_{10} are sediment potential factors to be obtained from Table 2.6.2.

The probabilistic approach for the computation of a sediment yield using equation 2.6.2 requires that the estimated median sediment yield (SY_{est}) value be multiplied by a factor to get the estimated sediment yield value with respect to the required exceedance probability. The multiplication factor, which is dependent on the preferred confidence band, catchment area size and sediment yield region is obtained from sediment yield confidence bands' graphs for the three regions that have been attached in Appendix F. The determination of the sediment yield confidence bands is described in section 2.6.4.

The relationship is shown below:

$$SY_{fest} = \textit{Multiplication Factor} \times SY_{est} \quad 2.6.3$$

Where

SY_{fest} = Factored estimated median sediment yield value ($t/km^2.a$)

2.6.6 Verification of results

In order to check the extent of the predictive accuracy of this probabilistic method, the sediment yields that were computed using equation 2.6.2 were checked using the discrepancy ratio test at 50% exceedance probability. The technique compares all the predicted sediment yields against all the observed sediment yields using the discrepancy ratio, x_i , whereby each predicted value is divided by the corresponding actual observed value. The discrepancy ratio x_i , should be a good indicator of the predictive accuracy of the probabilistic approach in predicting the sediment yield.

In mathematical terms the discrepancy ratio would be given by the following relationship:

$$\frac{SY_{sim}}{SY_{obs}} = x_i \quad 2.6.4$$

Where

SY_{sim} = Simulated sediment yield

SY_{obs} = Observed sediment yield

The simulated sediment yields refer to the sediment yields calculated using equation 2.6.2. The simulated sediment yields using equation 2.6.2 were divided by their corresponding observed sediment yields in Appendix C for all the regions. The following relationship was obtained relating to the calculated value of x_i .

$0.33 \leq x_i \leq 3$; 81% of the data was in this range

$0.5 \leq x_i \leq 2$; 68% of the data was in this range

$0.67 \leq x_i \leq 1.5$; 43% of the data was in this range

The ranges of the discrepancy ratios obtained in the current statistical approach were compared with those obtained in the previous statistical approach (Rooseboom et al., 1992) and the results were:

$0.33 \leq x_i \leq 3$; 70% of the data was in this range (Rooseboom et al., 1992)

$0.5 \leq x_i \leq 2$; 47% of the data was in this range (Rooseboom et al., 1992)

$0.67 \leq x_i \leq 1.5$; 32% of the data was in this range (Rooseboom et al., 1992)

The results for individual regions are shown in Table 2.6.3 for the probabilistic approach in this study.

Table 2.6.3 Discrepancy ratio results for the probabilistic method

Region	Obs. n	Percentage of the data in this range		
		$0.67 < x_i < 1.5$	$0.5 < x_i < 2.0$	$0.33 < x_i < 3.0$
1				
2				
3	7	71	71	86
4				
5				
6	10	56	67	89
7				
8				
9	9	44	78	89

These ranges are within the limits of acceptable predictive accuracy considering the complex nature of the spatial variability in sediment yield. The small number of observations in Table 2.6.3 has sufficient statistical significance within the objectives of the study since the catchment areas when added together represent a large area in relation to the total area in the region under consideration. However, these values have been computed at 50% probability of exceedance implying that a factor of one (1) has been adopted for all calculated sediment yield values. For higher or lower confidence bands, the multiplication factors from Appendix F are applied. Caution must be taken when applying these factors to avoid over prediction. The probabilistic methodology/approach appears to over predict very small observed sediment yields and under predict high sediment yields at 50% probability of exceedance. This is evidenced by the relationship between the observed data and simulated data on the graphs in Appendix G. For example, the graph for region 9 in Appendix G shows higher calculated sediment yields in the vertical axis for corresponding low observed sediment yields in the horizontal axis while some observed sediment yields are much higher than predicted. This is because the method is based on the general concept of regional sample median assumed at 50% probability of exceedance.

In essence, the estimation of the sediment yield is developed from the average of the observed data series which is taken as the 50th percentile. Since theoretically a percentile is the value of a variable below which a certain percent of observations fall (Wikipedia, 2009), the estimated median sediment yield value calculated by equation 2.6.2 gives a sediment yield value below which 50% percent of observed sediment yields fall. The probabilistic method developed around the 50th percentile value should typically over predict probably at

least half of the sediment yields. The estimated median sediment yield calculated using equation 2.6.2 acts as a reference point whose main application is to provide a sediment yield value that has a 50% exceedance probability. This results in problems in regions where there is high variability in the sediment yield values from the lowest to the highest.

The standardised average yield itself may be already over predicting some small sediment yield in the region. This is the reason why data points on the graphs in Appendix G are characterised by poor scatter along the line of perfect fit. The probabilistic approach does not derive direct relationships between the observed and calculated sediment yields. The method calculates a value that statistically masks all values below it depending on the specified probability of exceedance.

The results given in Appendix G show that for some low observed sediment yields, say less than 100 t/km².a, the method gives relatively higher simulated yields. Similarly, the higher observed sediment yields above the standardised average yield appear to be under predicted. In practice to avoid over predicting or under predicting, two possible measures could be taken. The first measure would be to check the predicted sediment value at 50% confidence band against the nearest observed yield value within the region and compare the results. Secondly, the graphs for the statistical distribution (probability of exceedance) of the observed sediment yields for the nine regions, shown in Appendix E, can be used to compare the predicted value against the expected sediment yield value from the graph at any specific probability of exceedance. In other words, the probabilistic distribution of the observed sediment yields for the nine regions gives an estimate of the general variation of the expected sediment yields within a given region.

Depending on the comparative results, an appropriate confidence band can be adopted. If the estimated median sediment yield is found to be lower than the comparative sediment yield, then the factors provided in the confidence bands' graphs in Appendix F can be used depending on the preferred confidence band and applicable catchment area. The discrepancy ratio test outlined in Table 2.6.3 is considered a significant measure of the predictive accuracy of sediment yield prediction approaches in sedimentation engineering particularly where multiplication factors are applied to achieve higher confidence levels.

2.6.7 Example to illustrate the application of the probabilistic method

The following example illustrates the application of the probabilistic method in the prediction of sediment yields.

Example 1: A dam has been proposed at a location whose details are provided in Table 2.6.4 (a). The total catchment area of the dam is 3039 km².

Table 2.6.4 (a) Proposed dam's location data

LOCATION DATA					
Place	Tuintjeskraal	Drainage Region	J	Latitude	33 ^o 23'00" S
River	Tarka	Station Number	J3H002	Longitude	26 ^o 06'36" E

This dam falls in sediment yield Region 9 according to the sediment yield map in Figure 2.6-1. The erosion hazard class statistics for the area under consideration are given in Table 2.6.4 (b).

Table 2.6.4 (b) Case study area statistics – probabilistic method

Erosion Hazard Class	Area (km²)	Proportion to the total
1	513	0.167
2	608	0.200
3	1732	0.570
4	186	0.017
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
TOTAL	3039	1

From Table 2.6.2, the standardised average yield for Region 9 is 53 t/km².a. and the sediment potential factors for this region are as reproduced in Table 2.6.5:

Table 2.6.5 Region 9 erosion potential factors

REGION	Standardised Average Yield (t/km ² .a)	F ₁	F ₂	F ₃	F ₄	F ₅	F ₆	F ₇	F ₈	F ₉	F ₁₀
9	53	0.184	1.719	2.076	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Equation 2.6.2 is used to convert the *Standardised average yield* value to the *Estimated median sediment yield value*, SY_{est}.

$$\begin{aligned}
 SY_{med} &= 53[(0.184 \times 0.167) + (1.719 \times 0.200) + (2.076 \times 0.570) + (0.017 \times 0.000) \\
 &\quad + (0 \times 0) + (0 \times 0) + (0 \times 0) + (0 \times 0) + (0 \times 0) + (0 \times 0)] \\
 &= 83 \text{ t/km}^2 \cdot \text{a}
 \end{aligned}$$

A comparative check on this calculated value to the actual measured yields for comparable catchments has been done on Stompdrift Dam downstream of the proposed site and it has a value of 75 t/km².a which is close to the estimated median sediment yield of 83 t/km².a.

Since the calculated sediment yield value at 50% confidence is similar to the nearest regional observed sediment yield, a higher confidence band can only be applied if there is need to compute a sediment yield that is more conservative. A confidence band of 80% can be adopted and the multiplication factor is read on the graph for Region 9 in Appendix F as 1.50 for a catchment area of 3039 km².

The estimated sediment yield value at the required confidence band of 80% is:

$$\begin{aligned}
 &= \text{Estimated median sediment yield} \times \text{Multiplication factor} \\
 &= 83 \text{ t/km}^2 \cdot \text{a} \times 1.50 = 125 \text{ t/km}^2 \cdot \text{a}
 \end{aligned}$$

The results show that at 80% exceedance probability, the calculated sediment yield value for this catchment is approximately twice the standardised average yield resulting in a highly conservative value.

2.7 Empirical sediment yield prediction methodology

The objective was to find out if empirical relationships could be established that could provide a means of predicting the sediment yield from data of the significant variables that are involved in sediment yield processes. An investigation was done on the significant variables that would form part of the empirical equations to be derived through regression analysis. The unit stream power formed the theoretical basis for the development of the empirical method.

2.7.1 Concept of total input stream power

The rate of energy dissipation that would be required to transport material is related to the rate of material to be transported according to the general concept of physics. According to Yang (1996), the sediment transport rate is directly related to unit stream power. Therefore, sediment transport can be described by the following total input stream power relationship:

$$Q_s \propto \frac{\rho g Q S}{w} \quad 2.7-1$$

Where

Q_s = Sediment load

Q = Discharge

S = Energy slope

w = Settling velocity of sediment

$\rho g Q S$ = Total Input Stream Power (ρg is assumed constant)

Equation 2.7-1 assumes that there is a sediment transport capacity based on local hydraulic conditions and sediment characteristics. This is generally true for coarse sediment (sand and gravel), but in the South African condition where about 75% of the sediment transported consists of clay and silt fractions, the sediment transport capacity is high, but the sediment availability from the catchment could be limited. Therefore, additional variables had to be considered in equation 2.7-1 to account for the sediment availability. In other words, there is

joint effect of both sediment production and transport capacity controlling factors related to hydraulic conditions and sediment characteristics.

The settling velocity was therefore replaced by a weighted Erosion Hazard Class (EI_w) to account for sediment production. The catchment area (A) was also added to describe the sediment source spatial extent and characteristics. There was also consideration of the region to account for different climatic conditions in the country and also the need to work out the analysis on a relatively homogeneous region. The discharge (Q) was based on a recurrence interval flood proposed to be the 1:10 year flood (established from regression analysis checks of all available recurrence interval floods in Table 2.7.1). The energy slope (S) for a catchment was taken as the average river slope.

2.7.2 Dependent and independent variables

(a) Sediment load

The sediment load was taken as the dependent variable. The average sediment loads were derived from resurveys of sediment deposits in reservoirs and river sediment load sampling data. A critical component of the conversion of sediment deposit volume into mass is the variable density of the sediment deposits (Rooseboom et al., 1992). Equation 2.4.1 proposed by Rooseboom et al. (1992) was used to compute the equivalent fifty (50) year sediment volume.

Alternatively, the 50 year sediment volume was obtained from graphs of sediment volume with time as explained in section 2.4. Using the average density after 50 years, the 50 year sediment volume was converted to a 50 year sediment load in tonnes. The sediment loads from river suspended sediment sampling were obtained directly from river suspended sediment concentration data.

(b) Weighted Erosion Hazard Class

The development of the soil erosion hazard classes has been explained in paragraph 2.6.2. The weighted Erosion Hazard Class basically provides a quantitative measure of the

following parameters: climate, soil profile, relief, vegetation, land use and land management practices based on the Revised Universal Soil Loss Equation (RUSLE) model. The inclusion of the weighted Erosion Hazard Class per catchment in the regression analysis as one of the variable parameters proved to be a significant parameter for further derivation of the equations.

(c) River network density

River network drainage density can be classified as one of the factors that determine the catchment's sediment yield according to Strand and Pemberton (1982). It can be assumed that with all factors equal, for the same catchment area, longer length of river channel per unit area must be able to transport more sediment than shorter river channels within the catchment. This suggests that the river network density should be a significant variable in sediment load computations. Colombo et al. (2000) reported that there is a strict relationship between drainage density and the various factors that control the source area such as climate, vegetation, soil and rock. Since these factors have an effect on the sediment yield of a catchment, it can be concluded that there is a strong relationship between the sediment yield and the drainage density.

Drainage density is a measure of the length of stream channel per unit area of basin (Goudie, 1984). This measurement can vary according to the map scale used, as smaller scale maps will contain less drainage detail than larger scale maps resulting in lower drainage densities where small scale maps are used when compared to large scale maps. This is illustrated in Figure 2.7-1 where the difference in level of detail between rivers mapped at 1: 50 000 scale is shown compared to rivers mapped at 1: 500 000 scale. Theoretically using Figure 2.7-1, the drainage density calculated from the 1: 50 000 data is 1.02 km/km^2 while drainage density from the 1: 500 000 data is calculated to be 0.12 km/km^2 . At a scale of 1:500 000; only 0.12 km length of rivers per km^2 of catchment can be shown due to reduced details. In order to calculate the drainage density, the rivers that were mapped at 1: 500 000 scale obtained from the Department of Water Affairs (DWA) were used. Future application of the developed equations should therefore adopt the 1:500 000 scale for computation of the river network density data across the study area to ensure consistency in the approach.

Spatial data analysis of river channel length per dam or river catchment of known area size was done in ArcGIS based on digital elevation data. The methodology followed in the derivation of the drainage network data in a GIS environment was based on Colombo et al. (2000). The length of river channels was calculated in meters (m). The drainage density for each catchment was finally obtained by the division of the total stream length (km) by the catchment area (km^2) for each of the selected catchments to arrive at a drainage density in m/km^2 for each of the selected catchments.

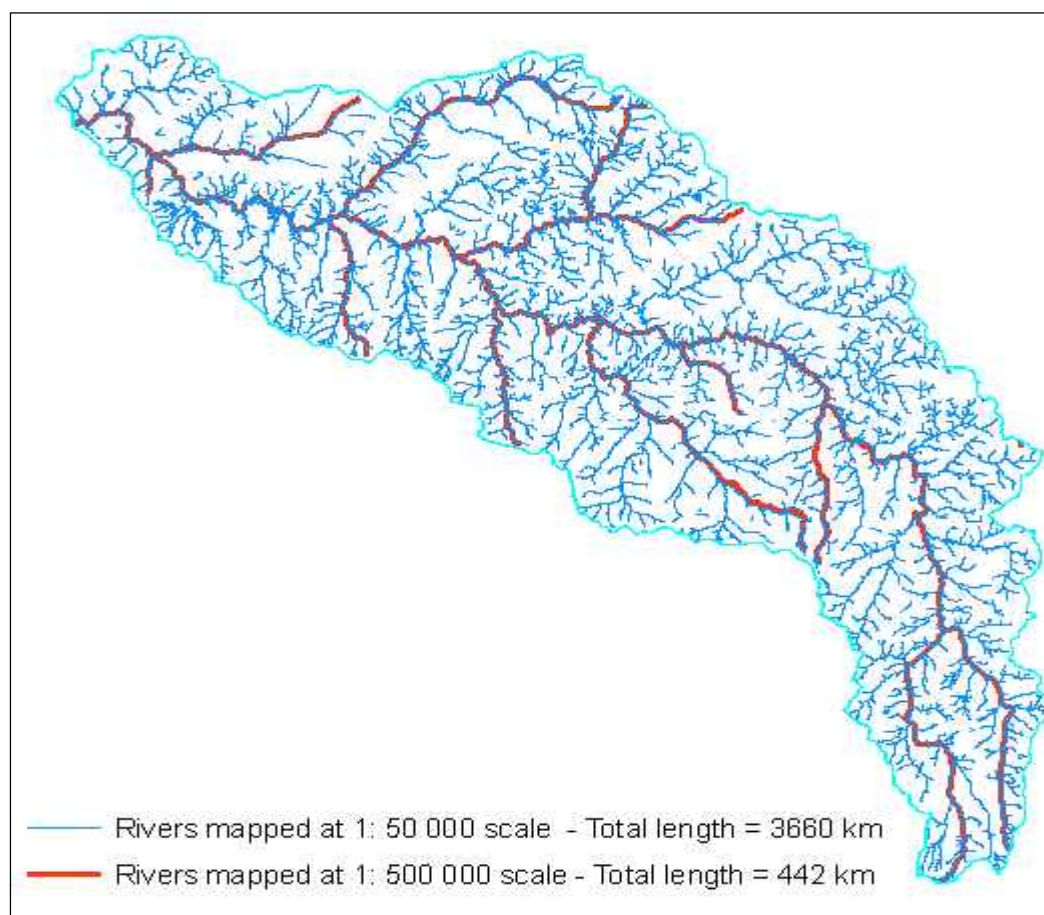


Figure 2.7-1 Illustration of scale effect on total stream length per catchment

(d) Recurrence interval flood

In the original application of the unit stream power, the instantaneous discharge was used in the relationship to describe the sediment transport. However, when considering sediment load over a long period of time then an effective discharge passing through a point along a river or a reservoir would best be represented by a recurrence interval flood, since more sediment is transported during floods than the average runoff from the catchment. All available recurrence interval floods were checked as shown in Table 2.7.1.

Table 2.7.1 Analysis of an optimum recurrence interval flood

Region	Obs. n		0.67<x _i <1.5						0.5<x _i <2.0						0.33<x _i <3.0					
			Q ₂	Q ₅	Q ₁₀	Q ₂₀	Q ₅₀	Q ₁₀₀	Q ₂	Q ₅	Q ₁₀	Q ₂₀	Q ₅₀	Q ₁₀₀	Q ₂	Q ₅	Q ₁₀	Q ₂₀	Q ₅₀	Q ₁₀₀
1	18	%	50	22	50	50	50	50	72	28	78	83	77	72	94	50	94	94	94	94
		r ²	0.59	0.59	0.67	0.68	0.68	0.64	0.59	0.59	0.67	0.68	0.68	0.64	0.59	0.92	0.68	0.68	0.68	0.68
2	25	%	32	40	40	40	40	40	68	76	72	76	68	68	88	88	88	88	88	88
		r ²	0.88	0.89	0.89	0.89	0.89	0.89	0.88	0.89	0.89	0.89	0.89	0.89	0.88	0.89	0.89	0.89	0.89	0.89
3	7	%	60	71	100	57	42.8	43	14	86	100	71	43	42	57	100	100	100	100	100
		r ²	0.80	0.97	0.99	0.94	0.93	0.94	0.8	0.97	0.96	0.94	0.93	0.94	0.8	0.97	0.96	0.94	0.93	0.94
4	30	%	13	43	40	40	40	40	16	50	50	53	57	53	33	77	76	76	76	70
		r ²	0.98	0.81	0.82	0.82	0.82	0.78	0.98	0.81	0.81	0.82	0.82	0.78	0.98	0.81	0.81	0.82	0.82	0.78
5	12	%	50	50	42	41	61	42	75	75	75	75	68	66	100	91	91	75	75	75
		r ²	0.92	0.9	0.88	0.87	0.86	0.85	0.92	0.9	0.88	0.87	0.86	0.85	0.92	0.9	0.88	0.87	0.86	0.85
6	10	%	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		r ²	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	19	%	42	42	42	38	38	38	74	68	84	73	73	73	89	94	95	94	94	94
		r ²	0.85	0.87	0.88	0.87	0.86	0.87	0.85	0.87	0.87	0.87	0.86	0.87	0.85	0.87	0.87	0.87	0.86	0.87
8	14	%	50	50	57	50	50	50	60	60	64	64	71	71	86	86	93	93	93	93
		r ²	0.67	0.68	0.73	0.68	0.67	0.67	0.67	0.68	0.68	0.68	0.67	0.67	0.67	0.68	0.68	0.68	0.68	0.67
9	9	%	33	33	44	44	33	33	56	56	56	56	56	56	74	74	78	78	78	78
		r ²	0.86	0.87	0.89	0.88	0.88	0.88	0.86	0.87	0.87	0.88	0.88	0.88	0.86	0.87	0.87	0.88	0.88	0.88

Notes: $x_i = \frac{SY_{sim}}{SY_{obs}}$ where SY_{sim} = Simulated sediment yield

SY_{obs} = Observed sediment yield

r² = r-squared

The values in Table 2.7.1 were obtained from different combinations of the regression analysis by varying the recurrence flood interval and leaving the rest of the independent variables intact. The data column (in Microsoft Excel) for recurrence interval floods was substituted with different recurrence interval flood datasets and the predictive accuracy of the subsequent regression equations was recorded. Analysis of the results in Table 2.7.1 showed that the best results were obtained from the application of the 1:10 year recurrence interval flood. The 1:10 year recurrence interval flood gave consistent results based on the value of the r-square and the discrepancy ratio results for each of the recurrence interval floods in all the regions.

(e) Average river slope

This was taken as the average slope of the longest watercourse in the catchment.

(f) Homogeneous regions and catchment areas

The sediment yield or sediment load must be related to the catchment area within a homogeneous region. It was therefore decided that the regression analysis should include the parameter of the catchment size as one of the variables. It has also been observed in the confidence bands' graphs in Appendix F that the sediment yield is related to the catchment area size.

(g) Other variables

Other additional variables could also have an effect on the sediment load. However, it was recognised that not all these parameters could be incorporated in the regression analysis. The adopted variables for regression analysis were only those that were seen to have a dominant effect in the correlative analysis within the prescribed theoretical basis.

2.7.3 The concept of multiple regression analysis

Regression represents a mathematical equation expressing one random variable as being correlatively related to another random variable or to several random variables (Yevjevich, 1972). Linear regression analysis is the investigation of an optimum mathematical model that can best predict one variable in terms of another variable. Multiple regression analysis is done when more than two variables are involved. So based on the concept of multiple regression analysis, a total of five independent variables were finally adopted in this study.

2.7.4 Results and derived equations

In order to carry out the multiple regression analysis, both the dependent variable of sediment load and the other variables were logarithmically transformed. According to Rooseboom et al. (1992), sediment transport is a hydrological process and therefore is a function of the same parameters that influence all hydrological processes. It has been observed that while hydrological data are usually strongly skewed, the logarithms of the data have a near symmetrical distribution (Hazen, 1914). The variables were logarithmically transformed to achieve a better regression fit. A column of the sediment load as a dependent variable and five columns comprising the recurrence interval flood, average river slope, river network density, catchment area and weighted Erosion Hazard Class were created in Excel. The regression analysis was performed in Microsoft Excel (2007) using Data Analysis tools. The proposed equations showing the results of the derived coefficients after regression analysis and correlation against observed data are shown in Table 2.7.2:

Table 2.7.2 Empirical equations based on regression analysis

Region	Proposed Equation
1	$Q_S = 22Q_{10}^{0.98}S_0^{-0.19}R_{nd}^{0.10}A_e^{0.10}EI_w^{0.95}$
2	$Q_S = 10Q_{10}^{0.44}S_0^{0.27}R_{nd}^{0.46}A_e^{0.88}EI_w^{-1.42}$
3	-
4	$Q_S = 0.61Q_{10}^{0.58}S_0^{0.28}R_{nd}^{0.88}A_e^{0.80}EI_w^{-0.92}$
5	$Q_S = 1432Q_{10}^{1.31}S_0^{0.74}R_{nd}^{-1.32}A_e^{0.41}EI_w^{-0.30}$
6	-
7	$Q_S = 30Q_{10}^{0.36}S_0^{0.33}R_{nd}^{0.29}A_e^{0.61}EI_w^{0.58}$
8	$Q_S = 0.003Q_{10}^{-0.25}S_0^{1.27}R_{nd}^{1.62}A_e^{1.26}EI_w^{-0.57}$
9	-
10	-

Notes: The equations for regions 3, 6, 9 and 10 have not been calculated because of poor and limited data. Instead the probabilistic method is recommended for regions 3, 6 and 9 (See section 2.6) while region 10 should use locally observed data.

Where:

Q_S = Sediment load (t/a)

Q_{10} = A flood of a recurrence interval of 1 in 10 years (m^3/s)

R_{nd} = River network density (m/km^2)

A_e = Effective Catchment Area (km^2)

EI_w = Weighted Erosion Hazard Class according to sub-catchment areas

S_0 = Average river slope (%)

The weighted Erosion Hazard Class can be determined using data obtained from electronic PDF maps by following the same procedure that has been explained in section 2.6.5 (a-d). This section presents the procedure for getting erosion hazard classes and their corresponding areas within a quaternary. The 1:10 year flood and effective catchment area can be calculated using standard hydrological methods.

The river network density can be obtained from electronic PDF maps in km/km^2 per quaternary. Since the area for each quaternary is known, the river length per quaternary can be computed by multiplying the total area and the corresponding river network density. The

summation of all river lengths at the preset scale on the electronic map for all quaternaries gives the total river length in the catchment. The river network density for the whole catchment can be computed by dividing the total river length against the total catchment area under consideration.

2.7.5 Confidence Intervals

The prediction of the sediment yield or load for individual loads or yields outside the original samples that were used to derive equations given in Table 2.7.2 requires confidence intervals. The prediction equations in Table 2.7.2 were derived to calculate the value of the predicted sediment yield around the regional mean. Due to the sample sizes, the prediction of any sediment yield outside the original data set was calculated to be within a 50% confidence interval upon analysis of the predictive accuracy.

In order to estimate sediment yields per region based on the empirical method, the methodology has provided the user with risk linked estimates of the sediment yields from a catchment based on both the location and size of the catchment. The derivation of the confidence bands for the empirical method has followed a similar procedure outlined in section 2.6.4 for the probabilistic method with the exception that sediment loads were used instead of sediment yields. However, the confidence bands need to be applied on the final sediment yield (computed from the sediment load) based on the catchment area. The confidence bands are attached in Appendix H.

2.7.6 Verification and analysis of results

It should be pointed out that the number of observations in all the nine regions was very small to allow the splitting of the sample and use portions of the data for independent verification of the results of the empirical model. Nevertheless, test application of the approach of the split sample in two regions (Regions 1 and 2) that had relatively larger sample sizes showed that the predictive accuracy of the empirical method is relatively good based on the model objectives. Table 2.7.3 shows data that was used for split sample analysis in Region 1. Ten observations were applied to derive regression equations.

The results were used to predict the sediment loads in eight independent observations within the same region. The similar procedure was done for Region 2 and the summary of results for both regions is shown in Table 2.7.4.

Table 2.7.3 Split sample analysis for Region 1

ID	Station Name	Log Sediment Load (Q_s)	Log 1:10 Year Recurrence Interval Flood (Q_{10})	Log Average Slope, S_o (river)	Log River Network Density (R_{nd})	Log Area (A_d)	Log Erodibility Index (EL_w)	Calculated Sediment Load (t/a)	Observed Sediment Load (t/a)
1	Albasini Dam	4.62	2.290	0.367	1.651	2.700	0.674		
2	Bospoort Dam	4.94	2.322	0.250	2.077	2.764	0.570		
3	Buffelspoort Dam	4.17	1.903	0.517	2.340	2.065	0.695		
4	Cross Dam	4.59	2.190	0.602	2.121	2.480	0.838		
5	Doomdraai Dam	4.81	2.176	0.312	2.108	2.587	0.736		
6	Hans Strijdom Dam	4.61	2.681	0.420	2.178	3.636	0.789		
7	Hartebeespoort Dam	5.58	2.789	0.441	2.120	3.541	0.793		
8	Klein-Maricopoort Dam	4.30	2.301	0.225	2.184	2.918	0.605		
9	Klipvoor Dam	4.78	2.342	0.124	2.056	3.673	0.545		
10	Koster Dam	3.90	2.041	0.236	1.955	2.461	0.498		
11	Kromellenboog Dam	4.86	2.371	0.320	2.069	2.783	0.567	38435	73012
12	Lehujwane Dam	4.32	2.061	0.086	2.177	2.302	0.509	31289	21102
13	Madikwe Dam	4.30	2.176	0.253	2.186	2.496	0.547	27307	19746
14	Marico-Bosveld Dam	4.77	2.230	0.500	1.972	2.977	0.674	18359	59334
15	Mzhelele Dam	5.36	2.724	0.699	3.048	2.920	0.845	115410	230847
16	Olifantsnek Dam	4.70	2.708	0.373	2.011	2.698	0.595	128227	50513
17	Roodeplaat Dam	4.82	2.360	0.312	2.185	2.838	0.693	66782	65418
18	Vaalkop Dam	5.32	2.886	0.143	2.095	3.593	0.523	193773	207877

Table 2.7.4 Results of split sample predictive accuracy analysis

Region	Obs. n	Percentage of the data in this range		
		$0.67 < x_i < 1.5$	$0.5 < x_i < 2.0$	$0.33 < x_i < 3.0$
1	18	50	63	88
2	25	42	58	77

Graphs were plotted for all regions to analyse the relationship between the observed sediment loads against calculated sediment loads using the derived regional empirical equations given in Table 2.7.2.

Predictive accuracy checks were done by way of inspection of the graphs, determination of the r-square and calculation of the extent of deviation (using the discrepancy ratio concept). APPENDIX I shows the plot of the results of the observed sediment loads against calculated sediment loads using the empirical method. Table 2.7.5 shows results of the discrepancy ratio test for each region.

Table 2.7.5 Discrepancy ratio results for the empirical method

Region	Obs. <i>n</i>	Percentage of the data in this range		
		$0.67 < x_i < 1.5$	$0.5 < x_i < 2.0$	$0.33 < x_i < 3.0$
1	18	50	78	94
2	25	40	72	88
3	7	100	100	100
4	30	40	50	76
5	12	42	75	91
6				
7	19	42	84	95
8	14	57	64	93
9	9	44	56	78
10				

The r-squares in Table 2.7.1 for the 1:10 year recurrence interval flood were analysed. Analysis of the graphs in Appendices I and the discrepancy ratio results in Table 2.7.5 for the empirical approach provided the following observations:

- a. Regions 1, 2, 4 and 5 regression equations have good predictive accuracy based on the discrepancy ratio. This is still satisfactory when one considers the general behaviour of sediment and the ranges of acceptable predictive accuracy that were targeted.
- b. Region 3 results appear theoretically good. But the few observations might be contributing undue leverage on the regression equation which is typical of regression analysis results when insufficient data is used, i.e. few observations (Wasson, 1994). Additionally, Region 3 falls in part of the region that was also difficult to derive satisfactory results in the previous report (Rooseboom et al., 1992) due to insufficient data and high variability in observed sediment yields.
- c. No reliable equation was developed for region 6 and 10 due to poor and limited data.
- d. Regions 7 and 8 have one outlier each that appear to be over predicting the low sediment yields. However, the outliers have been checked to have no significant effect on the overall predictive accuracy of the regression equation.

- e. Region 9 has fewer observations. The number of observations has a significant influence on the predictive accuracy and statistical significance of the regression equation.

Based on the issues raised in paragraph 2.7.6 (a-e), the regression equations with most reliable predictive accuracy are for those of regions 1, 2, 4, 5, 7 and 8.

2.7.7 Specific considerations associated with each region when estimating sediment yields

Figure 2.7-2 shows the observed sediment yield map of Southern Africa.

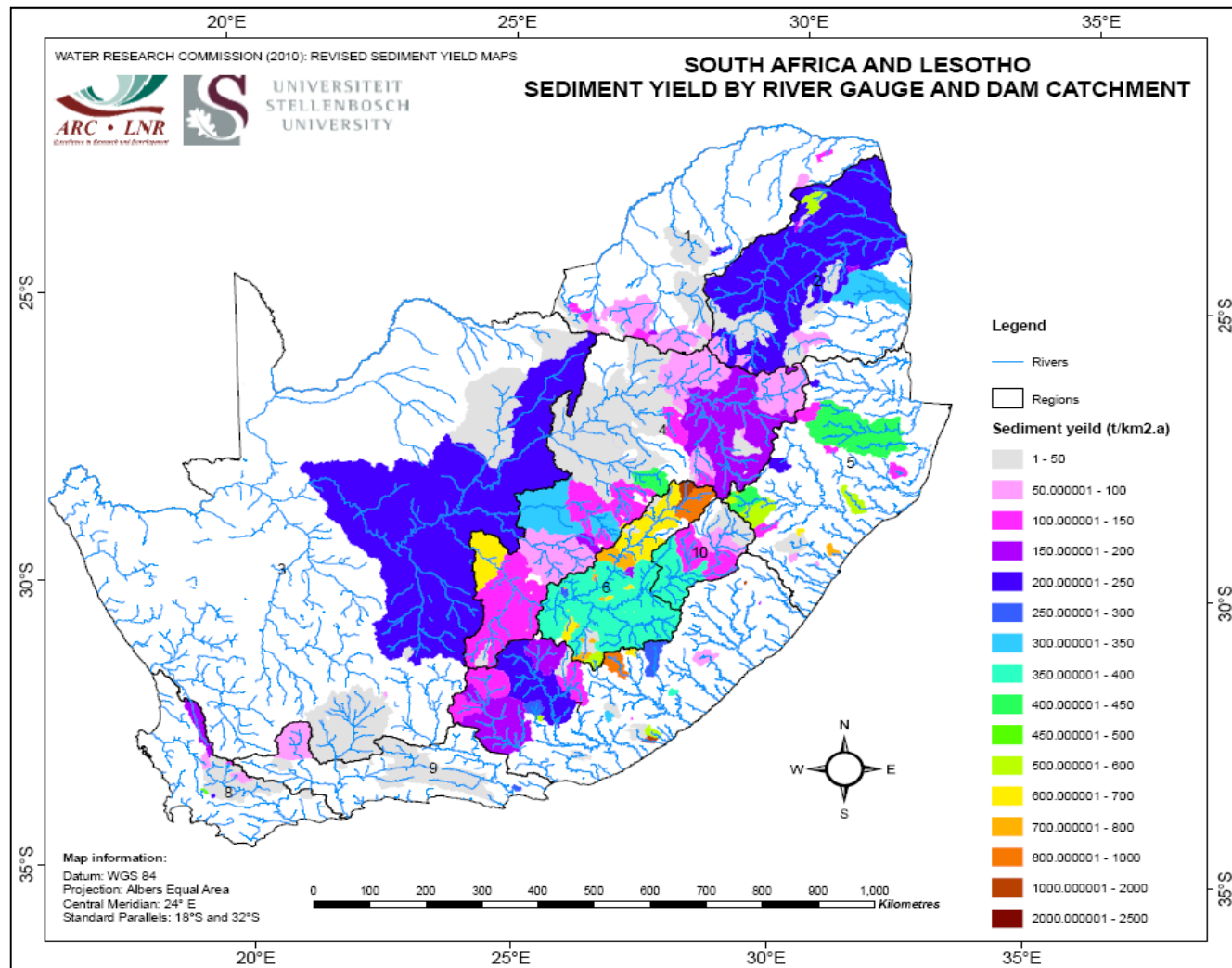


Figure 2.7-2 Observed sediment yield map of South Africa

The specific considerations associated with each region when estimating sediment yields based on the observed sediment yield map in Figure 2.7-2 and Rooseboom et al., (1992) are the following:

Region 1

The region consists of the tributaries of the Limpopo River on the Southern African side. Sediment yield data was available for twenty (21) sites within this region. Simultaneous sediment load and recurrence interval flood data was available for eighteen (18) sites. The land use is mainly agricultural (commercial and subsistence farming) with the major activities being grains (maize) cultivation, vegetable and livestock farming.

The observed sediment yields ranged from 9 t/km².a to 277 t/km².a. A reliable regression equation based on the empirical data was derived for this region. The confidence bands for the empirical method show that the observed sediment yield values converge to a regional mean value with increasing catchment area.

Region 2

This region comprises highly urbanised areas and the catchments of Olifants River, Corumana Dam and Massingir Dam in the Limpopo Province. The highly urbanised areas are characterised by mining, commercial and industrial areas. The rest of the region is comprised of agricultural and conservation areas. The highly industrialised and urbanised areas produce high sediment yields.

The sediment yield values vary from 25 t/km².a to 520 t/km².a. There is high variability in the sediment yields in this region even within neighbouring catchments owing to neighbouring urbanised and non-urbanised areas. The multiplication factors for use in the confidence bands for Region 2 need careful consideration for individual catchments with respect to urban, non-urban areas and geological diversity. The sediment yields in some areas are exceptionally high resulting in the high multiplication factors for this region. Sensible application of the factors is essential to avoid over prediction in some catchment areas whose sediment yields are expected to be low.

Region 3

This region is partly situated along the lower reaches of the Orange River and it is characterised by arid conditions. Part of this region is situated in the central Karoo and is geologically one of the more homogeneous regions. Sheep farming is the dominant land use. Though the region is geographically huge, the sediment load data was limited. The empirical method failed to come up with a reliable regression equation for this region. Reliable sediment yield data was available for seven (7) stations only. Six out of the seven catchments that have sediment yield values have a value of less than 50 t/km².a. The low sediment yields are due to the prevailing arid conditions whereby the sediment yields are limited by the transporting capacity rather than availability of sediment. A single value for each confidence limit was estimated for this region due to limited data. The limited number of points also precludes the possibility of detecting trends in sediment yield values with increase in catchment area.

Region 4

These catchments are smaller and are situated in the upper regions of the Vaal catchment. The sediment yield values converge towards a regional mean value with increase in catchment size.

Region 5

Region 5 is situated mainly in KwaZulu-Natal. Sediment yield information is available for 12 reservoirs. Measured sediment yield values vary between 30 t/km².a and 1,037 t/km².a. The reservoirs in which information is available, are not homogeneously distributed through the region. Most of the reservoirs are situated in the area between Durban and Lesotho within catchments of the Mgeni and Thukela Rivers. Little data is available in the vicinity of Swaziland.

The area is geologically varied. Land use varies from cattle farming in the KwaZulu-Natal midlands, to sugar cane farming along the coast, with large areas of subsistence farming scattered throughout the region.

Despite this diversity, sediment yield values tend to converge to a regional mean value, with increase in catchment size.

Sugar cane production areas are not well represented in the available data. As these areas have high sediment yield, care has to be taken when evaluating sediment yield for areas in which sugar cane production is significant. Yields in excess of 1000 t/km².a are possible (Rooseboom et al, 1992).

Region 6

The region consists of the upper Orange and Caledon catchments down to the Gariep Dam including the south eastern part of Lesotho. Some of the highest sediment yield areas in the country are situated in this region, mainly within the Caledon River catchment. Sediment surveys for 4 reservoirs are available. Some data obtained from suspended sediment yield measuring stations in Lesotho was also used. Measured sediment yield values range from 392 t/km².a. to 1141 t/km².a. Once more, due to limited sediment yield data, only single confidence limit values were estimated without any indications of trends for increase in catchment size. The regional average is high and generally high sediment yields should be expected.

Region 7

Region 7 is situated in the Eastern Cape.

Sediment survey information for 18 reservoirs is available. Measured sediment yield values are between 94 t/km².a. and 1509 t/km².a.

The region's data display the expected tendency of convergence of sediment yields values to a regional mean value, with increase in catchment size.

Region 8

Region 8 is partly situated in the Western Cape. Fruit farming is the main land use. Sediment surveys are available for 14 reservoirs. Observed sediment yields are between 16 t/km².a. and 450 t/km².a.

Catchment sizes in this region are relatively small. This results in relatively small total sediment yields for catchments, even though the unit yields for some of the catchments are relatively high.

The sediment yield values converge very clearly to a regional mean value. Some of the smaller catchments have exceptionally high values relative to the mean value.

At least some of these high values notably that of Wemmershoek Dam, can be ascribed to some extent to the influence of bush fires. Fires increase the resistance of the soils to water penetration and change the soil texture, resulting in increased surface runoff, higher flow velocities and increased sediment yields.

Region 9

Region 9 is also partly situated in the Western Cape and partly in the south Eastern Cape and Transkei. Sediment survey information for 9 reservoirs is available. Measured sediment yield values are between 6 t/km².a. and 149 t/km².a. The limited number of points resulted in lack of meaningful trends in sediment yields values with increase in catchment area.

Region 10

Region 10 consists mainly of the basaltic regions of Lesotho situated along the upper Orange River (Senqu). Information of sediment yields in this region was obtained from a number of suspended sediment measuring sections with short records of about 6 years.

Due to the fact that the basaltic regions have low sediment yields, the regional average yield is low as well. Some very high sediment yields occur in cases where the same soils that are

present along the upper regions of the Caledon River, are included in certain catchments. This is the reason why the methodology has not recommended any method for this region due to unreliable data.

2.7.8 Illustration of the application of the empirical method

The following example illustrates the application of the empirical method in the prediction of sediment yields based on the methodology presented in the preceding section. Example 2 illustrates the prediction of the sediment yield when the catchment area falls in a single sediment yield region. A hypothetical dam that needs to be constructed on the Berg River has been used.

Example 2: For planning purposes, the sediment yield for the proposed dam's total catchment area of 1611 km² is required.

Table 2.7.6 gives the proposed dam's location data.

Table 2.7.6 Proposed dam's location data

LOCATION DATA				
Place	Zonquasdrift	Drainage Region	G	Latitude 33°20'03" S
River	Berg	Station Number	G1H079	Longitude 18°58'05" E

This example provides the procedure for the application of the empirical method where the catchment falls in the same sediment yield region. The proposed dam is located in sediment yield Region 8 of the new sediment yield regions in Figure 2.6.1 (at the bottom).

From Table 2.7.2 an applicable regression equation for the determination of the sediment load (Q_s) for Region 8 is shown below.

$$Q_s = 0.003Q_{10}^{-0.25}S_0^{1.27}R_{nd}^{1.62}A_e^{1.26}EI_w^{-0.57} \quad 2.6$$

The rest of the parameters were calculated as detailed below.

- (a) Flood peak discharge for a recurrence interval of 10 years, Q_{10}

The results of the flood frequency analysis at the dam site are summarised in Table 2.7.7:

Table 2.7.7 Flood frequency analysis

Probability of Exceedance (%)	50	20	10	5	2	1	0.5
Flood Peak (m^3/s)	170	371	541	725	1002	1243	1502

Therefore, a flood with a recurrence interval of 1 in 10 years (Q_{10}) is $541 \text{ m}^3/\text{s}$

(b) River network density, R_{nd}

The river network density at a scale of 1:500 000 was computed as $145 \text{ m}/\text{km}^2$.

(c) Average river slope, S_o

The average slope of the longest river was computed to be 8%

(d) Weighted Erosion Hazard Class, EI_w

Table 2.7.8 shows the sub-catchment areas and their corresponding soil erosion hazard classes.

Table 2.7.8 Case study area statistics – empirical method

Erosion Hazard Class	Area (km²)	Proportion to the total
1	260	0.161
2	1351	0.839
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
TOTAL	1611	1

From Table 2.7.8, the weighted Erosion Hazard Class, EI_w is 1.839.

The predicted sediment load using equation 2.6 above and substituting the computed parameters is as follows:

$$Q_s = 0.003 \times 541^{-0.25} 8^{1.27} 145^{1.62} 1611^{1.26} 1.839^{-0.57}$$

$$Q_s = 221963 \text{ t/a}$$

The predicted sediment yield = $\frac{221963}{1611} = 132 \text{ t/km}^2\text{.a}$. As recommended it is helpful to compare the results with neighbourhood dams' sediment yields. Observed sediment yields along the river based on sediment sampling give an average value of $150 \text{ t/km}^2\text{.a}$. The computed sediment yield is lower.

A confidence band of 80% can be adopted and the multiplication factor is read on the graph for Region 8 in Appendix H as 1.5 for a catchment area of 1611 km^2 .

The final adopted sediment yield is therefore: $(132 \times 1.5) \text{ t/km}^2\text{.a} = 198 \text{ t/km}^2\text{.a}$

2.8 Comparison of the empirical and probabilistic approaches

Table 2.8.1 shows the comparative analysis of the empirical and probabilistic methods.

Table 2.8.1 Comparative analysis of empirical and probabilistic methods using the discrepancy ratio

Region	Obs. <i>n</i>	Percentage of the data in this range					
		0.67 < x_i < 1.5		0.5 < x_i < 2.0		0.33 < x_i < 3.0	
		Empirical	Probabilistic	Empirical	Probabilistic	Empirical	Probabilistic
1	18	50	41	78	64	94	77
2	25	40	36	72	68	88	84
3	7	100	71	100	71	100	86
4	30	40	44	50	66	76	72
5	12	42	33	75	61	91	83
6	8	-	56	-	67	-	89
7	19	42	46	84	65	95	77
8	14	57	26	64	60	93	80
9	9	44	44	56	78	78	89

Based on the discussions in paragraph 2.7.6, the empirical method is comparatively the most reliable prediction method for sediment yield. It can be concluded from the discussions in paragraph 2.7.6 and paragraph 2.6.6 that the most reliable method to adopt for regions 1, 2, 4, 5, 7 and 8 should be the empirical method. The empirical method is not being recommended in regions 3, 6 and 9 because of the relatively small sample sizes. Therefore, the empirical method should be applied in regions 1, 2, 4, 5, 7 and 8. By implication, sediment yield predictions for sediment yield regions 3, 6 and 9 should make use of the probabilistic method. Similarly, the probabilistic method will not be applicable to regions 1, 2, 4, 5, 7, 8 and 10. For region 10, locally observed data should be used.

3.0 MATHEMATICAL MODELLING OF SEDIMENT YIELD

3.1 Catchment erosion and sediment yield modelling

3.1.1 Models for erosion and sediment yield modelling

(a) Background

Numerical models are very useful tools in the estimation of erosion and sediment yield from a watershed and analysis of land-use impacts on sediment generation (Schmidt et al., 2008). Modelling of erosion and sediment yield plays a significant role during the design stages of a project particularly in the development of effective catchment management and sediment control strategies. This is in most cases achieved by spatially distributed models that have the ability to provide spatially distributed information on erosion and sediment yield within the catchment which can be used for planning catchment management and sediment control strategies. The spatial information is either presented in the form of data for individual grid squares making up the catchment or sub-catchment that can be calculated as single computational units.

Models can be fully physically-based, empirically-based or mixed empirical and physically-based (Randle et al., 2006). This classification is applied with reference to the description of the hydrological processes that are involved. Parameters used in the physically-based models are measured and/or are assessed from field data and conditions that describe the physical characteristics and properties of the catchment. Physically-based models can represent the catchment as either lumped or distributed. Physically-based, spatially-distributed modelling systems have particular advantages for the study of basin change impacts and applications to basins with limited records (Basson & Di Silvio, 2008). The capability to simulate land use changes by a model is significant where there is need to examine the effectiveness of applying site/sub-catchment specific soil conservation techniques within the watershed.

A considerable number of models have been developed over the years to simulate and predict flow processes and sedimentation loads in order to predict sediment yields from catchments. These numerical models have the ability to simulate spatial and temporal variation of

sediment yields. The basic application of numerical models requires information such as meteorological and topographical data as well soil properties and vegetation characteristics.

(b) Empirically based models

Empirically based models are derived from what is experienced or seen rather than on theoretical grounding of erosion and sediment processes. Empirical equations are developed using data collected from specific geographical areas; application of these equations should be limited to areas represented in the base data (Randle et al., 2006). Development of the equations mostly makes use of regression and statistical analysis. Erosion and sediment yield in a catchment is determined by the following factors according to Strand and Pemberton (1982):

- Rainfall amount and intensity
- Soil type and geological formation
- Ground cover and land use
- Topography
- Upland erosion rate, drainage network density, slope, shape, size, and alignment of channels
- Runoff
- Sediment characteristics-grain size, mineralogy, etc.
- Channel hydraulic characteristics

Few empirical methods have been developed to compute sediment yield as a function of the catchment area. The drainage characteristics are used in empirical relationships. However, it is mostly the Universal Soil Loss Equation (USLE) or its modified versions such as MUSLE that has been widely applied in most empirically based models.

The mathematical models have their algorithm for the computation of erosion and sediment yield based on the USLE parameters or its modified versions as explained in 3.1.5. The ACRU model (Agro hydrological modelling system of the Agricultural Research Unit, South Africa) uses the Modified Universal Soil Loss Equation (MUSLE) for the estimation of sediment yield (Smithers et al., 2002).

(c) Physically based models

Physically-based models are based on physical and theoretical interrelationships between erosion and sediment yield controlling processes. They have the ability to simulate erosion and sediment yield both in time and space. The models give a detailed description in time and space of the flow and transport processes that are involved in erosion and sediment yield. Some of the available physically based models include: SHETRAN (Ewen et al., 2000) and Water Erosion Prediction Project (WEPP) (Nearing et al., 1989),

Other models include: Areal Non-point Source Watershed Environmental Response Simulation (ANSWERS) (Beasley et al., 1980), Hydrological Simulation Programme – Fortran (HSPF) (Bicknell et al., 1997), Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) (Kinsel, 1980), Kinematic runoff and Erosion model (KINEROS) (Woolhiser et al., 1990) and European Soil Erosion Model (EUROSEM) (Morgan et al., 1998).

(d) Mixed empirical and physically based models

Mixed empirical and physically based models are based on both empirical and theoretical erosion and sediment yield processes.

3.1.2 SHETRAN AND ACRU

The models that have been outlined in paragraph 3.1.1 were reviewed with respect to three major considerations: being applicable to relatively larger catchment sizes, ability to simulate erosion and sediment yield on a continuous basis and the ability to simulate wide range of land-use types and land cover.

Two models were selected for further evaluation namely ACRU and SHETRAN. A detailed evaluation of the relevant literature on SHETRAN will be presented in the following paragraphs.

SHETRAN, is a physically based, spatially distributed, hydrological and sediment yield modelling system applicable at the river basin scale (Ewen et al., 2000). It uses the

application of physical and mathematical relationships by utilising internally coded equations and functions to simulate erosion, transport and sediment deposition processes in the catchment for both overland and channel flow.

The ACRU model gives daily event by event catchment sediment yield estimation by the application of Modified Universal Soil Loss Equation, MUSLE (Smithers, 2002; Williams, 1975).

3.1.3 General comparative analysis of SHETRAN and ACRU models

The SHETRAN model capabilities were compared with those of ACRU after a review and investigation of the SHETRAN model as explained in this report and the experience gained from using the ACRU model.

Table 3.1.1 ACRU and SHETRAN comparative analysis

Parameter	ACRU	SHETRAN
Rainfall Daily Input	Uses daily data	Uses hourly data
Spatial distribution of data	GIS raster	Grid squares and links
River/channel sediment routing	No channel or river sediment is routed	Channel sediment can be routed including estimation of the proportion of sediment coming from channel erosion
Discharge data output	Daily	Both hourly and daily
Sediment particle distribution	All sediment are routed as a single load	Has the ability to give results indicating the proportion of the amount sediment of a specific sediment size group
Output of water depths and water tables	Only soil water content results can be generated	Can provide data on sub-surface and surface levels for water in the soil

Sediment process routing method	Uses MUSLE	Uses empirical mathematical equations from literature that describe physical characteristics of flow and land interaction that result in erosion, transport and sediment deposition
Temporal variation in sediment yields	Capable of generating time series of flow	Capable of generating time series of flow
Typical Maximum catchment size (km ²)	10000	2500
Land use change simulation	Y	Y
Overland flow: Rainfall Excess	Y	Y
Overland flow: Upward Saturation	Y	Y
Erosion process: Raindrop impact/Overland flow	Y	Y
Erosion Map	Y	Y
Erosion process: Rilling	Y	N
Erosion process: Crusting	Y	N
Erosion process: Gullying	N	Y
Erosion process: Channel banks	N	Y
Erosion process: Land sliding	N	Y
Land Use	Mainly agricultural	Most vegetation types

3.1.4 The SHETRAN model

SHETRAN is characterised by its comprehensive nature and capabilities for modelling subsurface flow and transport (Ewen et al., 2000). The SHETRAN model uses a grid network to describe the catchment areas and links as river networks. It is a three dimensional model that has a column of horizontal layers underlying each grid square in the vertical direction within each soil layer. The layers represent the soil thickness and the top layer surface represents the overland surface. Flow is routed from surface, subsurface and up to the channel or gullies (Ewen et al., 2000). According to Ewen et al. (2000), the three major components of the SHETRAN model responsible for physical process modelling are water flow, sediment transport and solute transport.

3.1.5 The ACRU Model

According to Schulze (1975), the ACRU model was originally developed to study catchment evapotranspiration in Natal in the early 1970s. The acronym *ACRU* is derived from the agricultural *Catchments Research Unit* within the Department of Agricultural Engineering of the University of Natal in Pietermaritzburg, South Africa (Schulze, 1995). The agrohydrological component of ACRU, which was added later, resulted in the ability of the model to simulate the integration and inter linkage of agrohydrological and hydrological processes related to applied engineering, scientific hydrology and water resources as reported by Schulze et al (1995). The ACRU agrohydrological model concepts are illustrated in Figure 3.1-1.

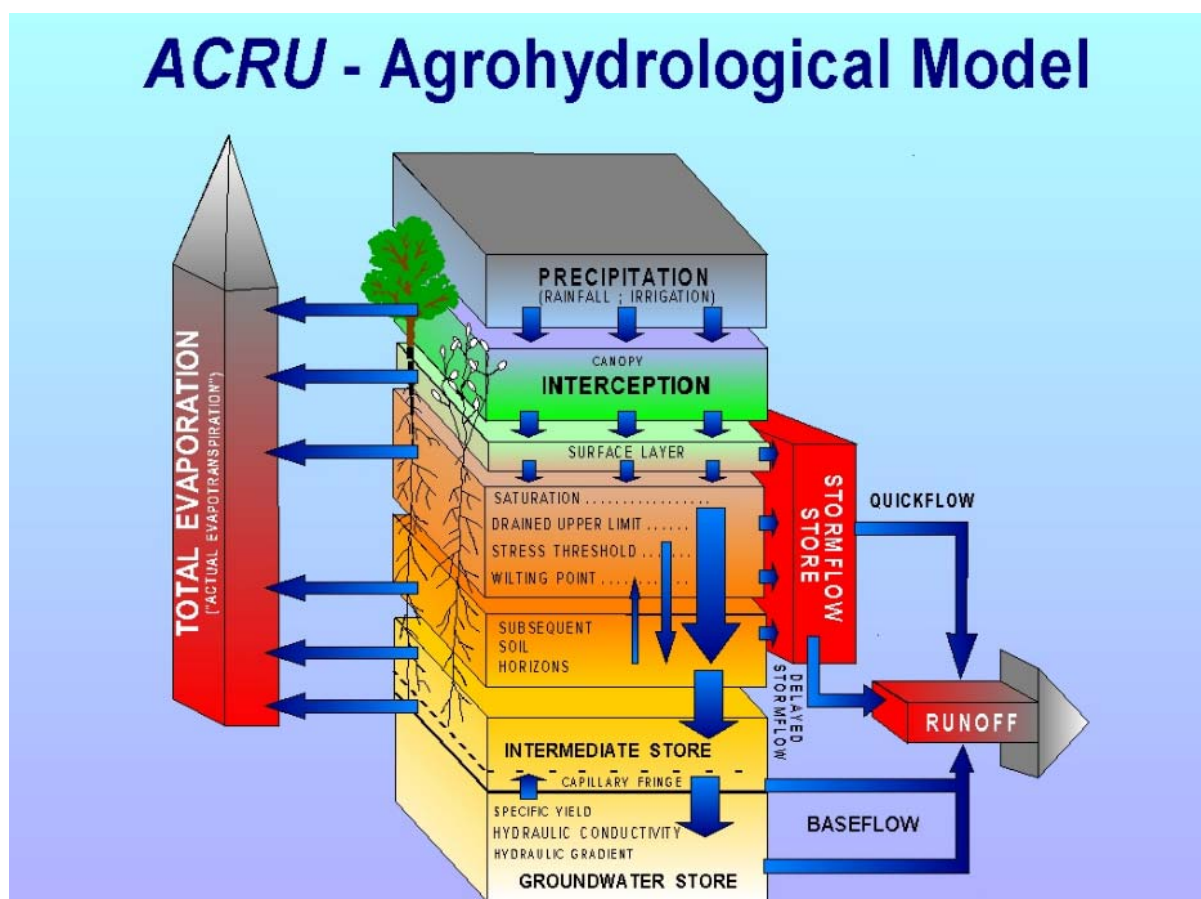


Figure 3.1-1 ACRU Agrohydrological model concepts (Schulze et al., 1995)

The ACRU modelling system can be applied in crop yield modelling, design hydrology, reservoir yield simulation and irrigation water demand/supply, regional water resources assessment, planning optimum water resource allocation and utilization, climate change, land use and management impacts, and resolving conflicting demands on water resources (UNFCC, 2010). In addition, the ACRU model can be applied in sediment yield prediction. The specific components of sediment prediction include sediment generation and reservoir siltation. The ACRU model inputs, operational modes and simulation options are given in Figure 3.1-2.

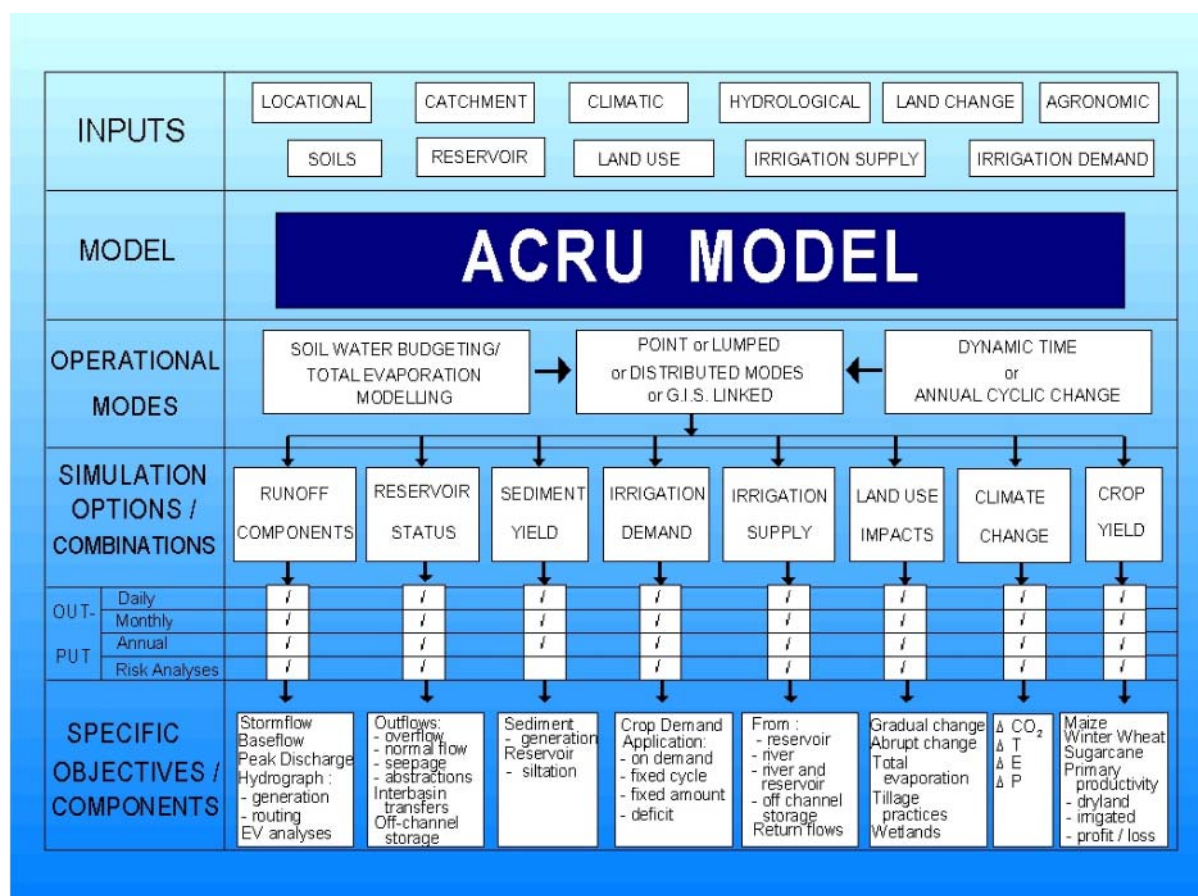


Figure 3.1-2 ACRU Agrohydrological model inputs, operation modes and simulation options (Schulze et al., 1995)

Sediment yield estimation uses the MUSLE approach to determine the delivery of sediment at a catchment outlet. According to Van Zyl and Lorentz (2003), the MUSLE approach was followed because of its ability to estimate sediment yield from individual rainfall events at a catchment scale taking into consideration that ACRU applies modified SCS techniques for storm flow generation. The MUSLE factors define the catchment characteristics and hence the predicted amount of sediment to be delivered is based on the prevailing catchment conditions. Some of the data that is required for the estimation of sediment yield from a catchment include location, catchment properties, climate, soil type, slope length, land use, soil surface cover and conservation practices.

3.2 Description of the study area for SHETRAN application

The application of SHETRAN was reviewed through a case study of the catchment of the proposed Polihali Dam in Lesotho. This catchment was chosen because it could offer a practical example of the application of SHETRAN in Southern Africa.

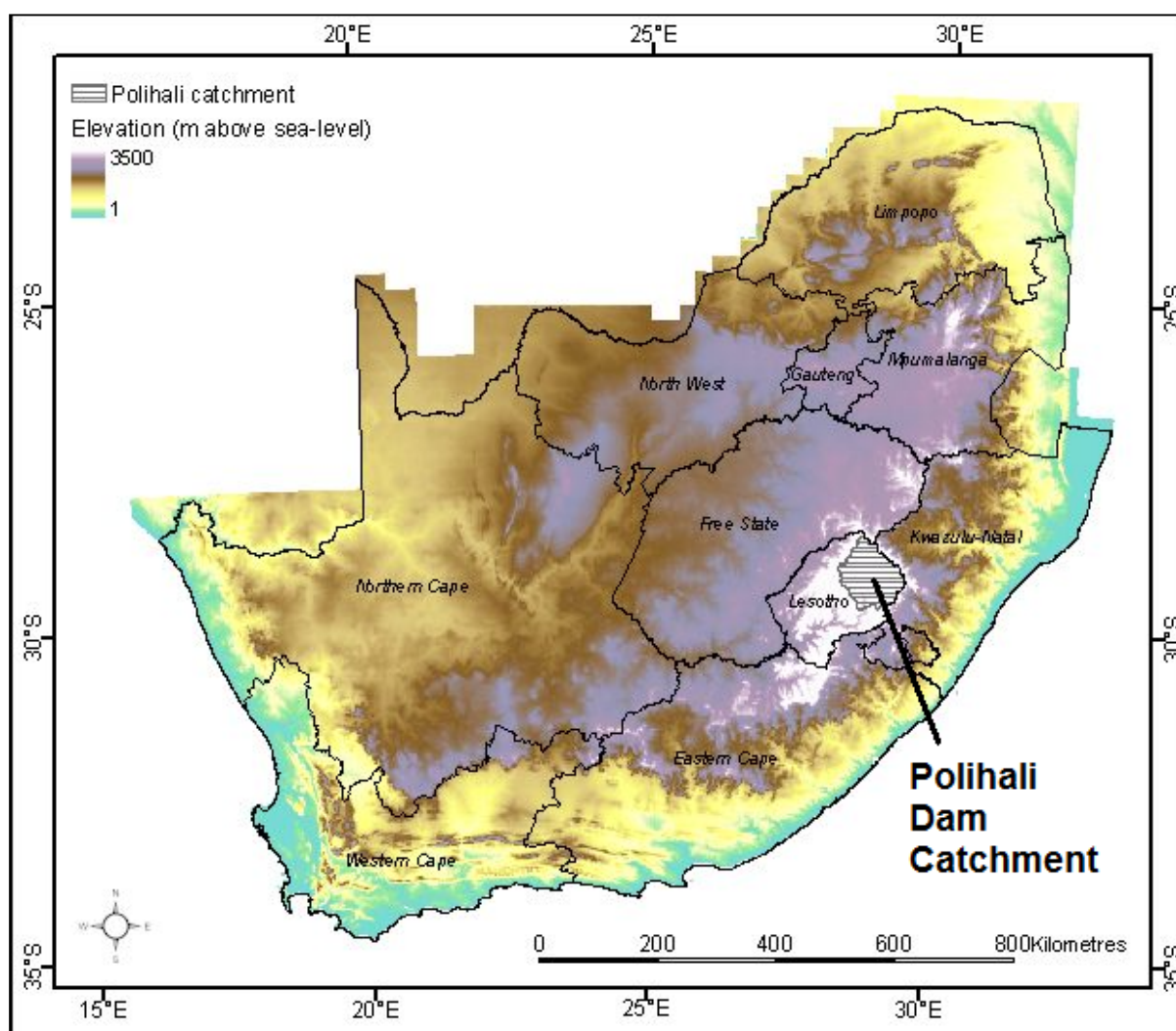


Figure 3.2 -1 Location of Polihali Dam Catchment

The total catchment area is 3164 km², which was represented by 791 grid squares of 2 km by 2 km each. The grid size was limited by the number of columns and rows that the model can handle with respect to the catchment area since it has a maximum allowable number of basic grid elements in the x and y direction. However, similar larger grid sizes have been successfully simulated by the model users elsewhere (SHETRAN Version 4, 2008b). The

elevations ranged from around 3300 masl (highest point) to 1977 masl at the lowest point located at the outlet of the Polihali Dam site.

The catchment is dominated by shallow soils and steep slopes. The three main types of vegetation are shrubland and low fynbos, natural grassland, degraded unimproved natural grassland (bare ground) and wetlands. The major land uses are pasture and cropland. Average annual precipitation is 735 mm/year with low lying areas in the valleys and foothills receiving around 450 mm of precipitation per year and higher lying areas (in the mountains) getting an average annual precipitation of 1000 mm (Sene et al., 1998).

3.3 Model set up – SHETRAN

The catchment description parameters outlined in paragraph 3.2 were applied in the model. The period of the sediment yield study was from 1975 to 1984. The meteorological and flow data was available for the whole of this period. The basic time step was taken as one hour.

Figure 6.3-1 shows the catchment boundary of Polihali Dam and rain gauge and flow gauging station locations. Three meteorological stations were used for input of meteorological data within the catchment and these are: Lelingoma, Seshote and St Martin's.

The catchment boundary and the river network were established from Digital Elevation Model (DEM) using geographical information systems (GIS) techniques. The ground surface elevations for each grid square and river network elevations for each link were obtained from Digital Elevation Maps through processing using AUTOCAD.

The rainfall distribution with respect to position of rainfall/meteorological stations was determined using the Thiessen polygon method. The available rainfall data was limited to the three meteorological stations in Figure 3.3-1. These meteorological stations are confined to relatively lower altitudes. There is normally a high variability in rainfall over a relatively larger geographical area due to elevation and other climate attributes. Therefore, a linear interpolation technique was used to interpolate rainfall data between these meteorological stations and farthest areas based on the elevation data (contour lines) and mean annual precipitation. The average hourly rainfall data and daily evapotranspiration data was used for the stations indicated in Figure 3.3-1.

Figure 3.3-2 shows the catchment palette as generated by SHETRAN with variations in the elevation indicated by grid square colour contrast. The rivers are shown as links between the grid squares.

The land cover distribution was analysed and assessed from photos, maps and satellite images. The soil distribution, depths and catchment geology were obtained from relevant technical reports and soil maps.

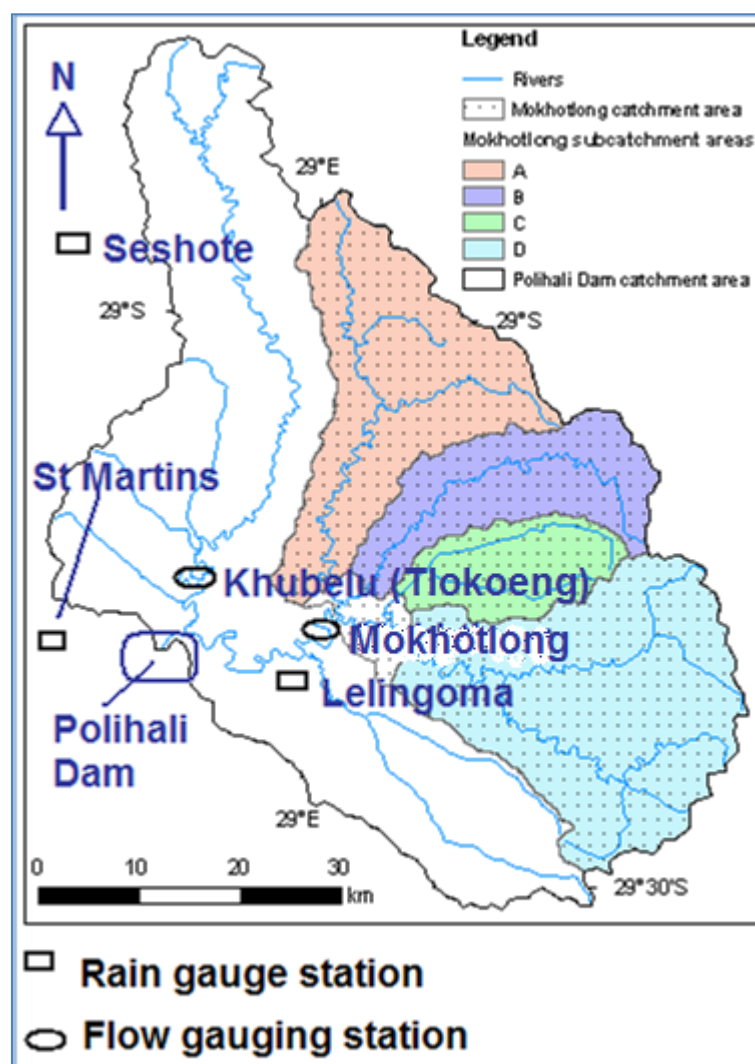


Figure 3.3-1 Study area showing Polihali Dam site with rain gauge and flow gauging stations

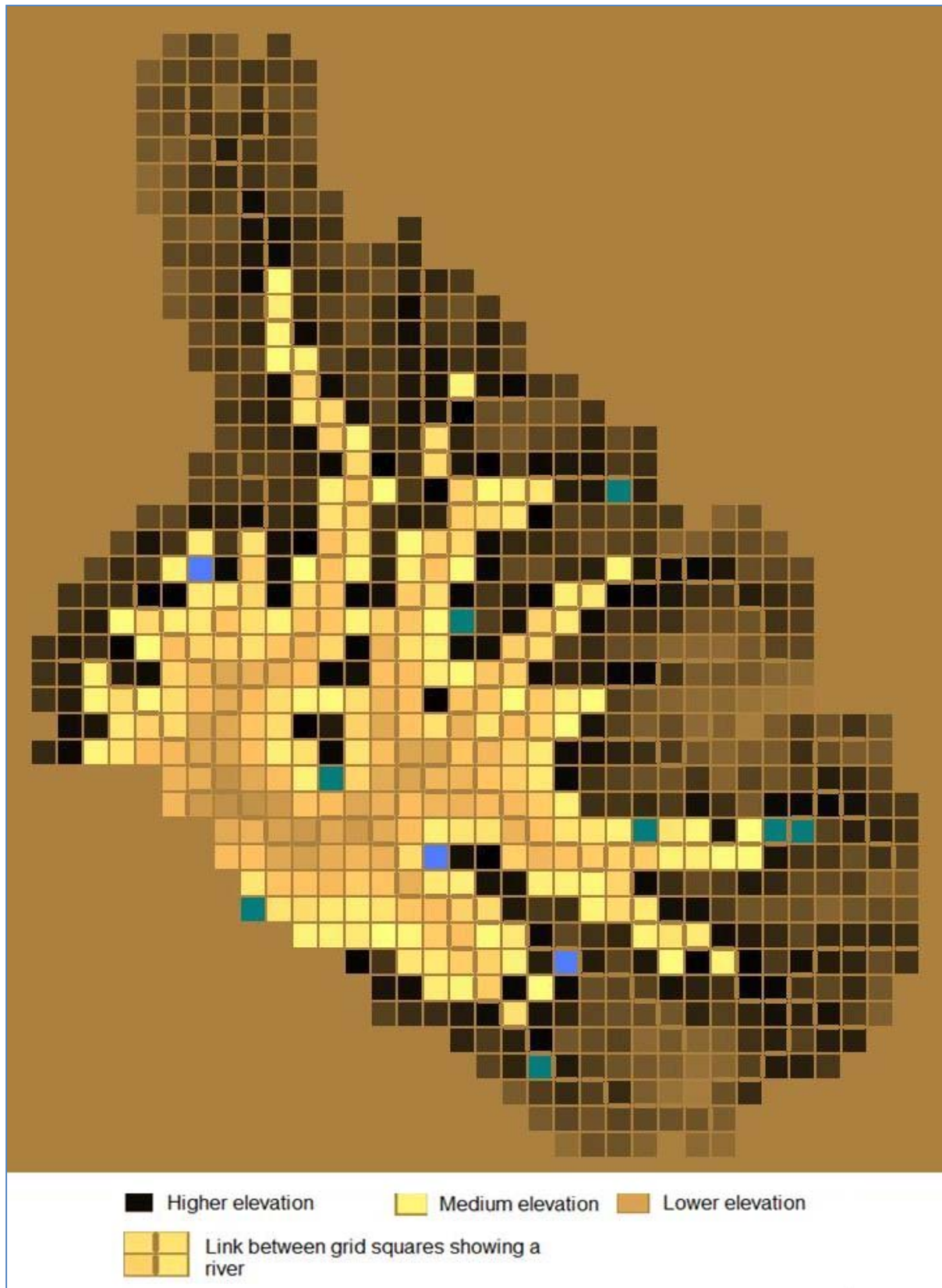


Figure 3.3-2 SHETRAN generated catchment palette for Polihali Dam site showing elevation and rivers as links

The canopy and leaf parameters such as canopy drainage, canopy storage and vegetation cover indices were based on standard parameters specified in SHETRAN Version 4 User Guide (2008) for various standard vegetation types. The default characteristic values for standard vegetation types were used. Although more detailed vegetation types could be distinguished, the number of vegetation types was limited to the allowable cumulative maximum of individual parameters for vegetation, soils, rainfall stations and meteorological stations that the model can ably handle per simulation.

The Manning's roughness coefficient for channels was set between 0.033 and 0.025 (Strickler resistance coefficients between 30 and 40 respectively). The Manning's roughness coefficient for overland flow was set at an average of 0.03. There were four soil types set up in the whole catchment in three different layers. The saturated hydraulic conductivity in the x, y and z direction was set up at an average of 4 m per day. The simulated soil porosity ranged from 0.16 around the bedrock to 0.412 in the upper layers. Data for the rest of the relevant parameters was entered for each of the grid squares and links.

The sediment yield component was set up with input data pertaining to some of the following significant parameters:

- (i) Mobile sediment concentration
- (ii) Raindrop and leaf drip soil erodibility coefficient (J^{-1})
- (iii) Overland flow soil erodibility ($kgm^{-2}s^{-1}$)
- (iv) Channel bank erodibility coefficient ($kgm^{-2}s^{-1}$)
- (v) Average height that drips fall from canopy to ground (m)
- (vi) Bulk dry soil density ($kg m^{-3}$)
- (vii) Fractional clay content of soil
- (viii) Threshold depth of loose soil above which erosion is zero

The flow calibration and validation, sediment yield calibration and validation and the application of mathematical modelling results in SHETRAN have been conducted on Mokhotlong station which is a sub-catchment of the Polihali catchment.

3.4 Flow calibration

Upon setting up the appropriate hydrological, meteorological and spatial data, the model was calibrated against observed flow for the period from 1975 to 1979. Systematic adjustment of the most significant hydrological and flow calibration parameters such as: roughness/resistance (Manning) for overland and channel flow, saturated conductivity and unsaturated conductivity and soil depths was done. The discharge data from 1975 to 1979 was used for calibration of the flow. The simulated stream flow hydrograph at Mokhotlong Station was compared with the observed hydrograph during this period. The graphs showing the results of the calibration at Mokhotlong Station is shown in Figure 3.4-1.

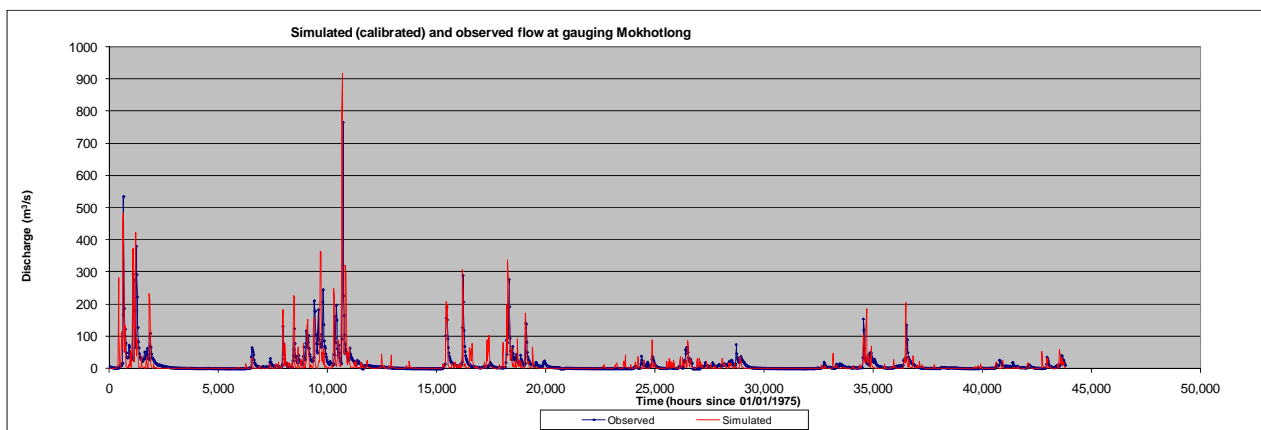


Figure 3.4-1 Flow calibration for Mokhotlong flow gauging station

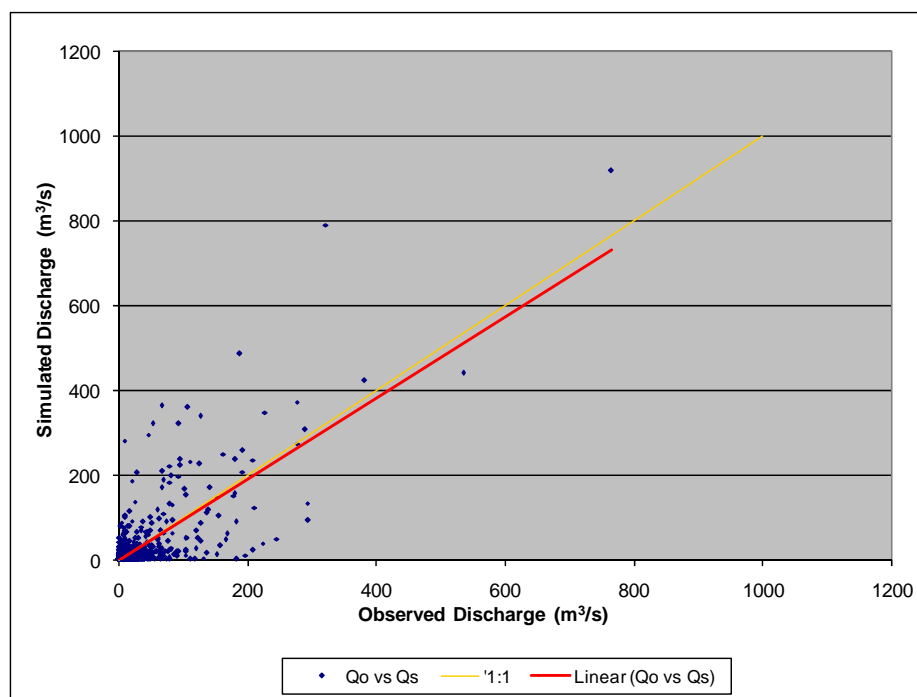


Figure 3.4-2 Simulated (calibrated) and observed discharge showing the scatter around the line of perfect fit

The model uses hourly rainfall for its simulation but the actual observed hourly rainfall data was not available. Therefore, daily rainfall was used in the simulation by disaggregating it into average hourly rainfall based on the typical daily rainfall patterns in the area. The hourly output flow data was generated after each time step which depends on the available rainfall volume per hour. The model has the ability to reduce the basic time step depending on the rainfall volume at a particular point in time.

The accuracy of the calibration was checked through visual inspection of the hydrographs based on experience as well as determination of the degree of correlation. The hydrographs were inspected to ascertain that the simulated peak discharges closely resemble the observed peak discharges. The peak discharge rates for significant storms appear to be simulated better by the model. The other criteria for checking the degree of calibration was through the inspection of the scatter along the line of perfect fit as depicted in Figure 3.4-2. During flow calibration from 1975 to 1979, the calculated r-square was 0.58 for the Mokhotlong flow gauging station. The calculated r-square is reasonably good considering the high spatial and temporal variability in rainfall in the catchment area.

However, some peak flows appeared to be overestimated by the model such as during the 1975/1976 rainfall season, possibly because of the modelling of the soil properties and river networks. The flow could also be overestimated because of some of these reasons: poor representation of the land cover and vegetation properties which in turn may not properly describe the natural soil infiltration rates, the effect of ponding/sinks within the catchment, small natural depressions within the catchment could not be clearly modelled by lack of capacity to simulate water falling into natural sinks and river sinuosity not being accurately represented because of the scaling resulting in theoretically straight rivers (in model configuration) contrary to the actual river network configuration in the field which is characterised by smooth meandering.

However, the overestimation of the flow was found to have minimal repercussions on the accuracy of the final calibrated sediment yield and sediment load as will be shown in section 3.6.

In conclusion, the extent of the correlation is deemed reasonable considering the time period that the flow was being simulated and size of the mesh that was applied which could not adequately represent some natural catchment conditions such as infiltration and storage due to scaling problems. According to Bathurst (2002), use of large grid squares (up to 2 km x 2 km) may introduce scaling problems. The other reason could be the length of the calibration period which could likely be affected by some temporal changes not just resulting from meteorological factors but other human induced factors. In most SHETRAN calibrations, shorter periods are used hence it is easier to achieve better correlation since the chance of encountering significant temporal changes that may be contributed by other factors could be minimal.

Nevertheless, the calibrated flow is sufficient for sediment yield prediction purposes.

3.5 Flow validation

Due to availability of sufficient data, it was possible to split the data set and use one continuous period of data set for calibration (1975 to 1979) and the other data set period for validation. Therefore, flow validation for the SHETRAN model was done using independent data from the period 1980 to 1984. It was done by comparing the simulated flow against the flow that was measured at the Mokhotlong flow gauging station. The validation hydrograph

is shown in Figure 3.5-1. Analysis of the correlation or lack of correlation between observed and simulated flow was done based on the value of the coefficient of determination (r-square) and the scatter of the data around the line of perfect fit in Figure 3.5-2. During flow validation from 1980 to 1984, the calculated r-square from regression analysis was 0.49.

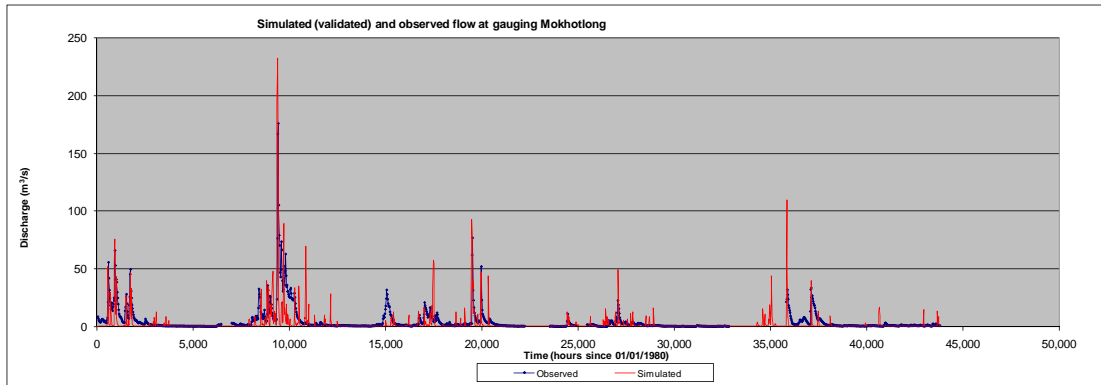


Figure 3.5-1 Flow validation for Mokhotlong flow gauging station

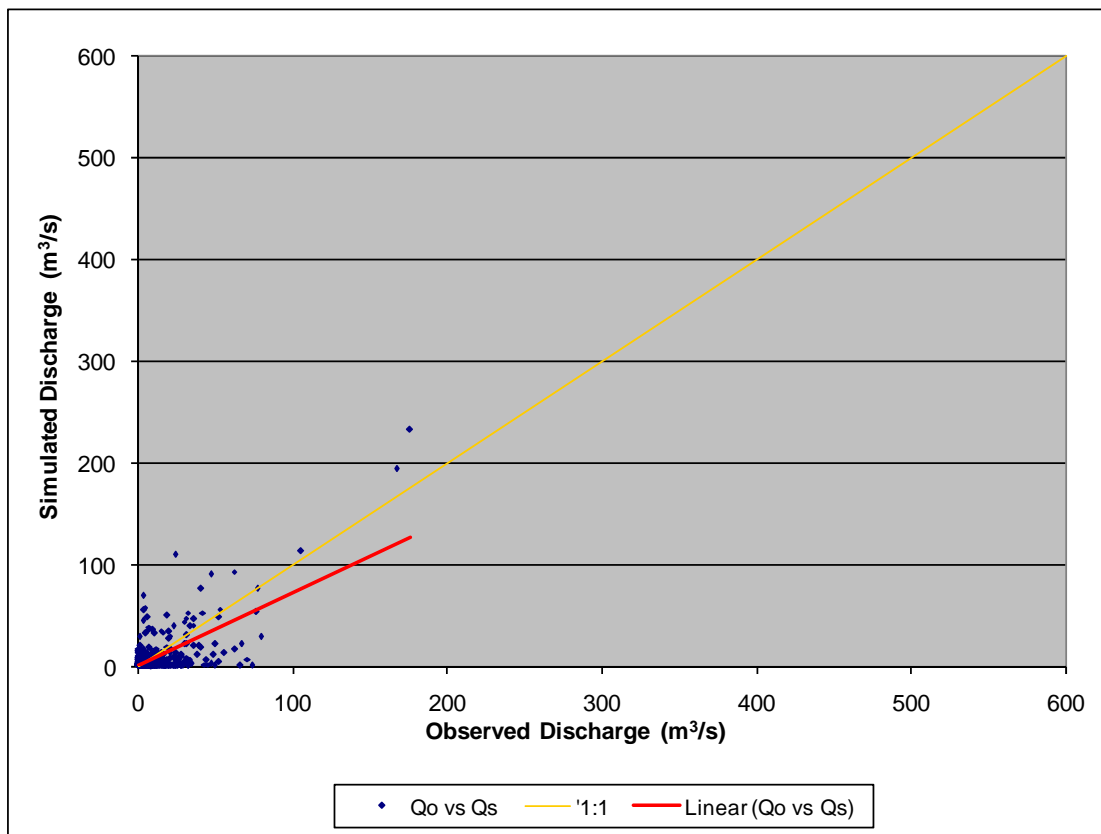


Figure 3.5-2 Simulated (validated) and observed discharge showing the scatter around the line of perfect fit

The r-square is relatively low. The observed flow has gaps in the record. Therefore, the low r-square is an expected outcome considering that the simulated flow does not have a corresponding observed flow to match with in some cases.

3.6 Sediment load calibration and validation

There was not enough data for sediment load calibration using total suspended solid concentration observations at the Mokhotlong flow gauging station. The model was calibrated against the sediment yield at the Koma Koma flow gauging station on the Senqu River that covers a catchment area of 7950 km² of which the Polihali Dam site catchment is included. The average sediment yield for the Koma Koma flow gauging station on Senqu River was 78 t/km².a. This is the average sediment yield because of the high variability in the annual sediment yield along the Senqu River which was calculated to be ranging from 30 t/km².a. to 250 t/km².a. during drought years and flash floods years respectively. Sediment yield calibration sensitive parameters included some of the following: mobile sediment concentration, raindrop and leaf drip soil erodibility coefficient (J^{-1}), overland flow soil erodibility ($\text{kgm}^{-2}\text{s}^{-1}$), channel bank erodibility coefficient ($\text{kgm}^{-2}\text{s}^{-1}$). The results of the calibration are attached in **Figure 3.6-1**. The sediment yield calibration was done at the Mokhotlong flow gauging station.

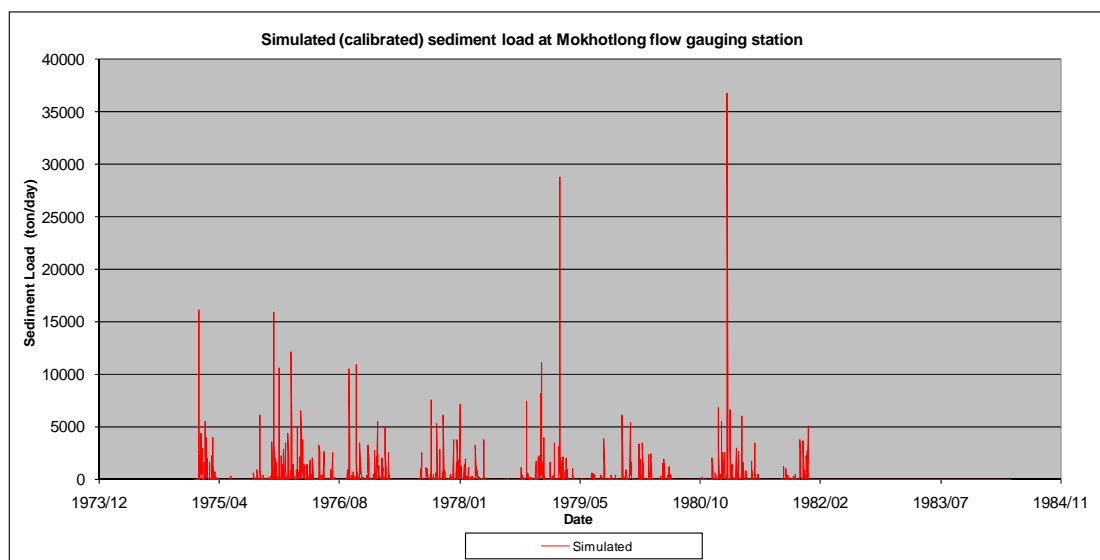


Figure 3.6-1 Sediment yield calibration for Mokhotlong flow gauging station

The sediment yield calibration was done from 01/01/1975 to 31/12/1981.

Table 3.6.1 shows some of the sediment load calibration parameter values.

Table 3.6.1 Significant sediment load calibration parameter values

Parameter	Average/Range
Raindrop and drip soil erodibility	$0.11J^{-1}$
Overland flow soil erodibility	6.7×10^{-10} to $6.7 \times 10^{-9} \text{ kgm}^{-2}\text{s}^{-1}$
Channel bank erodibility coefficient	$1.0 \times 10^{-10} \text{ kgm}^{-2}\text{s}^{-1}$
Threshold depth of loose soil above which erosion is zero	0.05 m

The total sediment load during these seven (7) years was 892,164 tonnes. The sediment yield was calculated using the average annual sediment load and dividing it by the area of the catchment upstream. For the catchment area of 1634 km² for Mokhotlong station, the calculated average sediment yield was 78 t/km².a. The application of the calibrated model results is to identify main sources of sediment and areas of higher sediment yield.

The assumptions that were made in the derivation of the sediment yield for calibration could be unreliable. For example the use of the sediment yield for Koma Koma station might not be reliable for the site specific conditions at the Mokhotlong flow gauging station. The actual sediment yield could be higher or lower since the Mokhotlong station is situated in the upper catchment of the Koma Koma station.

The results were verified by running the simulation using the calibrated sediment load parameters during the period from 1982 to 1984. The results of the validation are attached in Figure 3.6-2.

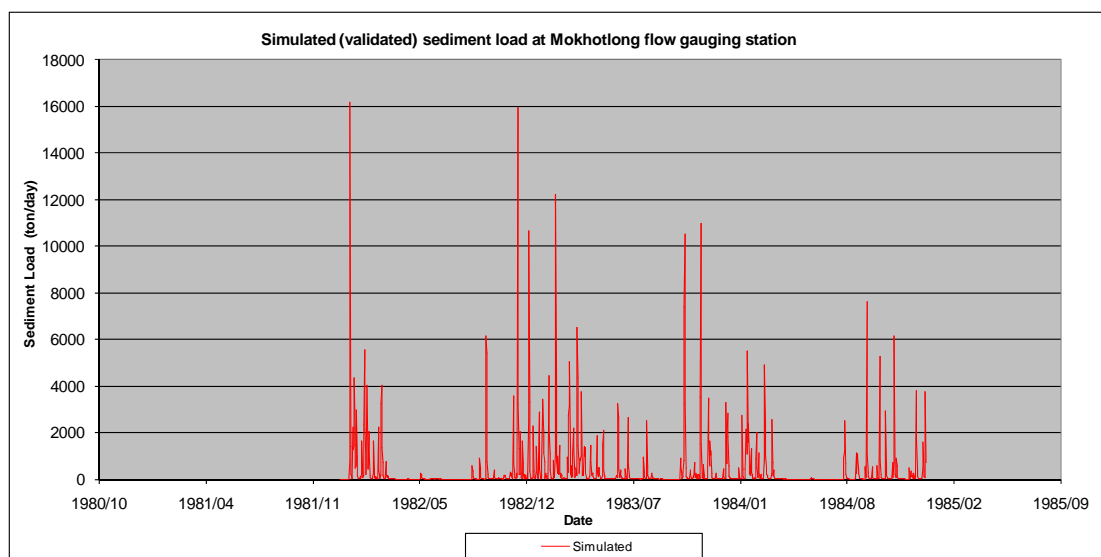


Figure 3.6-2 Sediment yield validation for Mokhotlong flow gauging station

The results of the sediment load validation for the Mokhotlong flow gauging station give an average sediment yield of $38 \text{ t/km}^2\text{.a}$. The relatively lower simulated average sediment yield could be as a result of the dry period during these years which is characterised by low observed flows. The average sediment yield recorded in this catchment at Koma Koma flow gauging station was $45 \text{ t/km}^2\text{.a}$. This agrees well with the simulated sediment yield during the dry period at Mokhotlong flow gauging station. This scenario confirms the capability of the model to compute temporal variations in sediment yield based on the input variables.

3.7 Identification of high sediment yield areas

SHETRAN has the capability to show the sediment yield from each sub-catchment area within the watershed. The SHETRAN model can be instructed to calculate the sediment load at any grid square or link within the catchment. In order to investigate potential sources of sediment, four sub-catchment areas within the Mokhotlong catchment were assessed. The sub-catchments are labelled A to D in Figure 3.7-1.

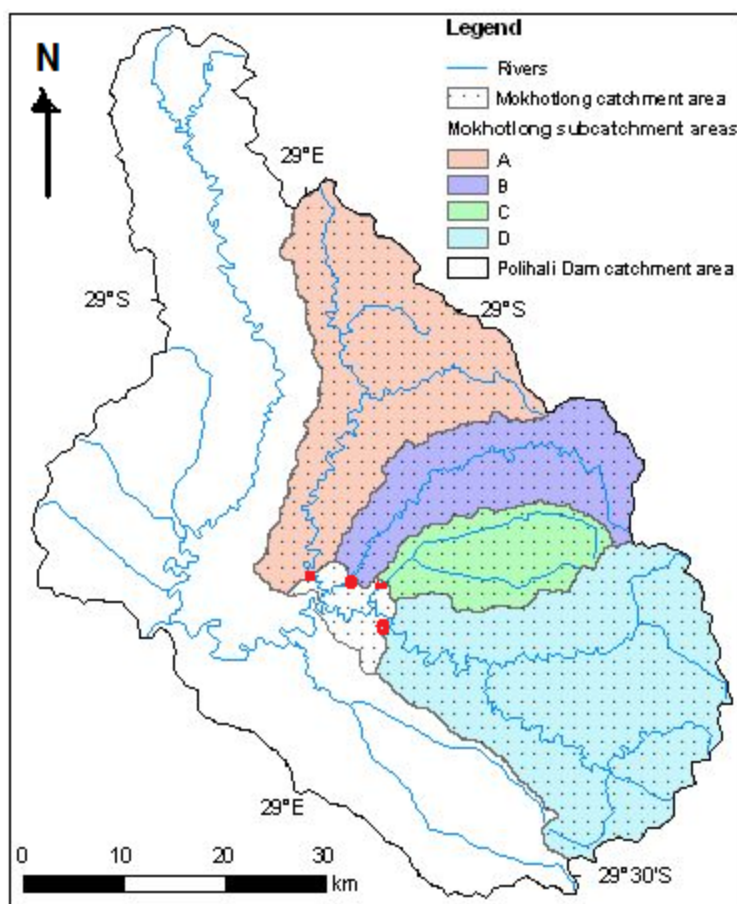


Figure 3.7-1 Sediment yields from sub-catchment areas

Each of the four sub-catchments had a pour point on a river for sediment load simulation from upstream shown by the red dot close to the Mokhotlong catchment pour point. The simulation to identify the sub-catchment that has the highest sediment yield was done for the period starting from 1975 up to 1981 (seven years). The results are summarised in Table 3.7.1.

Table 3.7.1 Results showing simulated sediment yields from each sub-catchment area

Sub-catchment number	Area (km ²)	Cumulative sediment load (ton)	Calculated sediment yield (t/km ² .a)
A	483	94,668	28
B	271	98,644	52
C	168	151,704	129
D	657	271,341	59

Sub-catchment C has the highest sediment yield while sub-catchment A has the lowest sediment yield. Sub-catchment C is in an area that is dominated by degraded unimproved natural grassland in the foothills where sediment yields are expected to be high. Erosion could be comparatively higher in this area due to subsistence farming and cattle rearing. Sub-catchment A comprises of natural grassland, shrubland and low fynbos situated in the higher elevation areas. This could be the reason why the sediment yield is not as high compared to the rest of the sub-catchments. There is negligible agricultural activity taking place in this part of the Mokhotlong catchment.

The average sediment yields of 52 t/km².a and 59 t/km².a in sub-catchments B and D respectively could be because of the presence of diverse types of land covers such as wetlands in the valleys, degraded unimproved natural grassland in the foothills and low fynbos and shrubland in the higher elevation areas of the catchment. The presence of such geological diversity and multiple land uses may result in net average sediment yield values. The detailed land cover for Polihali Dam site catchment is shown in Figure 3.7-2.

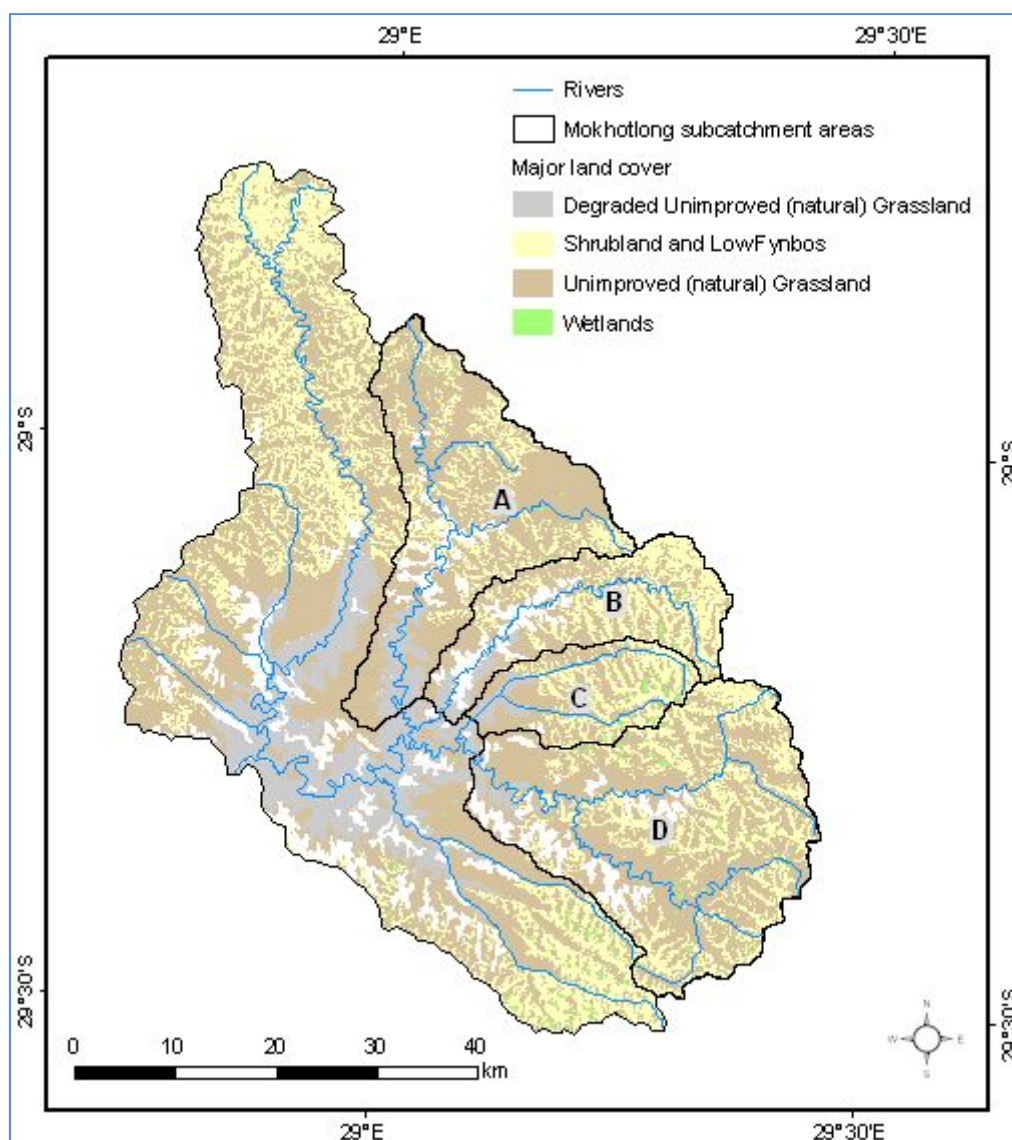


Figure 3.7-2 Land cover for Polihali Dam catchment

These results show the ability of the model to detect and assess spatial and temporal trends in the sediment yields of a catchment area.

3.8 Conclusions on the application of the SHETRAN modelling system

SHETRAN is written in FORTRAN 77. The SHETRAN modelling system has two versions. These are SHETRAN Windows and SHETRAN Standard. The SHETRAN Windows version cannot run sediment and solute transport. Sediment and solute transport can only be run in the SHETRAN standard version (SHETRAN Version 4, 2008). The SHETRAN Standard version does not have a graphical user interface (GUI). The SHETRAN Standard version uses text files to run the model. The model takes more time to set up since data is entered and edited in

text files. The user must be able to prepare and generate a certain amount of data independently before applying it in the modelling system. It took approximately five months to know how to use the modelling system and how to set up and run the model. However, with prior experience in using the model, the time taken to come up with the results can be significantly reduced. Additionally, the time and ease in the use of the model depends on the data requirements and availability, size of the catchment and the nature of the simulations to be done.

3.9 ACRU model set up, validation and simulation

ACRU can operate as a point or as a lumped small catchments model (Schulze, 2005). Data is input for each sub catchment that is configured when setting up the model. The main input parameters for sediment yield prediction purposes include daily rainfall data, evaporation, mean annual precipitation, land use and soil and catchment characteristics. The output from ACRU needs to be verified against observed data. The observed data can be flow and sediment load or sediment yield. Upon verifying the simulated data, the modelling system can be used for decision support in sediment generation and land use impact assessment.

3.10 ACRU Application

According to Schulze (1995) the ACRU modelling system has been applied and verified widely on data from southern Africa (Botswana, Lesotho, Namibia, South Africa and Swaziland) and the USA. Van Zyl and Lorentz (2003) verified the performance of ACRU and WEPP models by comparing the model predictions against measured data on research catchments in South Africa to determine the ability of the models in predicting sediment yield. The goodness of fit around the 1:1 relationship between measured and simulated values was one of the criteria that was used in the analysis. Different scenarios of land management practices and extreme rainfall events were simulated.

The results showed that the daily sediment yield predicted by the ACRU modelling system was in closer agreement with the measured daily suspended sediment yield than the sediment load predicted with the WEPP model. It was also found out that the ACRU model simulated long term sediment yields much more adequately and consistently than the observed daily sediment yield. The ACRU model was successfully used to predict the impact of varying agricultural management practices on sediment yields.

Ma (2006) applied the ACRU modelling system in the prediction of sediment yields in two catchments of limited data availability in Kenya. The model was used to simulate different scenarios of land use to investigate how soil erosion could be reduced.

4.0 PROPOSED SEDIMENT MONITORING IN SOUTH AFRICA

4.1 Background

Extensive river suspended sediment sampling was carried out in SA since the 1920s to about 1970. Since the 1970s suspended sediment samples are still taken, but so infrequently that most of this data cannot be used to determine the sediment yield of a catchment. Most of the dams in SA were constructed in the 1960s and 1970s, and therefore a decision was taken by DWA to rather focus on reservoir surveys to determine reservoir sedimentation and sediment yields. These surveys are carried out typically every 10 to 15 years at most of the DWA reservoirs in the country. Some critical reservoirs are however surveyed more frequently. This data is sufficient to determine a long term average sediment yield for a catchment if say at least 20 years of data is available and relatively large floods have been experienced between the surveys.

There is however a need for more detailed data such as for:

- Calibration of hourly or daily rainfall-runoff-sediment yield prediction mathematical models which predict spatial and temporal trends, and which could be used to design hydraulic structures and to design soil-water conservation programmes in the catchment.
- Sediment load-discharge rating curves to understand the flood and seasonal behaviour of the river in terms of sediment transport capacity and sediment availability. This data could be used for ecological and IFR studies, or to determine sediment yields.

4.2 Reservoir surveys

Reservoir surveys should consider the following:

- Surveys should be carried out following a 1:20 year flood or larger
- Surveys should be carried out to the Non overflow crest level (NOC) and should therefore extend above ground level

-
- The vertical survey accuracy required is 20 mm (A small error gives very large sediment volume differences).
 - The survey should be at fixed cross-sections
 - The control beacons at cross-sections should be surveyed during each survey for possible settlement.
 - The water level in the reservoir should never be used as datum level for the survey
 - If a sonar is used, it should be calibrated daily based on the local sediment and water quality
 - 3D surveys could be carried of a reservoir to create a DTM by using a multi-beam sonar, but the fixed cross-sections locations should always also be surveyed.
 - When a dam is raised (or lowered), it is very important that a survey is carried out when the raising is completed.

4.3 River sediment sampling

There are many very sophisticated methods of sampling available, but for South African conditions it is proposed that a simple, but reliable methodology is used. The USGS (2007) provides a guide to the proper selection and use of federally approved sediment and water quality samplers. During a workshop held in the USA in 2003 (USGS, 2003), on Sediment monitoring equipment and analysis, it was emphasized that conventional sampling methods should still be used, but that there is a need for collection of higher frequency data maybe with new technology such as single frequency acoustics, multi frequency acoustics, laser diffraction, optical sediment flux or digital image analysis. The basic information on each, as well as strengths and limitations are listed in Table 4.3.1. Fouling, accuracy and capital cost are the major constraints for implementation in SA of these instruments. The instruments are expensive and could easily be stolen based on experience on the Berg River baseline study of DWA, 2003 to 2005.

Pumping of samples from the river is not recommended as a methodology due to the intake velocity, pipeline sedimentation and flushing, and distance and height requirements on the floodplain during a flood.

Most of the sediment in South African rivers is relatively fine and is transported as washload (silt and clay). The fine sediment concentrations with depth and across the river are usually

very uniform. This means that a grab sample taken near the surface of the river and near a river bank could be representative of the cross-section suspended sediment concentration.

It is therefore proposed that daily suspended sediment grab samples are taken at flow gauging stations where flow is measured. This is the methodology followed from 1920 to 1970s in SA, and also in Botswana and Lesotho. The following methodology is proposed:

- 0.5 l plastic “milk” bottles should be used with large openings.
- The date and time of sample should be provided on a label on the bottle.
- The bottle should be fixed in a stainless steel holder with string attached and lowered in the turbulent fully mixed zone downstream of the low notch of the gauging weir to about 0.3 m into the water.
- When the bottle is half full to full it could be removed from the water, capped and stored.
- The sampling procedure and location should be consistent at a specific site.
- Sampling frequency is proposed daily.
- Sampling could be carried out by local people living near the site.
- In thunderstorm generating storm catchments, sampling should be carried out in the afternoon.
- Sampling should be seen as a way to generate work for local people. Depending on travel time and distance, a payment of R30/sample is proposed.
- Standard methods should be used to determine the sediment concentration in a laboratory
- Bed sediment samples should be collected once a year and grading analysis: sieve and hydrometer tests should be carried out to determine the sediment grading.
- In all samples when the suspended sediment collected is sufficient for grading analysis, this should be carried out. The pipette method is more suitable for fine sediment than the hydrometer test, and requires less sediment, only about 20g dry sediment is required. The laboratory should however use either the hydrometer or pipette methods, and not switch between the two methods. Samples from a single storm event could also be put together to determine the suspended sediment grading.

- River sediment concentration sampling should be continued for a minimum continuous period of 5 years. Following this period sampling could only be carried out during the flood season and during floods.

Once a year during a flood at a specific station the reliability of the grab sample procedure should be validated by DWA by sampling the suspended sediment using a depth integration method with different nozzles depending on the flow velocity (Figure 4.3-1), and for the bed load a BL-84 sampler (USGS, 2005) (Figure 4.3-2). This could be done by wading, from a boat or by cableway. Standard sampling techniques should be followed. Sediment samples of the river bed should also be taken by using bottom grab samplers (Figure 4.3-3).

ADCP measurement should be done with the suspended sediment sampling to determine the sediment load across the river (Figures 4.3-4 and 4.3-5).

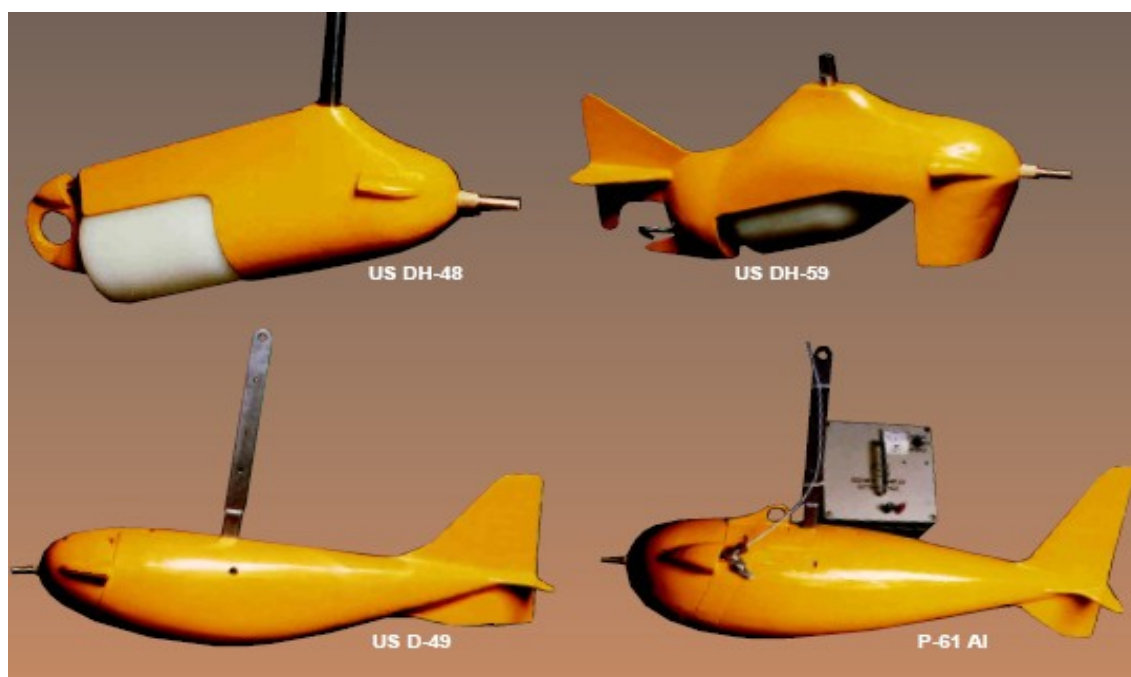


Figure 4.3-1 Typical depth integration suspended sediment samplers



Figure 4.3-2 Typical bed load sampler (BL-84) and testing of the bed load sampler on the Berg River



Figure 4.3-3 Ekman (left) and Van Veen (right) bottom sediment grab samplers



Figure 4.3-4 ADCP for discharge measurement

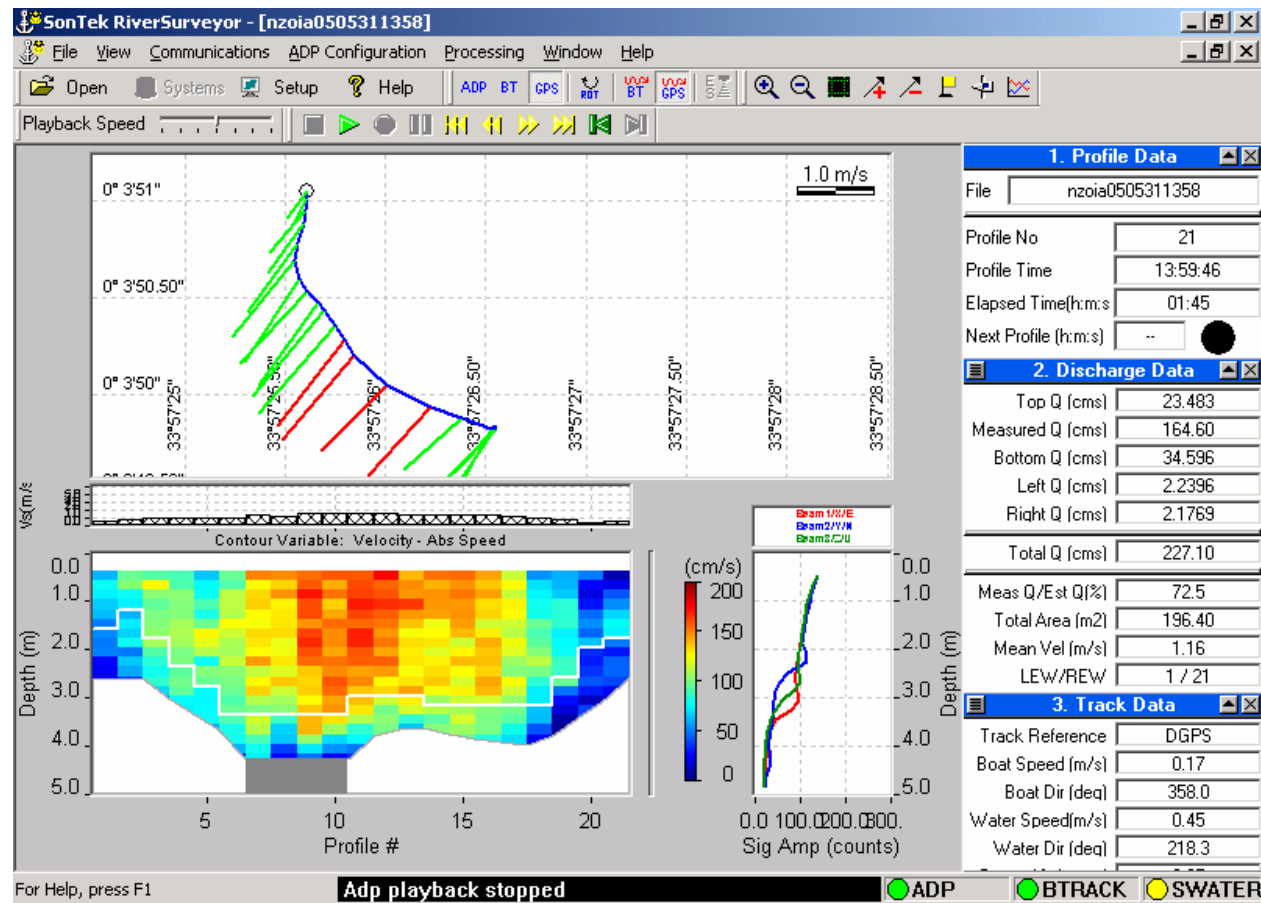


Figure 4.3-5 ADCP output showing velocity vectors and velocity distribution with depth

Table 4.3.1 New technology for suspended sediment concentration measurement (USGS, 2003)

Information	3a: Single-frequency acoustics	Table 3b: Multi-frequency acoustics	Table 3c: Laser diffraction	Table 3d: Optical-sediment flux	Table 3e: Digital-image analysis
Measurement type:	Particle backscatter	Particle backscatter	Multi-angle scattering of diffracted light	Modulated light	Digital photographic analysis
Measurement use:	SSC (volumetric)	SSC (volumetric), grain size	SSC (volumetric) and grain size	Particle sizing/counting velocimeter	Volumetric SSC and size
Instrument(s):	Acoustic Doppler current profiler (ADCP)	Aquascat (\$30K)	LISST series (\$5K-\$30K)	In development	In development
Manufacturer(s):	Nortek AS (2004), RD Instruments USA (2004), Sontek/YSI, Inc. (2004), Aanderaa (2004)	Aquatec (2004)	Sequoia Scientific, Inc. (2004)	No units commercially available	Not yet available off the shelf
Measurement location:	Vertical/horizontal profile	Vertical or horizontal profile	Point measurement	Point (limited profiling capability)	Point/depth integrated; also laboratory
Status, Progress, trends:	Commercially available, primarily used for flow velocity	Hardware proven and available; software/algorithms under active development	Mature technology	Under development, proof of concept performed	Prototype planned for 2004, proof of concept completed in lab
Range of size, concentration, flow depth:	Insufficient information available	Hardware specific	1.25-1,500 μ for three models	30 μ and larger; unknown concentration limit—probably better for dilute solutions	2-4,000 μ , 0-10,000 mg/L
Sensor(s):	Piezoelectric transducer	Piezoelectric transducer	Silicon photo-diode; similar in principle to Beckman-Coulter and other such laboratory instruments	Laser diode	CCD, custom lenses
Sources of information:	Manufacturer's literature; Gartner and Cheng (2001); David Topping, USGS, 2003, oral commun.; Nancy Powell, U.S. Army Corps of Engineers, New Orleans District, 2003, oral commun., James Chambers, National Center for Physical Acoustics, Univ. of Mississippi, 2003, oral commun.	Smith, (2004), Thorne and Hanes (2002), Thorne and Taylor (2000), Crawford and Hayes (1993), Thorne and others (1991)	Agrawal and Pottsmith (2001), Gartner and others (2001)	Jan Northby, University of Rhode Island, oral commun., 2003	Dan Gooding, USGS, oral commun., 2003
Strengths:	Deployed in many locations, profile measurements, non-intrusive	Profiling, non-intrusive, no biofouling, good spatial/temporal resolution	Particle-size and SSC	Simultaneous velocity/concentration measurement, non-intrusive, potential for measuring fluorescent effects; low cost	Discrete information on particles including aggregates, measurements of organics, visual confirmation using archived images; air bubbles not a problem
Limitations:	Dual dependency on concentration and particle sizes; assumption of mean particle density for mass computations; air-bubble interference; upper concentration	Difficult inversion of data to concentration, including particle-density assumptions; no commercial software currently available to make this	Requires dilution >3,000 mg/L (particle-size dependent), may bio-foul, air bubbles	Concentration limited	Fouling

	limits unknown	conversion, sensitive to air bubbles; upper concentration limits unknown			
Accuracy:	Insufficient information available	±30 percent concentration--needs further testing in various environments; particle-size accuracy unknown	±20 percent	Undetermined—velocity on the order of a few percent	±10 percent in lab, as yet unknown in field
Recommendations/goals:	Further, careful testing against isokinetic samplers, may be valuable if used in conjunction with additional instrument; theoretically based limits for size/concentration measurement should be established	Continued development and careful comparison with established techniques, especially field deployment in fluvial systems	Complete LISST-SL isokinetic profiler development for riverine applications; test in controlled laboratory conditions	Continued development; use in sediment resuspension studies	Prototype in 2004
Calibration requirements:	Calibrations are essential	Calibrations are essential	Not needed according to manufacturer, but recommended	Calibrations presumably will be necessary	Recommended

4.4. River sediment concentration sampling network

Ideally suspended sediment grab samples should be taken daily at the following stations:

- All river flow gauging stations, except the dam outflow gauges and dam spillway (R) stations.
- The stations include gauges in the upper catchments above dams, and in the lower reaches downstream of dams.
- Lesotho where phase II of the Lesotho Highlands Water Project is to commence soon (Region 10), should also be sampled and this should be negotiated with the Lesotho Highlands Water Commission (LHWC) at the followings sites: Khubelu at Tlokoeng, Senqu at Mokhotlong, Senqu at Koma-Koma, Senqu at White Hills, Malibamatso at Paray, Senqunyane upstream of the Senqu River confluence.

Depending on the cost of sampling and finance available, it is proposed that DWA design a river sampling network for sediment.

5.0 CONCLUSIONS

If reservoir sedimentation in South Africa is to continue at the rate it is happening, it is likely that serious problems on water yield will be encountered in the near future. This scenario provides a grim picture on the long-term sustainability of the existing reservoirs unless appropriate sediment control measures are put in place. One of these measures includes accurate prediction of sediment yields in existing and future reservoirs. This information is essential in the feasibility studies, planning and management of water resources with respect to sedimentation control and management.

The current sediment yield prediction methods have been revised. Ten relatively homogeneous sediment yield regions were demarcated across South Africa. Three sediment yield prediction methods have been presented. These approaches include probabilistic, empirical and mathematical modelling. The probabilistic method has been developed using statistical analysis of regional data on observed sediment yields and soil erosion hazard classes based on Rooseboom et al. (1992). The observed sediment yields were calculated from reservoir sediment deposition data and river sediment sampling. The empirical method has been developed from regression analysis of variables that control sediment yield with respect to the South African conditions namely floods, soil erosion hazard, river network density, catchment area and river slope. Two physically based numerical models have been reviewed and applied. These models are SHETRAN (Ewen et al., 2000) and ACRU (Smithers et al., 2002). The models have been reviewed in detail including the identification of a case study for the evaluation of the aspects of model set up, calibration, validation and simulation.

These models cannot be used without calibration and validation against flow and observed sediment loads. The validity of the modelling systems for site specific conditions can be judged by the results of the validation exercise.

The empirical and probabilistic methods of sediment yield prediction are important for decision-making in the feasibility studies and planning of water resources. In the detailed design of water resources, the use of numerical models, specifically physically based

distributed models, is proving to be very significant particularly in the prediction of spatial and temporal variability of erosion and sediment yield within the catchment.

5.1 Criteria for the choice of a sediment yield prediction method

The empirical method is relatively more reliable based on the predictive accuracy check tests that have been done. The probabilistic method appears to be overestimating low value sediment yields as observed from the graphical plots of observed sediment yields against calculated sediment yield values especially for sediment yields below 100 t/km².a. It has therefore been proposed that sediment yield prediction for regions 1, 2, 4, 5, 7 and 8 should be done using the derived empirical equations in Table 5.7.2. Regions 3, 6 and 9 should make use of the probabilistic method. Region 10 should use locally observed data. The derived empirical equations and probabilistic approach can be applied in predicting sediment yields in rivers, lakes, reservoirs and estuaries. Detailed analysis of the temporal and spatial variability in sediment yield within the catchment can be done using physically based distributed models such as SHETRAN and ACRU.

Smaller catchments in all the regions should be treated with care as the sediment yield potential is highly unpredictable. It is recommended that for catchments that are less than 100 km², direct measurements of the sediment yield should be conducted.

5.2 Numerical model constraints and strengths

A review of the application of SHETRAN and ACRU as erosion and sediment yield models has showed that the models can be successfully used to simulate sediment yield in a catchment. Calibration of the sediment load was done at one flow gauging station on Mokhotlong flow gauging station which gave satisfactory results considering the limited data that was used. Upon calibrating and validating, the models were successfully used to predict significant sources of sediment. This helped in the identification of catchment areas with high or low sediment yields.

One of the constraints in the application of numerical models is the availability of sediment load and flow data to be used for sediment and flow calibration and/or validation respectively. It is therefore imperative that systematic measurements of sediment loads and flows should continue to be undertaken in important and strategic rivers for future use in numerical modelling. Sediment monitoring proposals are given in Chapter 4. SHETRAN uses hourly rainfall data and hourly time steps which could be a problem in South Africa especially in large catchments where only daily data is available. The model can however run with average daily rainfall that has been disaggregated into hourly rainfall although the results are not always very good. Data on sediment loads and flows would provide a wealth of information for flow and sediment yield calibration and validation and in turn boost the successful application of numerical sediment yield prediction models.

There is need for continuous suspended sediment sampling in rivers and streams to provide data for sediment monitoring. Reservoir surveys should be conducted at optimum intervals and relevant periods such as after a 1:20 year flood or larger and after the completion of dam lowering or raising.

6.0 RECOMMENDATIONS

There is need for more future research in the prediction of sediment yields in ungauged catchments. It has been observed that sediment storage could have a significant impact on the sediment yields observed in some South African catchments. Though quantification of sediment storage is generally problematic especially for large catchments according to Slaymaker and Spencer (1998), future research on the role of storage on the observed sediment yields in South Africa should provide an insight into the problem of lack of better correlation between the gross erosion as computed using the Revised Soil Loss Equation and the observed sediment yields. Such research would also determine whether possible depleting sediment storage capacity in some catchments would trigger future increases in sediment yields than currently predicted.

Future research on predicting sediment yields should also be directed towards investigating the climate change impacts on sediment loads and sediment yields. From the findings it has been observed that the sediment yields are correlated to the 1:10 year flood. In the event of increases in floods due to climate change in future, there is need for research to determine the future challenges in water resources management with respect to sediment control and management. Potential regions that would have their sediment loads increased by floods could be identified and the relevant mitigating measures could be undertaken.

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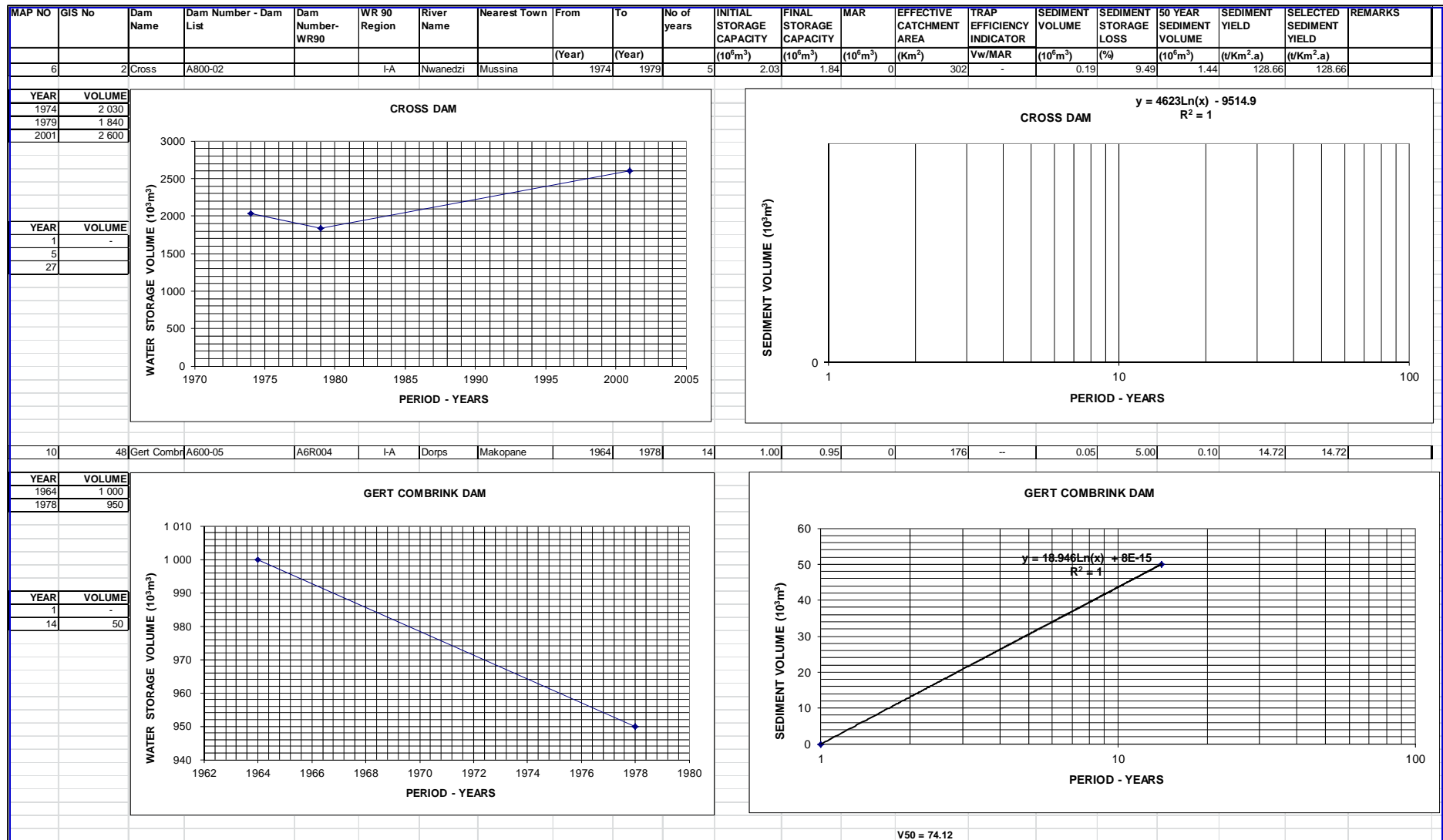
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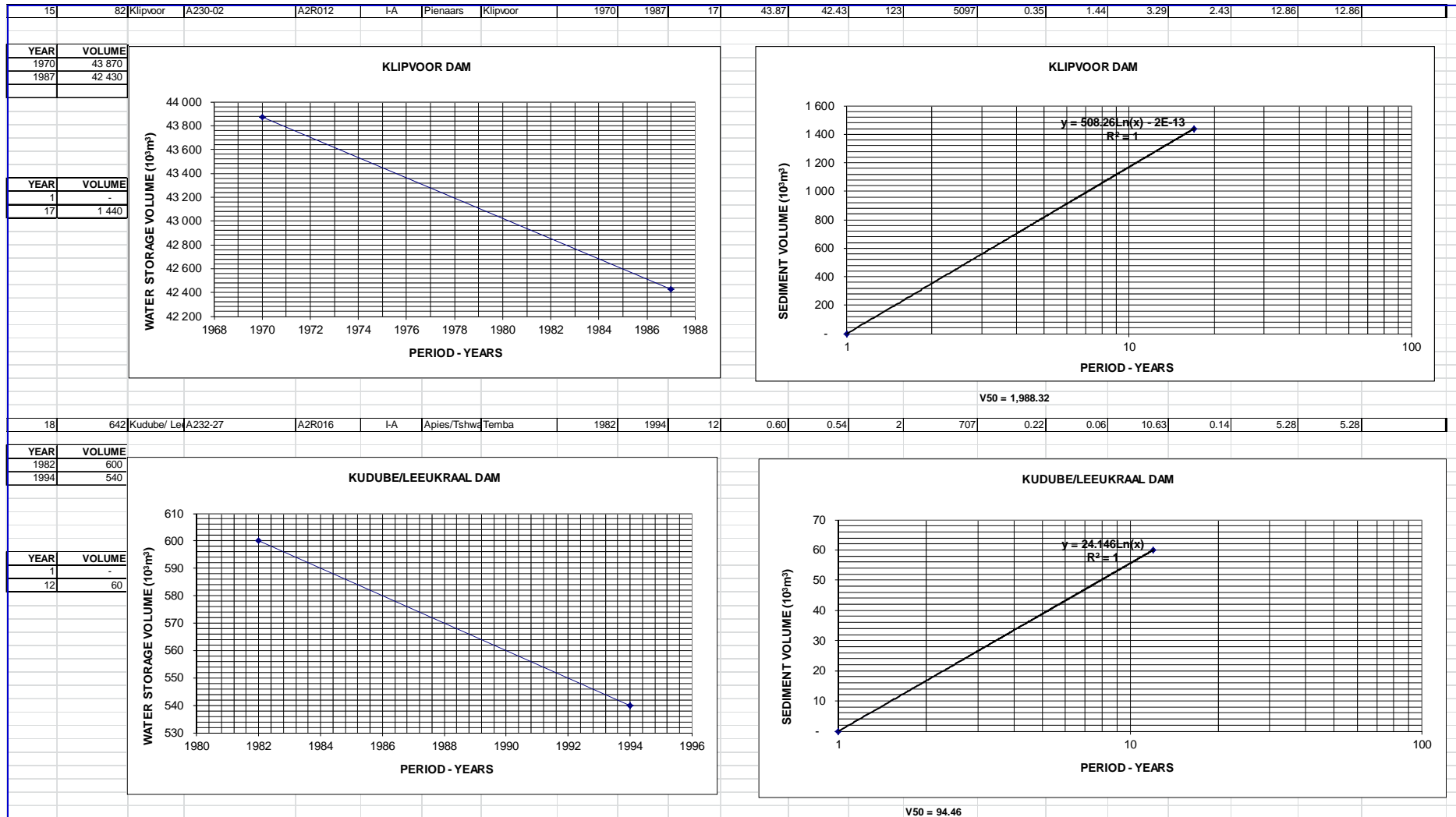
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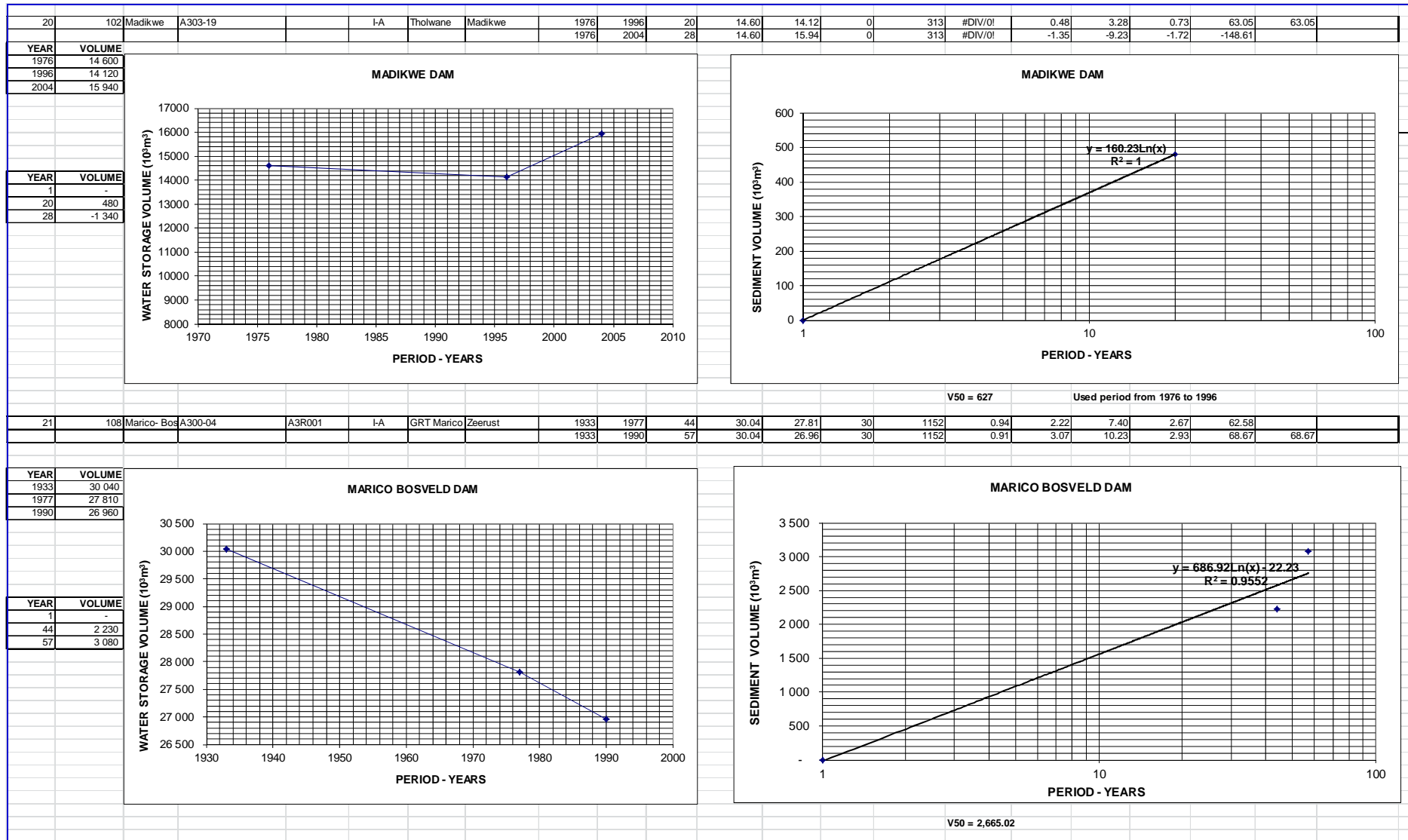
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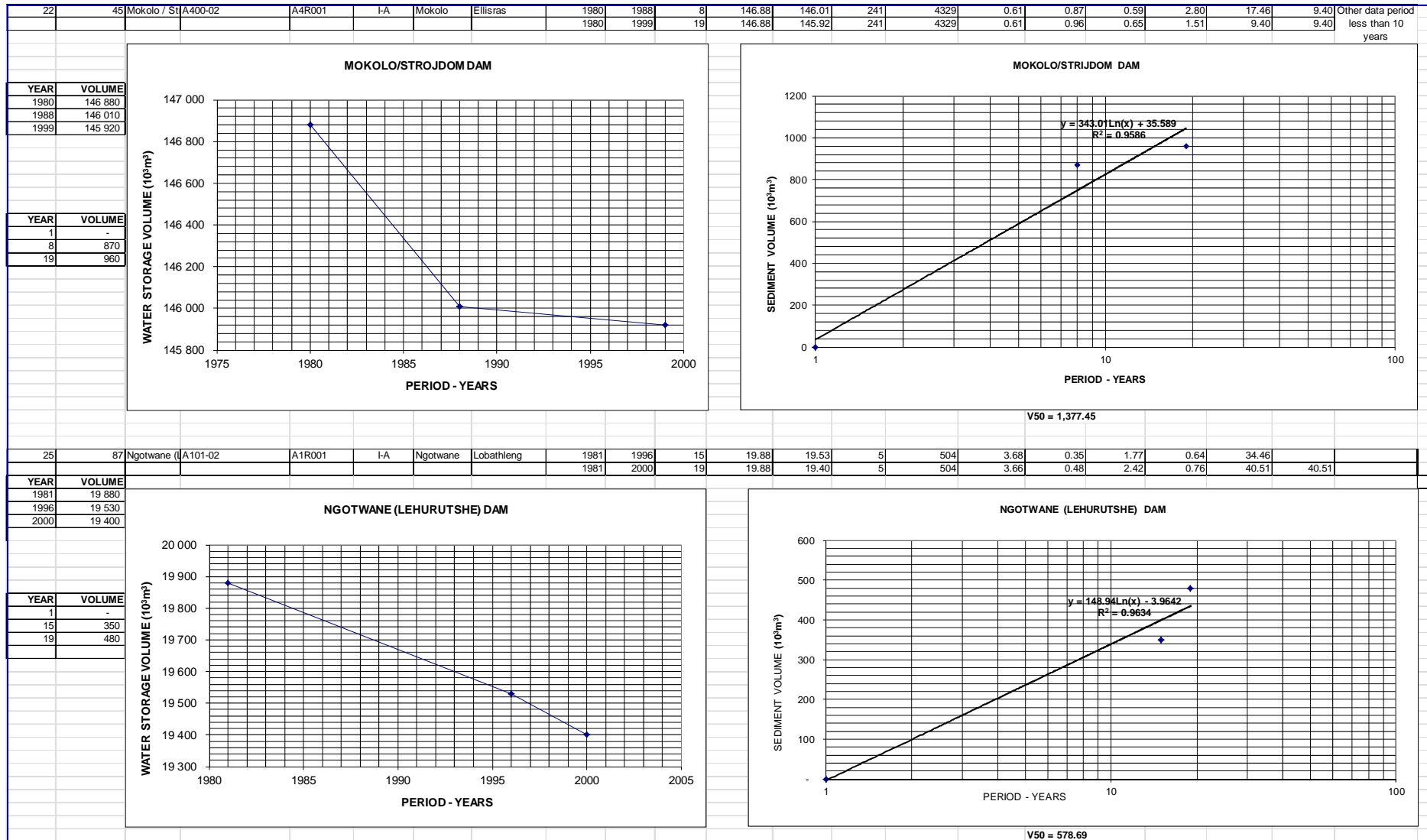
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APPENDIX A GRAPHS OF SEDIMENT VOLUME AGAINST TIME





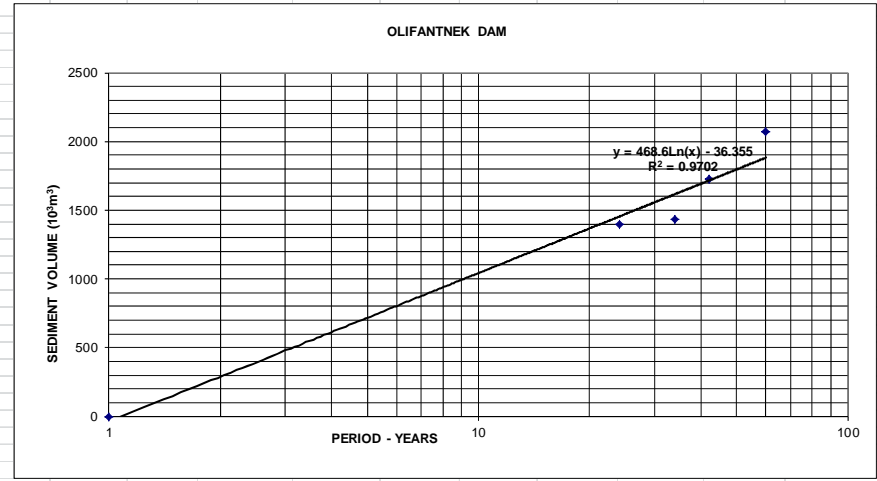
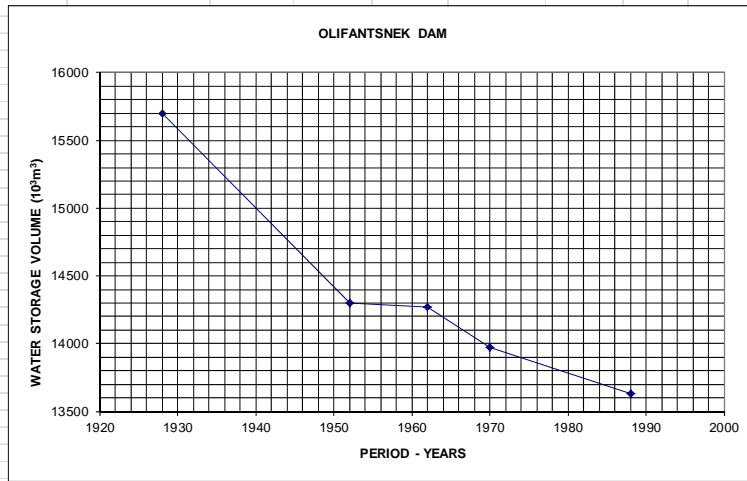




30	125	Olifantsnek	A220-02	A2R003	I-A	Hex	Rustenburg	1928	1952	24	15.70	14.30	12	499	1.22	1.40	8.92	1.80	97.39		
								1928	1962	34	15.70	14.27	12	499	1.22	1.43	9.11	1.80	97.39		
								1928	1970	42	15.70	13.97	12	499	1.19	1.73	11.04	1.80	97.39		
								1928	1988	60	15.70	13.63	12	499	1.16	2.08	13.22	1.80	97.39	97.39	

YEAR	VOLUME
1928	15 700
1952	14 300
1962	14 270
1970	13 970
1988	13 630

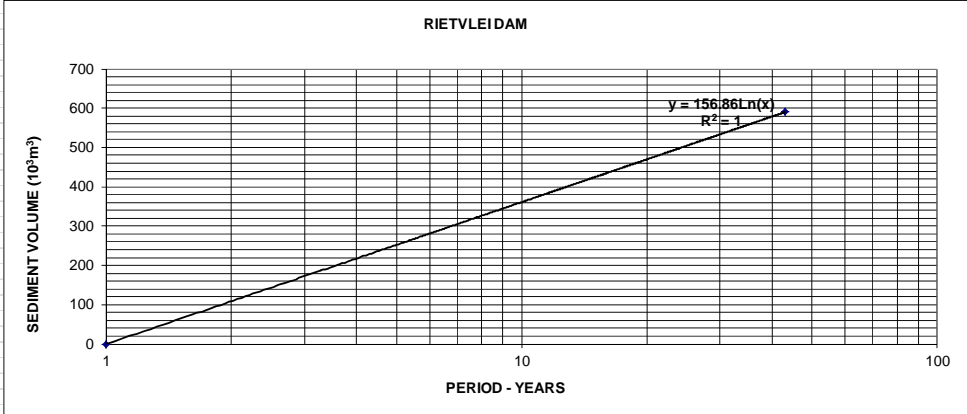
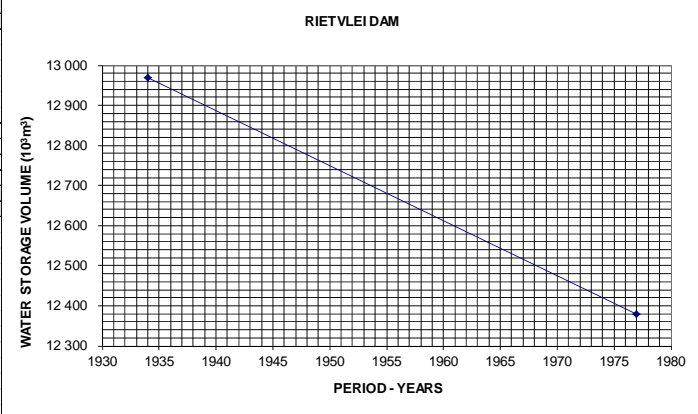
1	-
24	1 400
34	1 430
42	1 730
60	2 070



V50 = 1,796.82

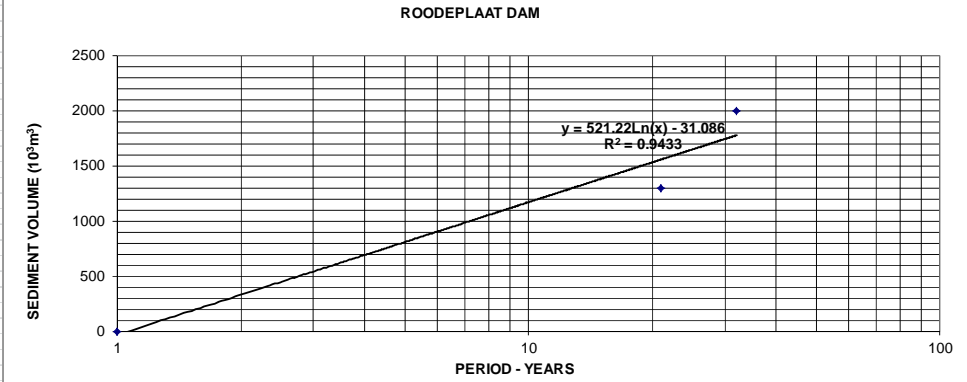
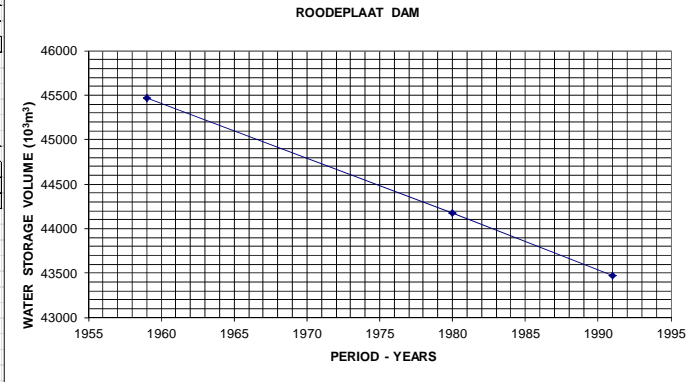
MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number - WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (Km ²)	TRAP EFFICIENCY INDICATOR (Vw/MAR)	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)	REMARKS
32	137	Rietvlei	A210-05	A2R004	I-A	Hennops	Pretoria	1934	1977	43	12.97	12.38	29	489	0.43	0.60	4.60	0.63	34.95	34.95	

YEAR	VOLUME
1934	12 970
1977	12 380

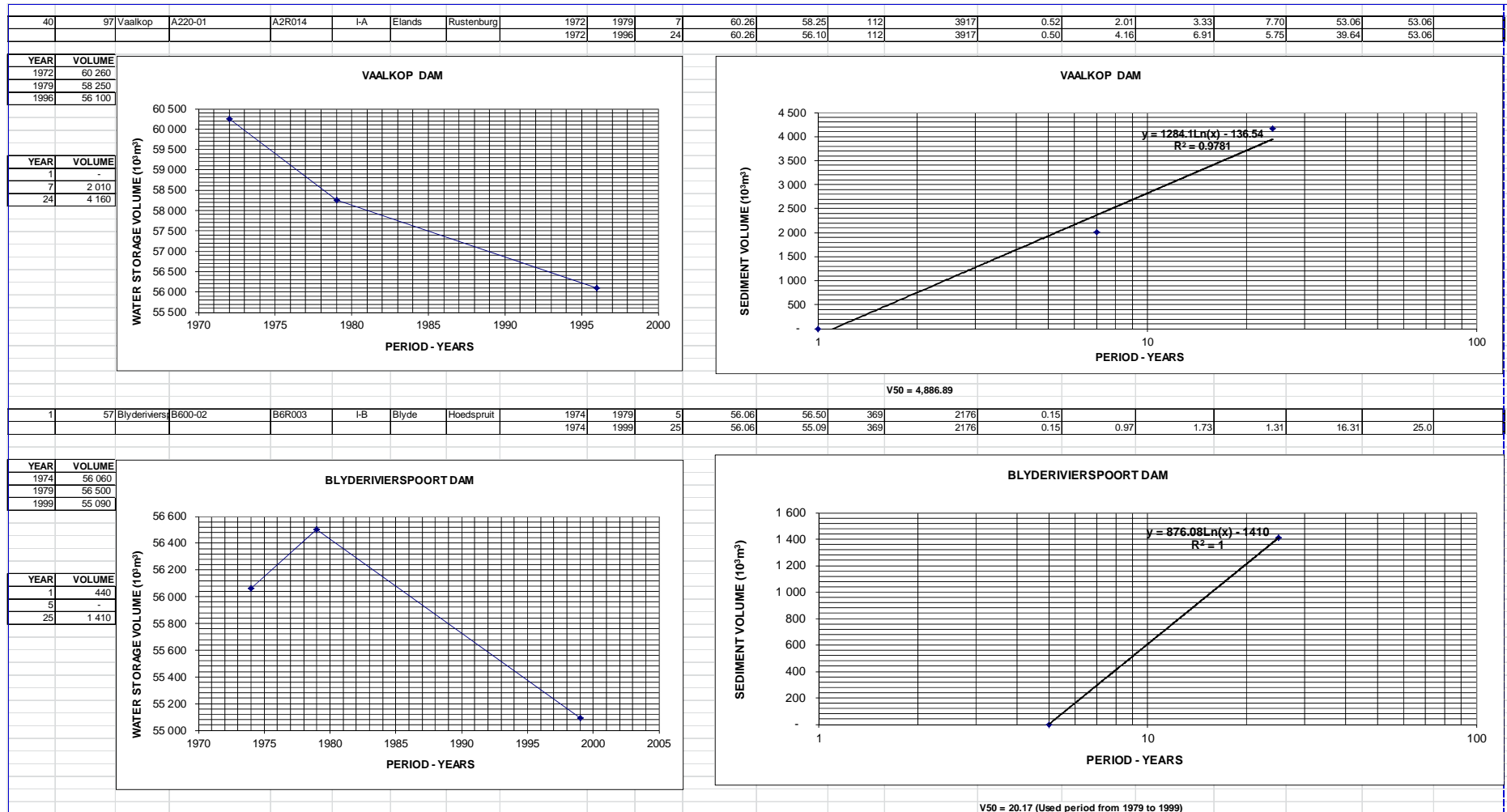


33	113	Roodeplaat	A230-01	A2R009	I-A	Pienaars	Pretoria	1959	1980	21	45.47	44.17	29	684	1.53	1.30	2.86	1.93	76.17	94.93	
								1959	1991	32	45.47	43.47	29	684	1.51	2.00	4.40	2.40	94.93	94.93	

YEAR	VOLUME
1959	45 470
1980	44 170
1991	43 470



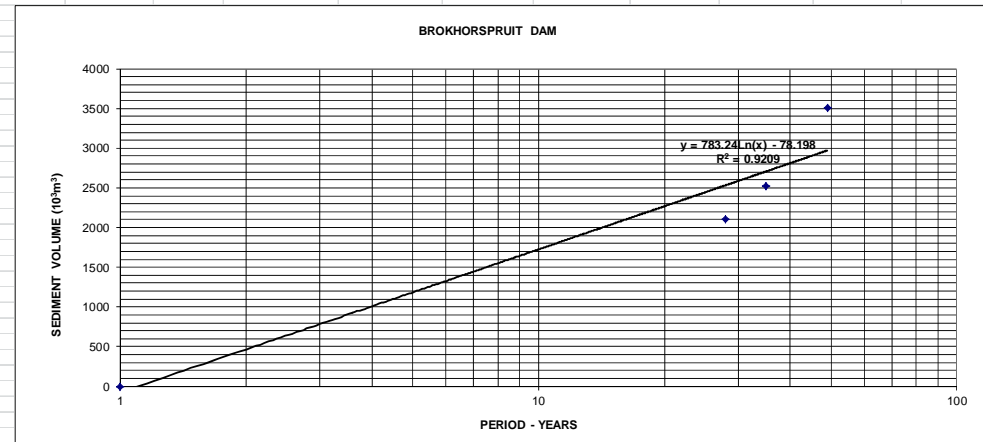
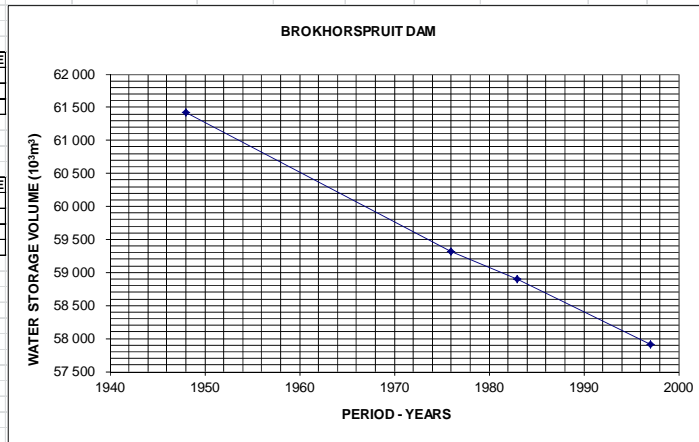
V50 = 2,007.94



2	138	Bronkhorst	B200-01	B2R001	I-B	Bronkhorst	Bronkhorst	1948	1976	28	61.42	59.32	47	1244	1.25	2.10	3.42	2.69	58.29	77.00
								1948	1983	35	61.42	58.90	47	1244	1.24	2.51	4.10	2.90	63.05	77.00
								1948	1997	49	61.42	57.91	47	1244	1.22	3.50	5.70	3.53	76.62	77.00

YEAR	VOLUME
1948	61 420
1976	59 320
1983	58 900
1997	57 910

YEAR	VOLUME
1	-
28	2 100
35	2 520
49	3 510

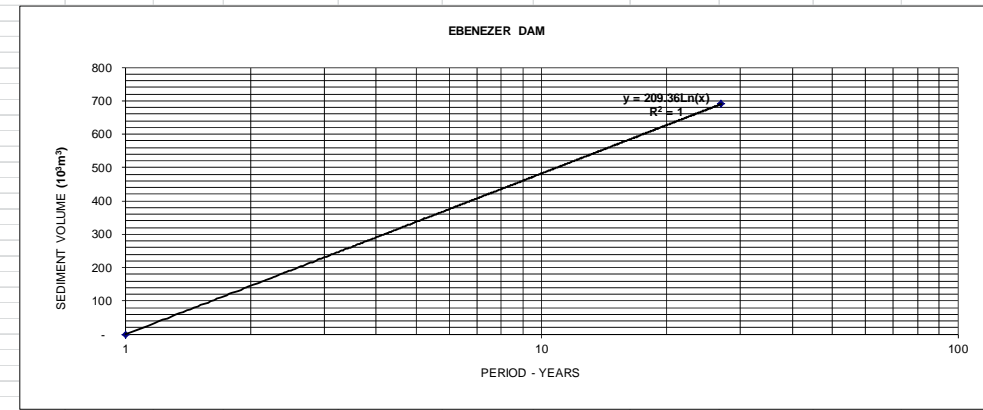
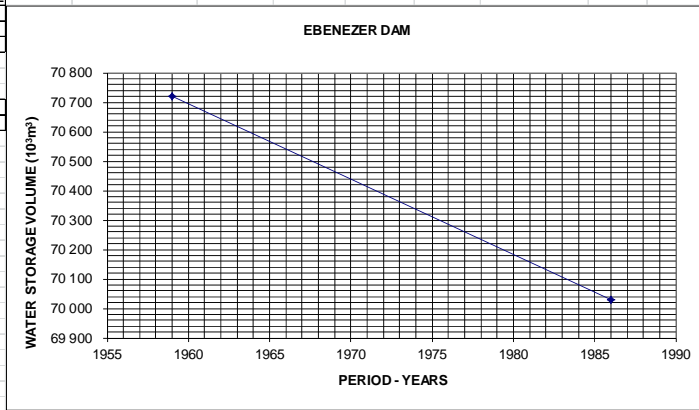


V50 = 2,985.85

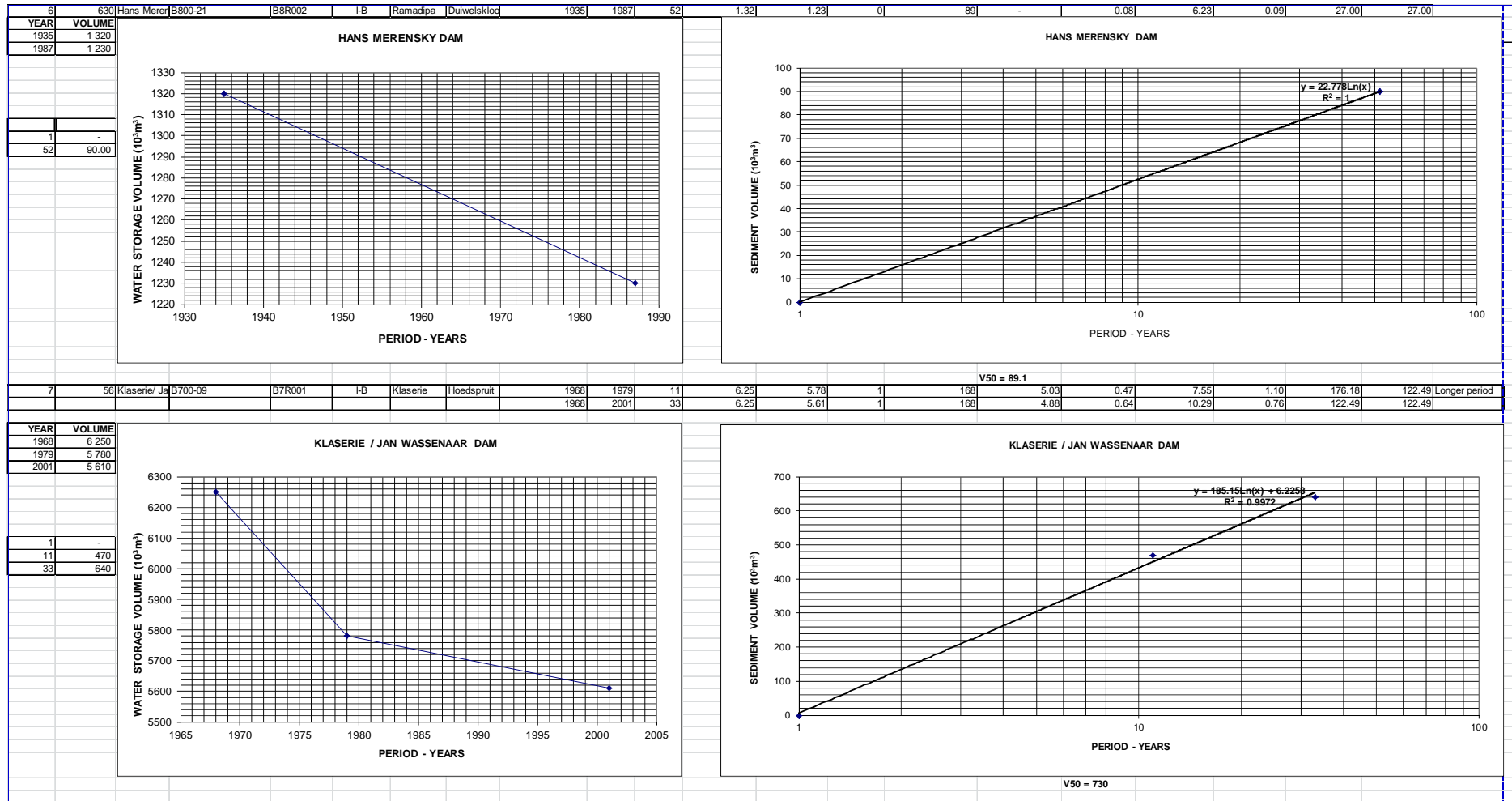
4	42	Ebenezer	B800-02	B8R001	I-B	Gr. Letaba	Umzinto	1959	1986	27	70.72	70.03	64	155	1.10	0.69	0.98	0.90	156.46	156.46
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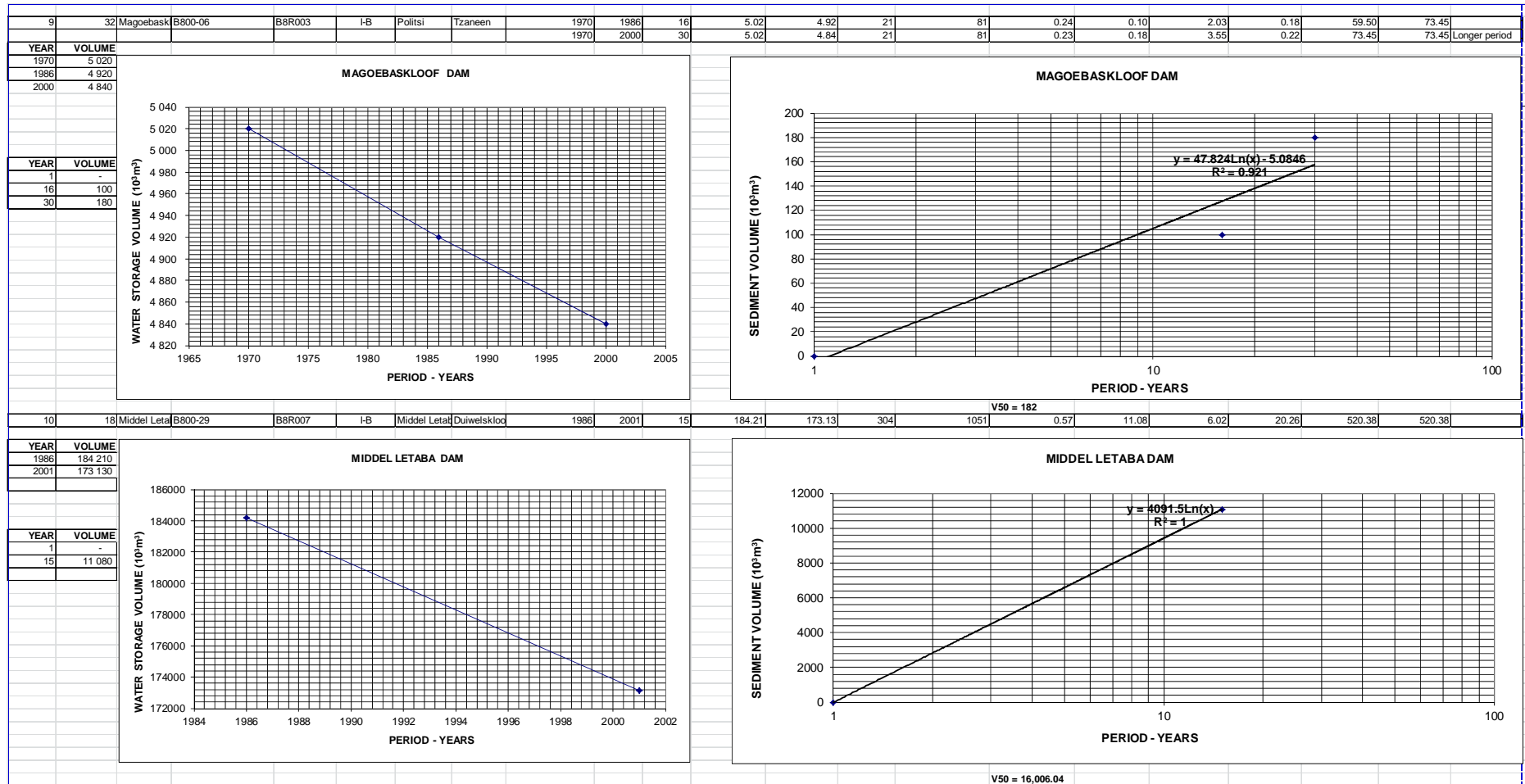
YEAR	VOLUME
1959	70 720
1986	70 030

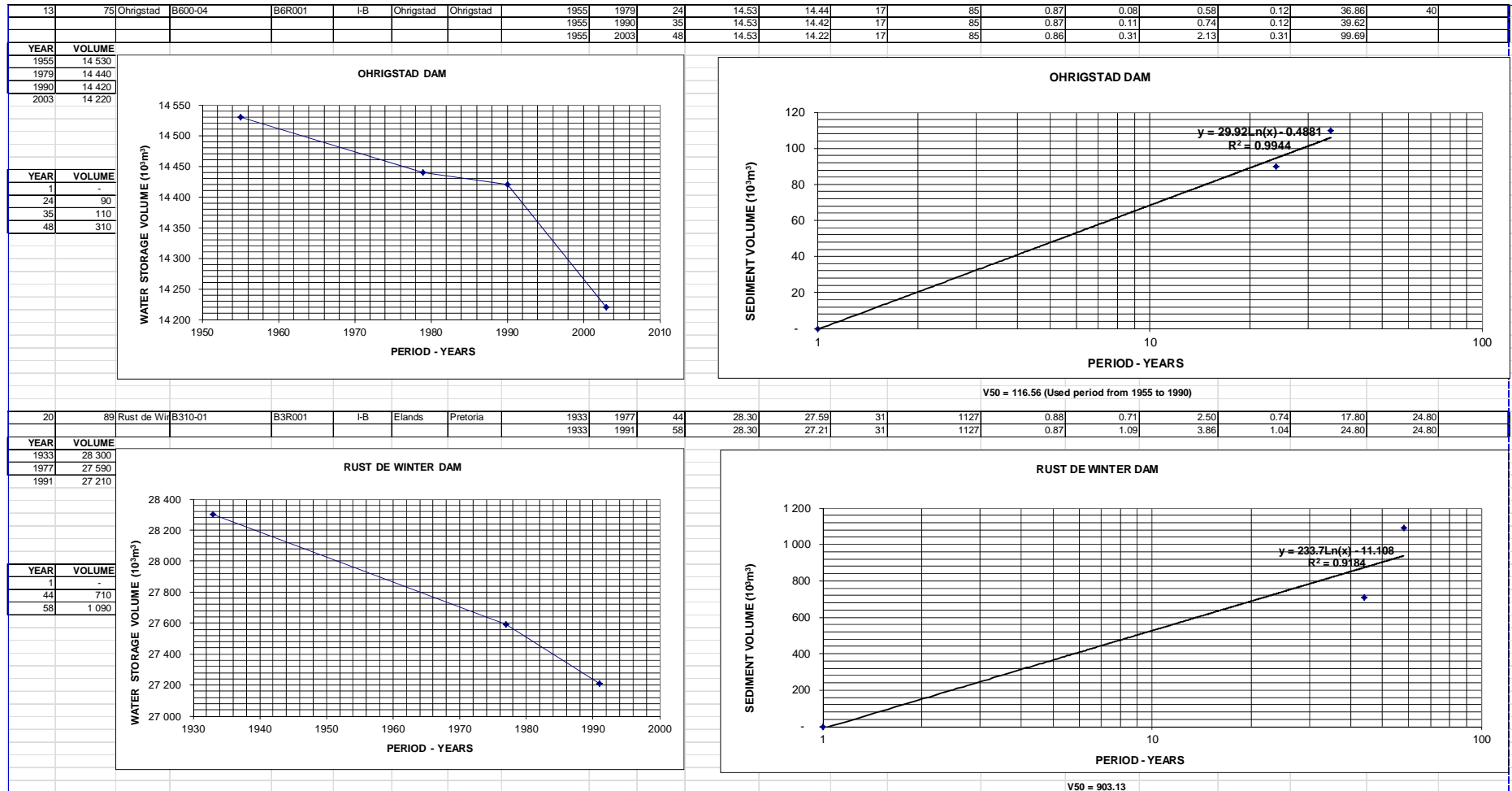
YEAR	VOLUME
1	-
27	690

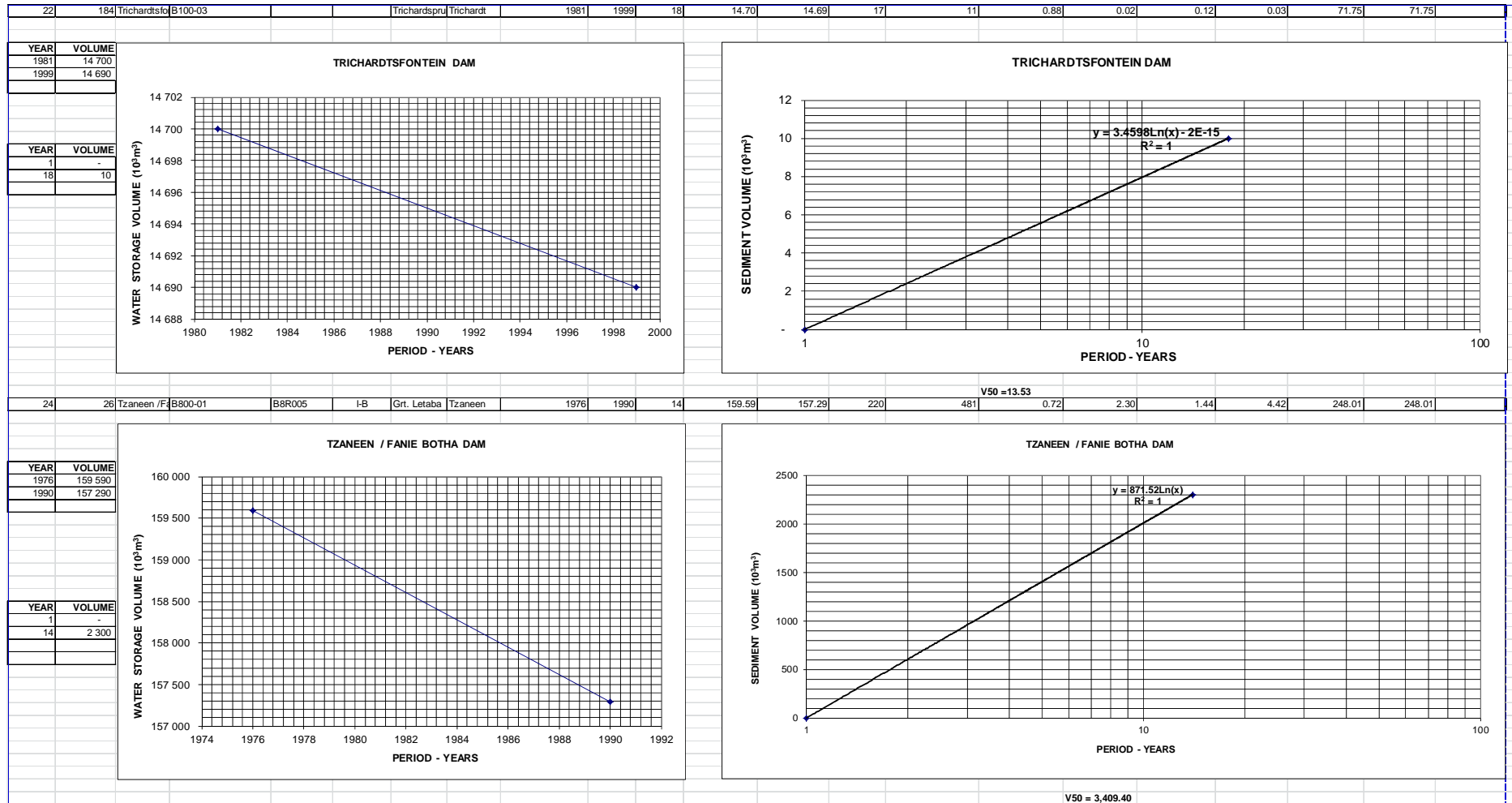


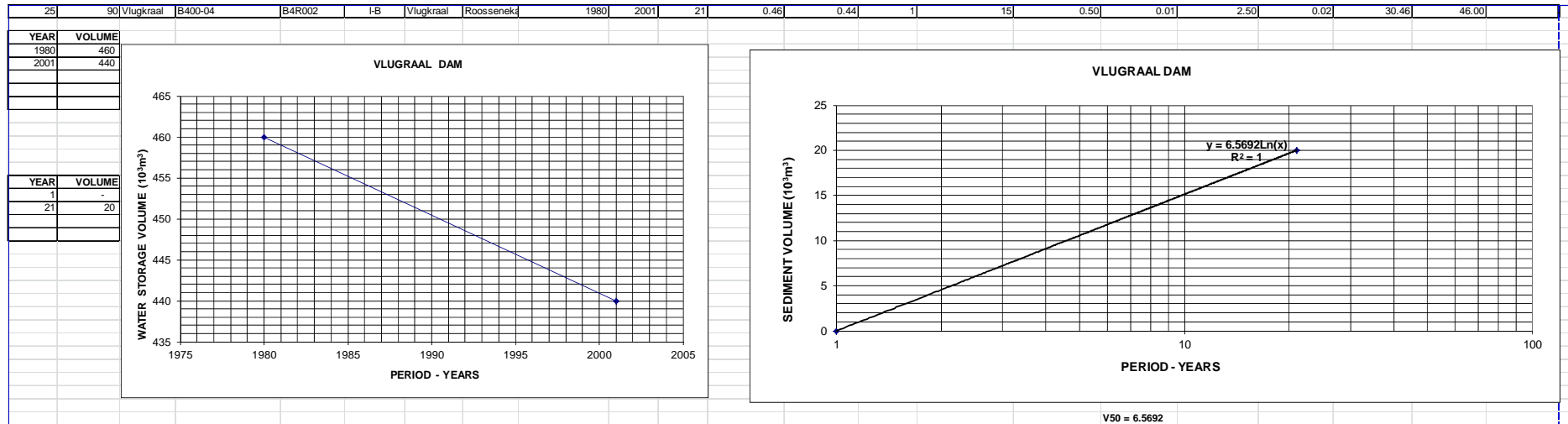
V50 = 819.02





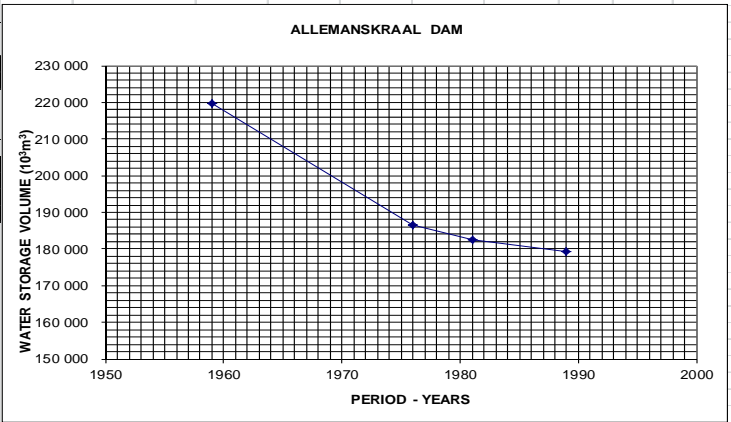




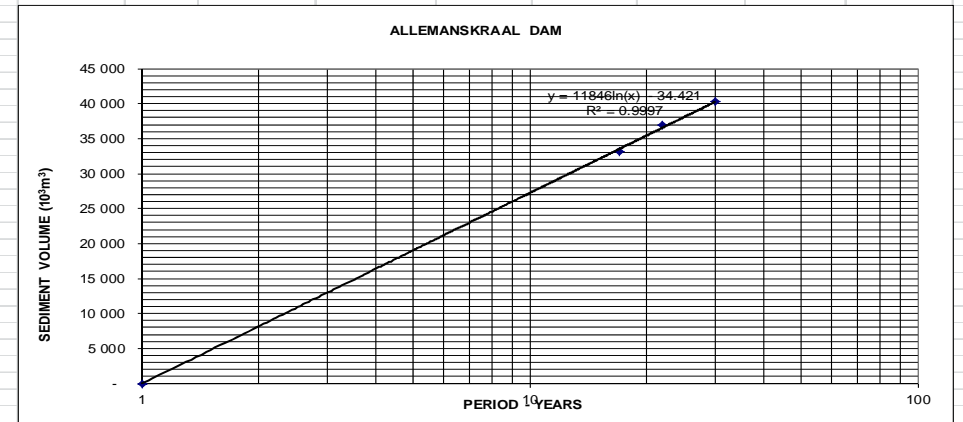


MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number- WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (Km ²)	TRAP EFFICIENCY INDICATOR (Vw/MAR)	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)
2	247	Allemandsk	C400-02	C4R001	III-C	Sand	Ventersbu	1959	1976	17	219.57	186.45	120	2405	1.55	33.12	15.08	55.73	625.69	
								1959	1981	22	219.57	182.62	120	2405	1.52	36.95	16.83	53.46	600.14	
								1959	1989	30	219.57	179.31	120	2405	1.49	40.26	18.33	49.83	559.46	411.0

YEAR	VOLUME
1959	219 570
1976	186 450
1981	182 620
1989	179 310



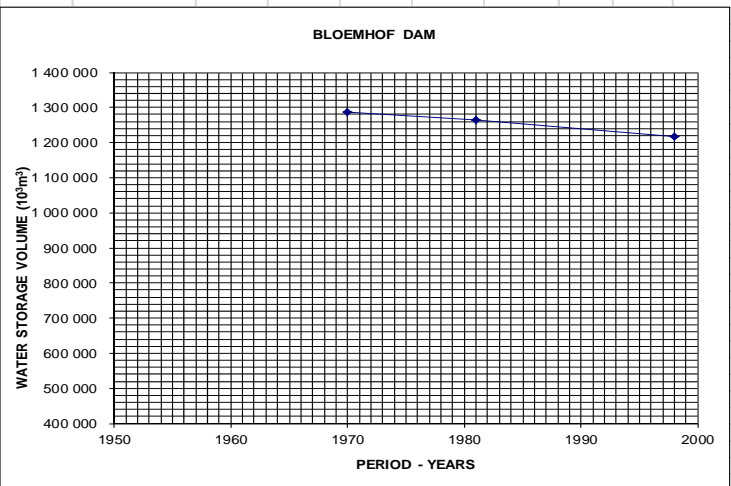
YEAR	VOLUME
1	-
17	33 120
22	36 950
30	40 260



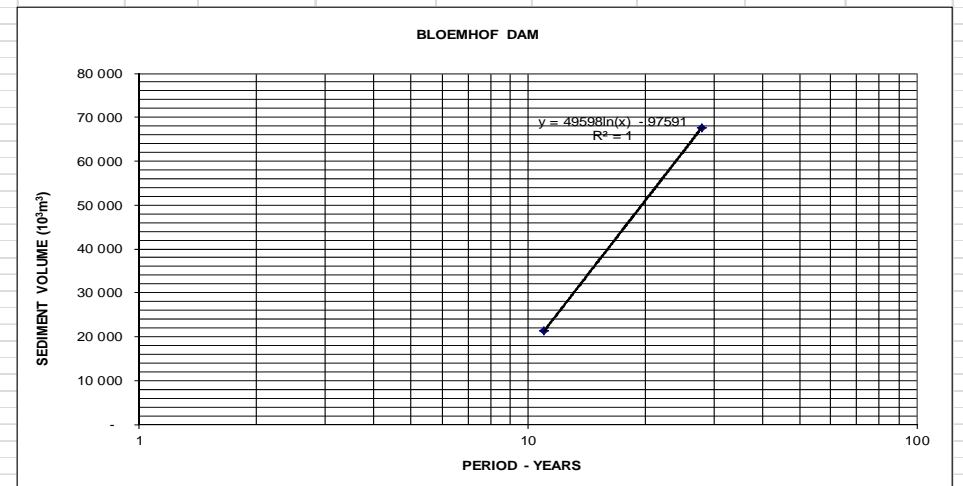
V50 = 46,307.40

5	219	Bloemhof	C900-07	C9R002	III-C	Vaal	Bloemhof	1970	1981	11	1285.76	1264.42	7163	30601	0.18	21.34	1.66	49.56	43.73	76.4
								1970	1998	28	1285.76	1218.08	7163	30601	0.17	67.68	5.26	86.56	76.38	76.4

YEAR	VOLUME
1970	#####
1981	#####
1998	#####



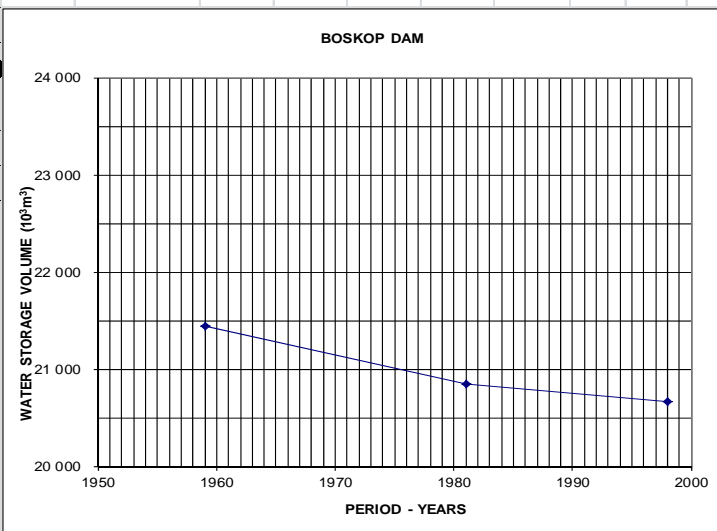
YEAR	VOLUME
1	-
11	21 340
28	67 680



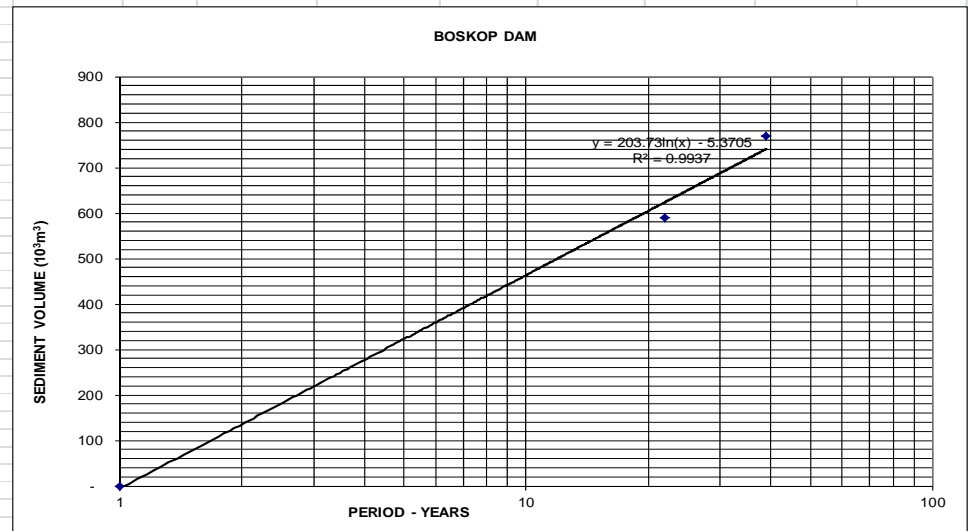
V50 = 96437.52 (Used period 1981 to 1998)

7	185	Boskop	C230-04	C2R001	III-C	Mooi	Potchefstr	1959	1981	22	21.44	20.85	82	2172	0.25	0.59	2.75	0.85	10.61	10.67
								1959	1998	39	21.44	20.67	82	2172	0.25	0.78	3.63	0.86	10.67	10.67

YEAR	VOLUME
1959	21 440
1981	20 850
1998	20 670



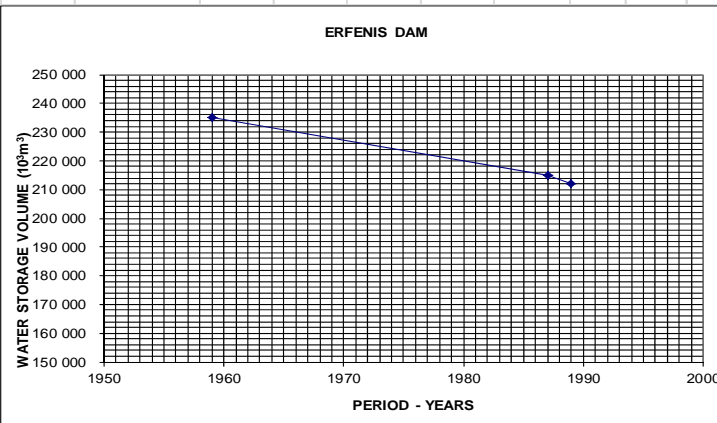
YEAR	VOLUME
1	-
22	590
39	770



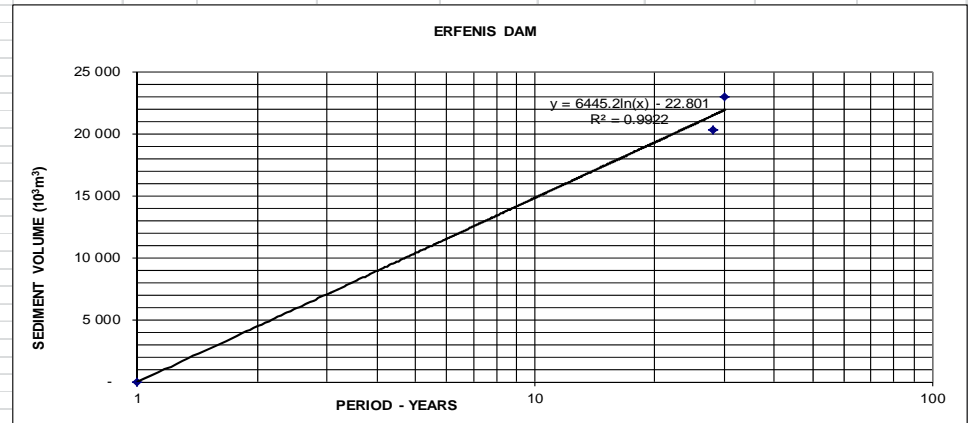
V50 = 791.63

14	254	Erfenis	C400-03	C4R002	III-C	Groot - Ve	Theunisse	1959	1987	28	235.20	214.87	237	4188	0.91	20.33	8.64	26.00	167.60	
								1959	1989	30	235.20	212.20	237	4188	0.90	23.00	9.78	28.47	183.53	163.00

YEAR	VOLUME
1959	235 200
1987	214 870
1989	212 200



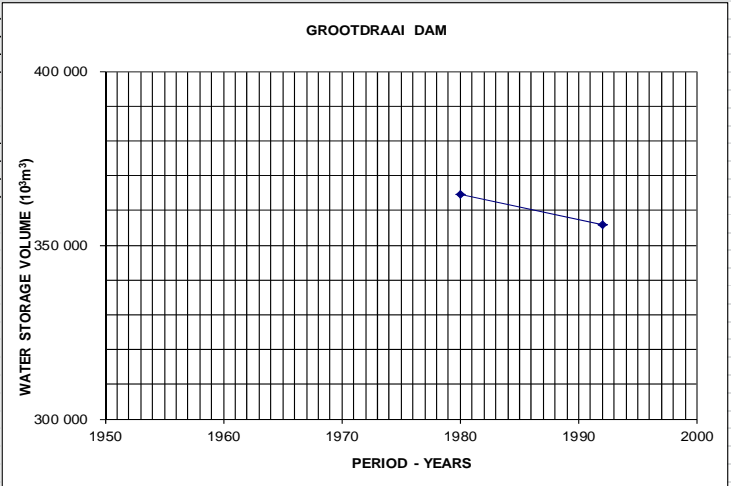
YEAR	VOLUME
1	-
28	20 330
30	23 000



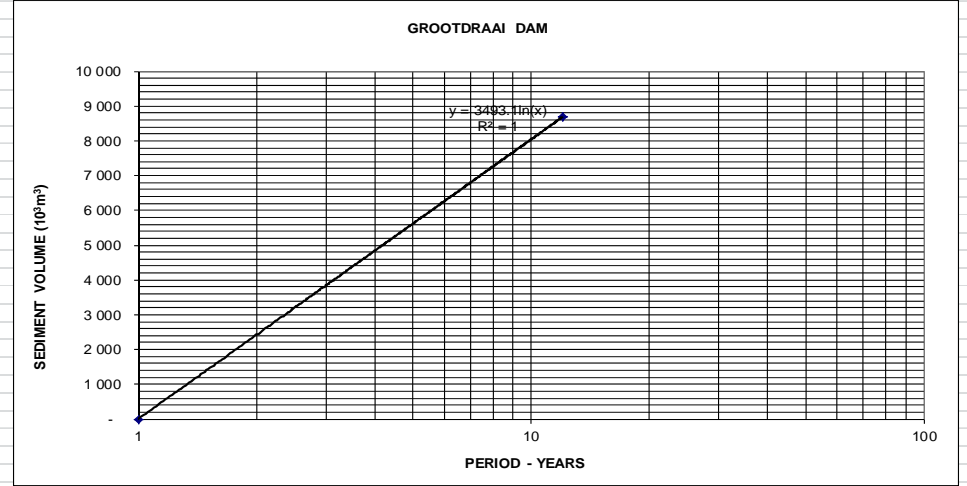
V50 = 25190.97

19	203	Grootdraai	C114-02	C1R002	III-C	Vaal	Standertor	1978	1980	2	0.00	0.00	514	7057	0.00	-	-	63.00	
								1980	1992	12	364.70	356.02	514	7057	0.69	8.67	2.38	18.72	71.63

YEAR	VOLUME
1980	364 700
1992	356 020



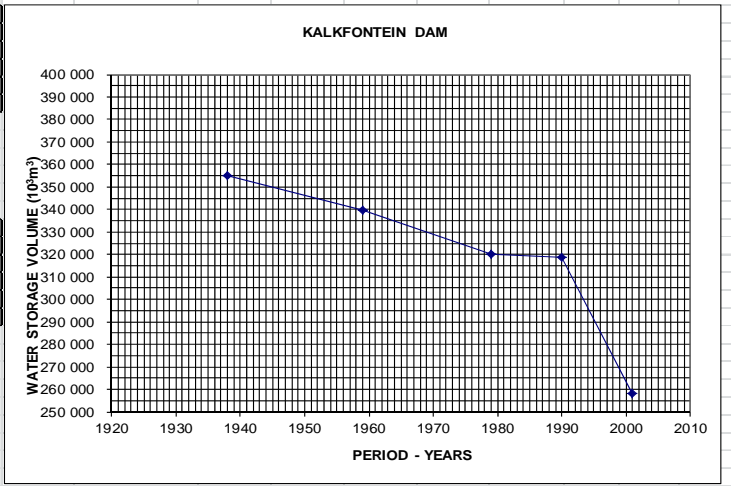
YEAR	VOLUME
1	-
12	8 680



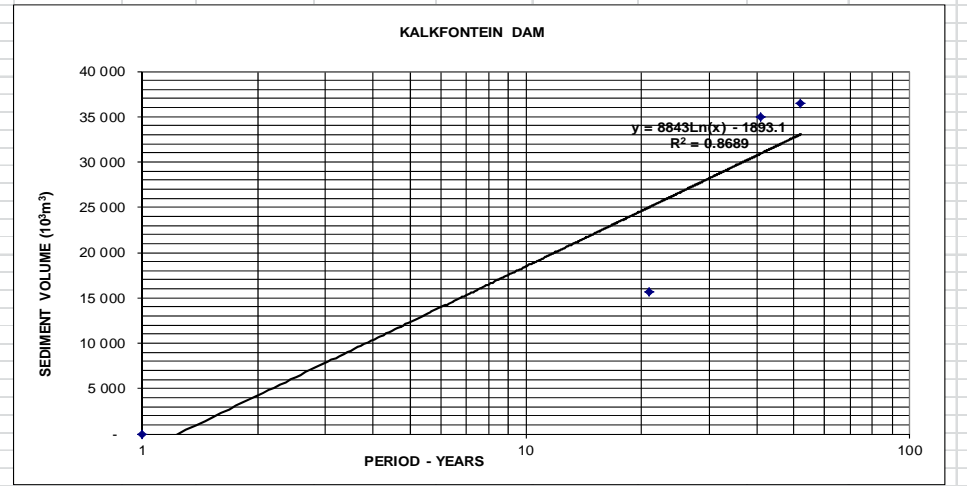
V50 = 13,665.08

21	310	Kalkfontein	C510-04	C5R002	III-C	Riet	Koffiefonte	1938	1959	21	355.21	339.49	216	8664	1.58	15.73	4.43	23.34	72.74
								1938	1979	41	355.21	320.22	216	8664	1.49	34.99	9.85	37.82	117.86
								1938	1990	52	355.21	318.79	216	8664	1.48	36.42	10.25	35.90	111.87
								1938	2001	63	355.21	258.27	216	8664	1.20	96.94	27.29	89.20	277.97

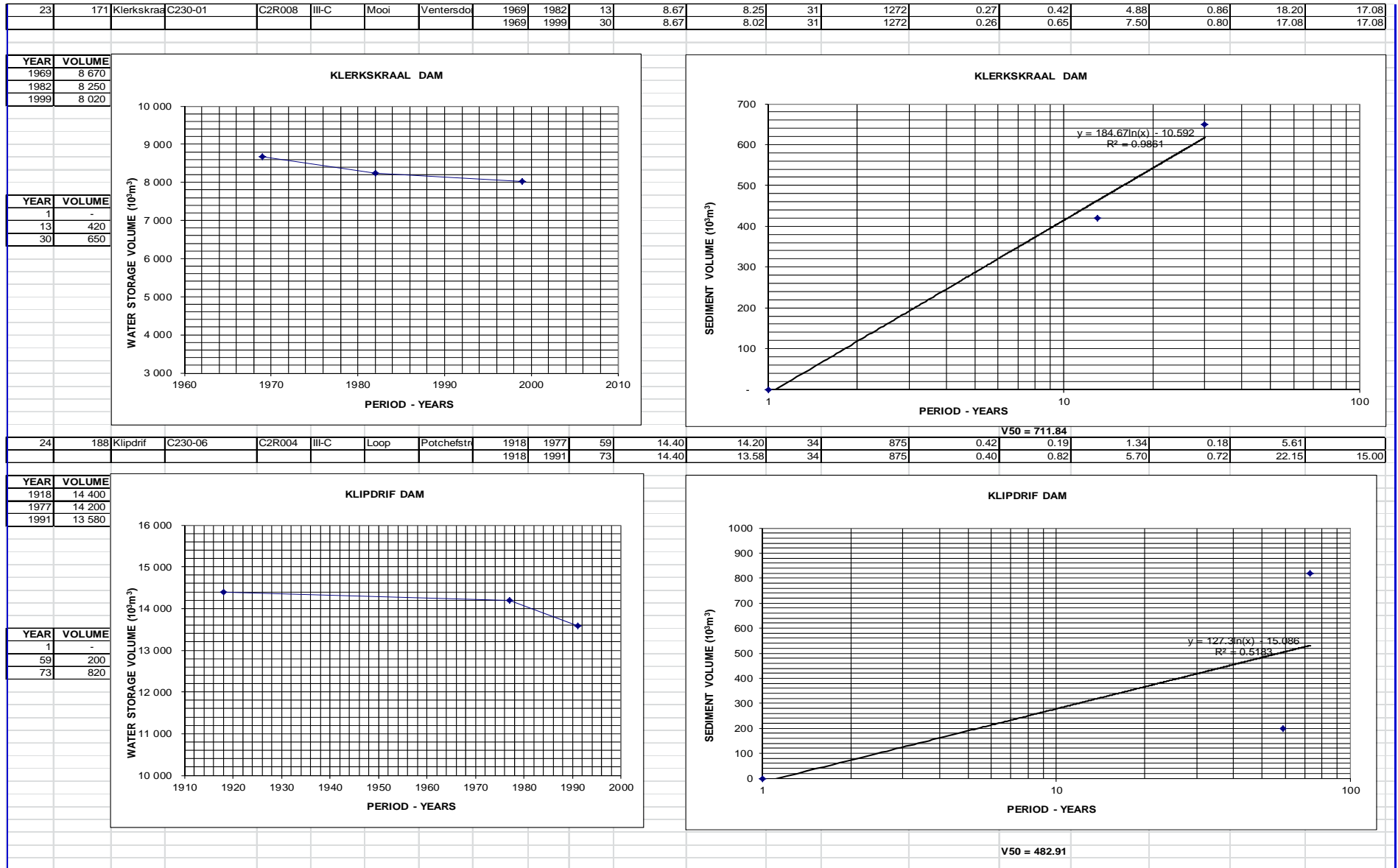
YEAR	VOLUME
1938	355 210
1959	339 490
1979	320 220
1990	318 790
2001	258 270



YEAR	VOLUME
1	-
21	15 720
41	34 990
52	36 420
63	96 940

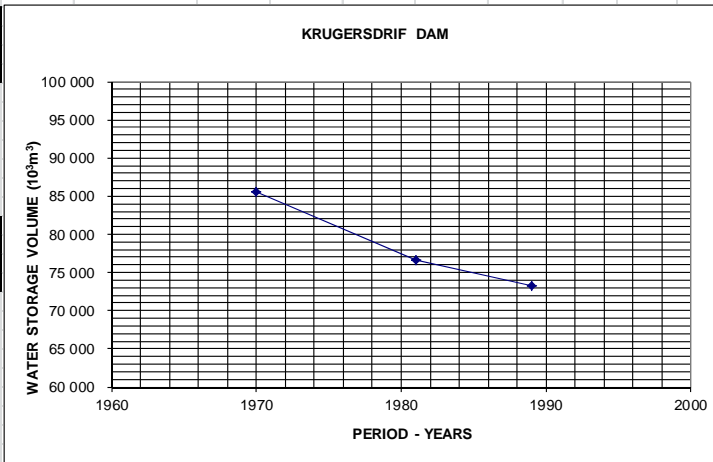


V50 = 34,594 (Used period from 1938 to 1990)

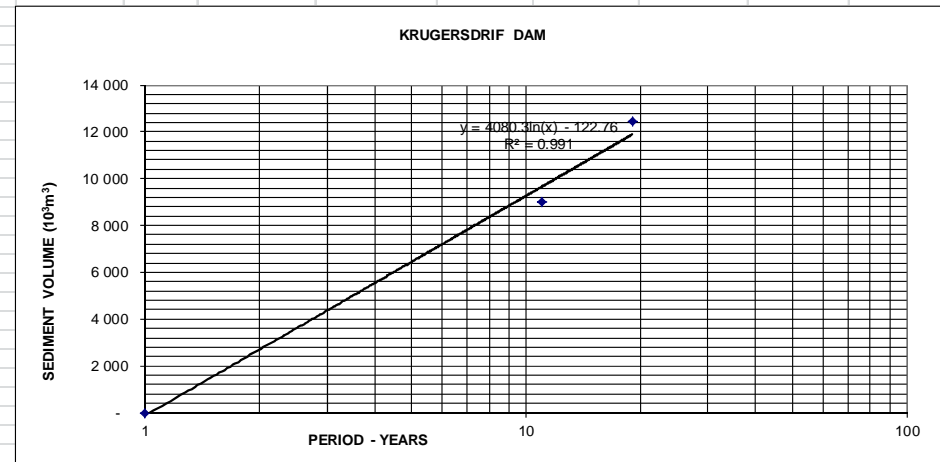


26	269	Krugersdrif	C520-02	C5R004	III-C	Modder	Bloemfontein	1970	1981	11	85.62	76.62	177	4453	0.43	9.00	10.51	20.90	126.74	
								1970	1989	19	85.62	73.19	177	4453	0.41	12.42	14.51	19.53	118.42	104.00

YEAR	VOLUME
1970	85 620
1981	76 620
1989	73 190



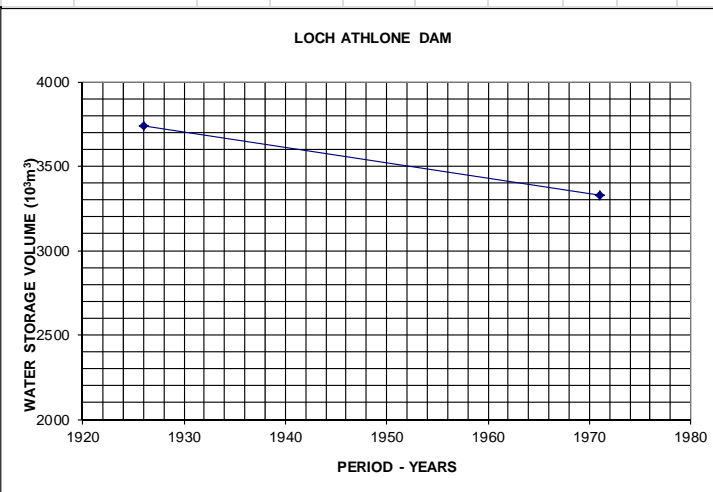
YEAR	VOLUME
1	-
11	9 000
19	12 430



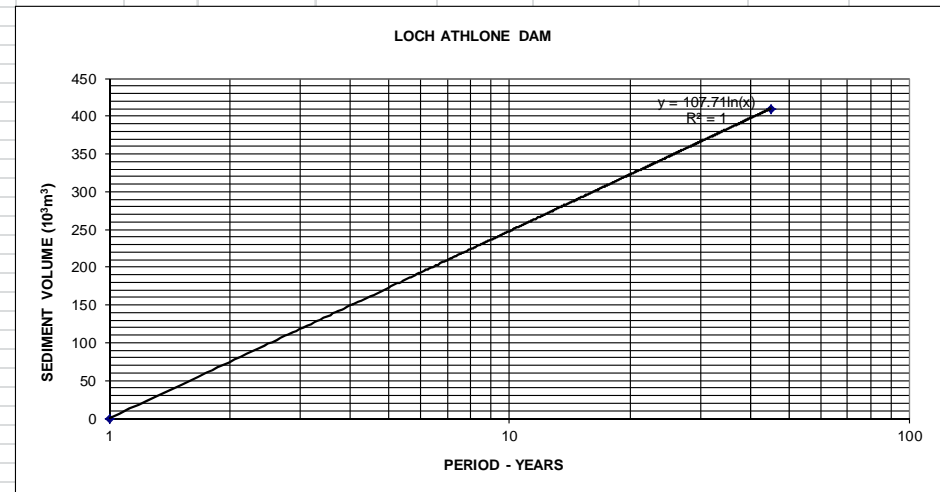
V50 = 15,839.46

29	246	Loch Athlone	C800-16	C8R005	III-C	Jordan	Bethlehem	1926	1971	45	3.74	3.33	0	0	-	0.41	11.07	0.43	95.00	95
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YEAR	VOLUME
1926	3 740
1971	3 330



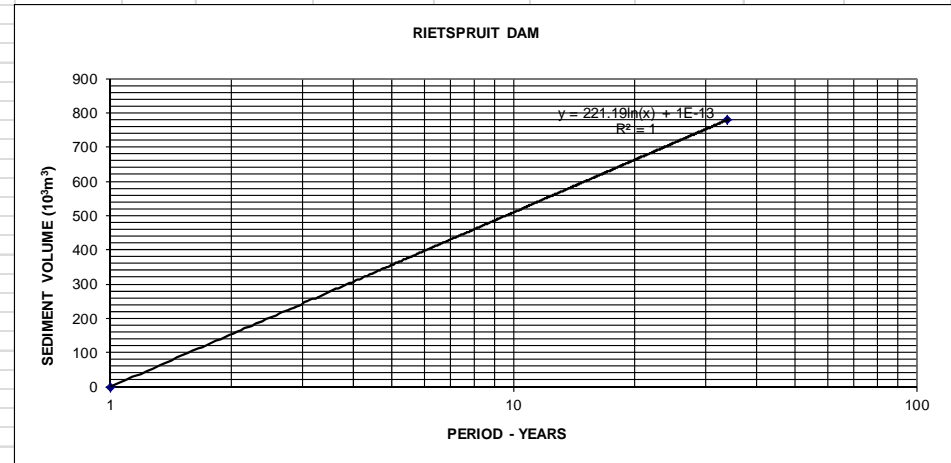
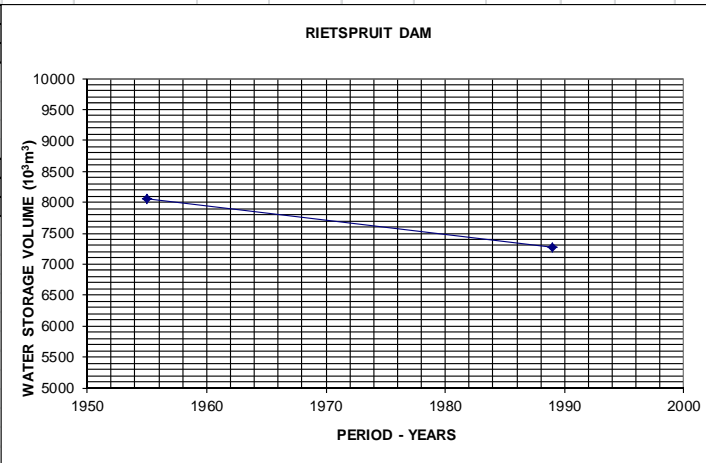
YEAR	VOLUME
1	-
45	410



V50 = 421.36

34	162	Rietspruit	C240-01	C2R007	III-C	Rietspruit	Ventersdol	1955	1989	34	8.06	7.28	10	392	0.72	0.77	9.61	0.91	62.36	62.36
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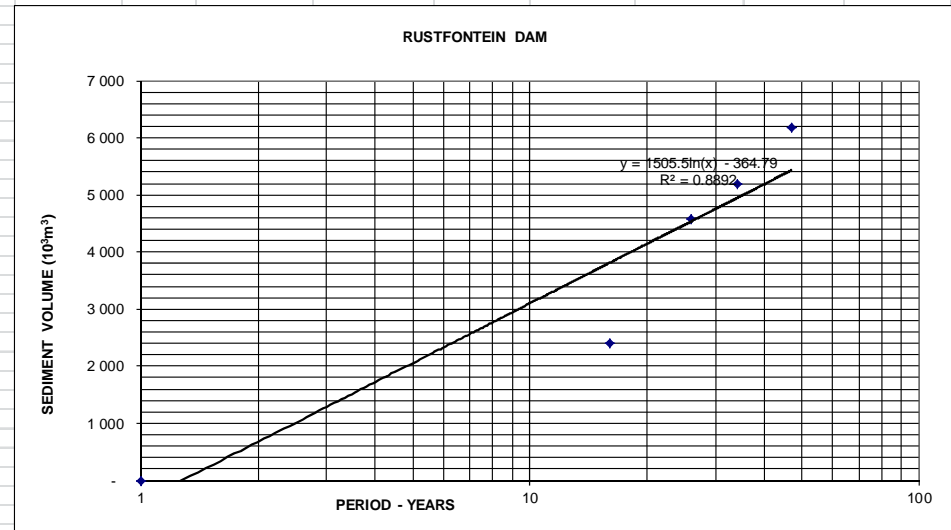
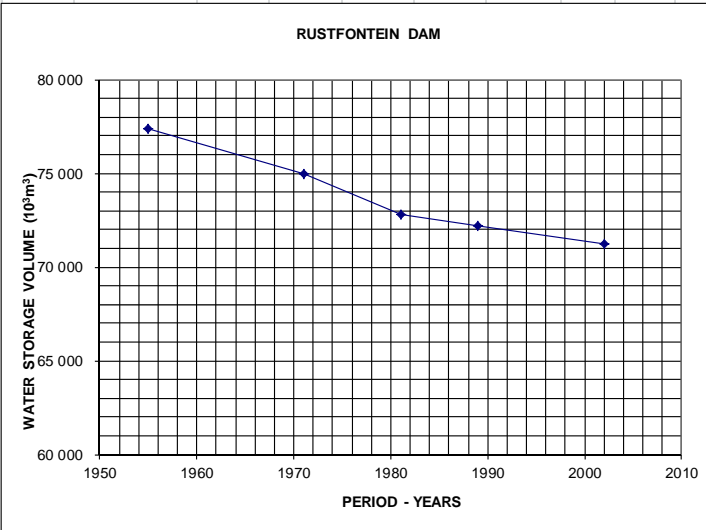
YEAR	VOLUME
1955	8 060
1989	7 280



V50 = 865.3

36	299	Rustfontein	C520-03	C5R003	III-C	Modder	Bloemfont	1955	1971	16	77.40	74.99	28	929	2.69	2.41	3.11	4.22	122.52	183.85
								1955	1981	26	77.40	72.82	28	929	2.61	4.57	5.91	6.07	176.31	183.85
								1955	1989	34	77.40	72.21	28	929	2.59	5.19	6.71	6.07	176.48	183.85
								1955	2002	47	77.40	71.22	28	929	2.55	6.18	7.98	6.33	183.85	183.85

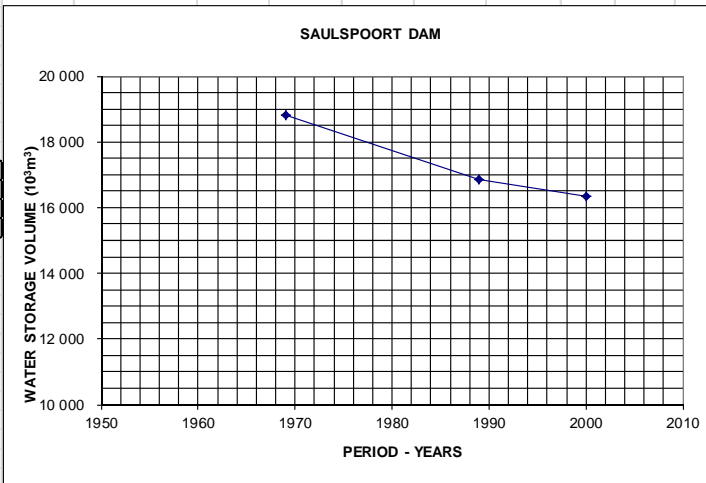
YEAR	VOLUME
1955	77 400
1971	74 990
1981	72 820
1989	72 210
2002	71 220



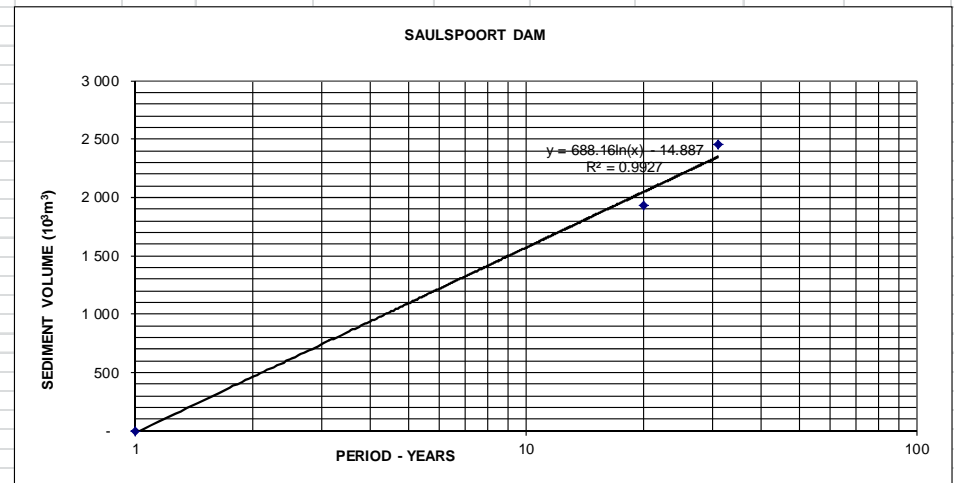
V50 = 5,524.76

37	244	Saulspoor	C800-14	C8R004	III-C	Nuwejaar	Harrismith	1969	1989	20	18.80	16.87	32	731	0.54	1.93	10.29	2.95	109.00	110.56
								1969	2000	31	18.80	16.35	32	731	0.52	2.46	13.06	2.99	110.56	

YEAR	VOLUME
1969	18 800
1989	16 870
2000	16 350



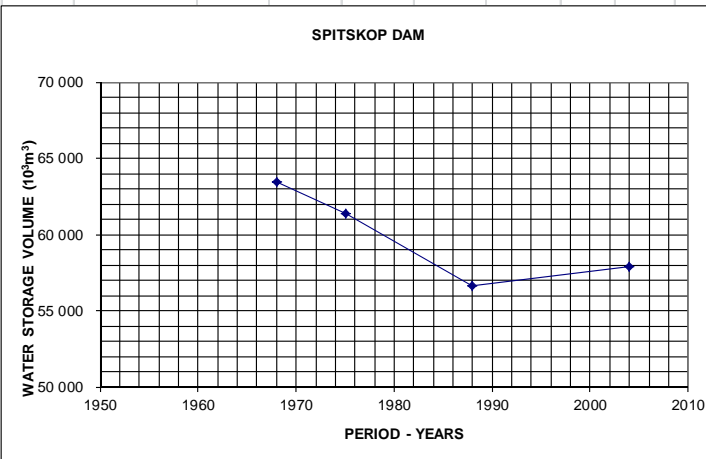
YEAR	VOLUME
1	-
20	1 930
31	2 450



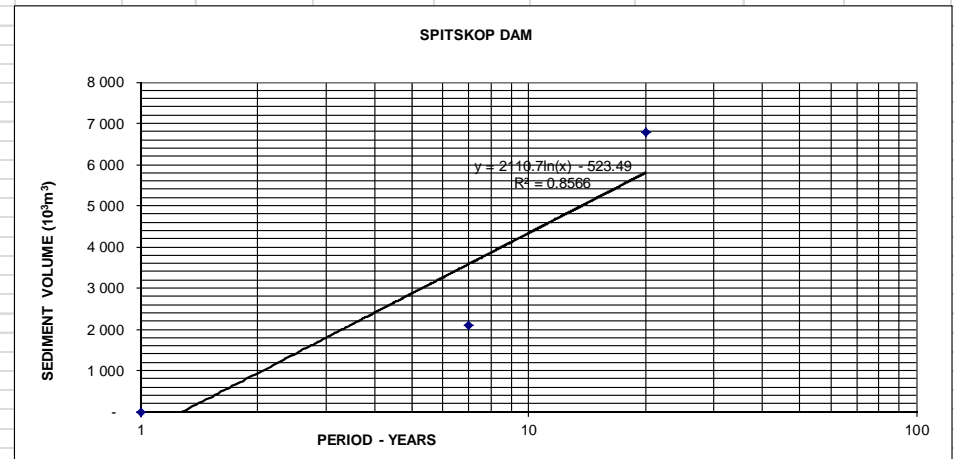
V50 = 2,677.21

40	237	Spitskop	C300-01	C3R001	III-C	Harts	Warrenton	1968	1975	7	63.43	61.34	202	14845	0.30	2.10	3.30	8.04	14.62	11.50
								1968	1988	20	63.43	56.66	202	14845	0.28	6.77	10.67	10.33	18.78	11.50
								1968	2004	36	63.43	57.89	202	14845	0.29	5.54	8.74	6.32	11.50	11.50

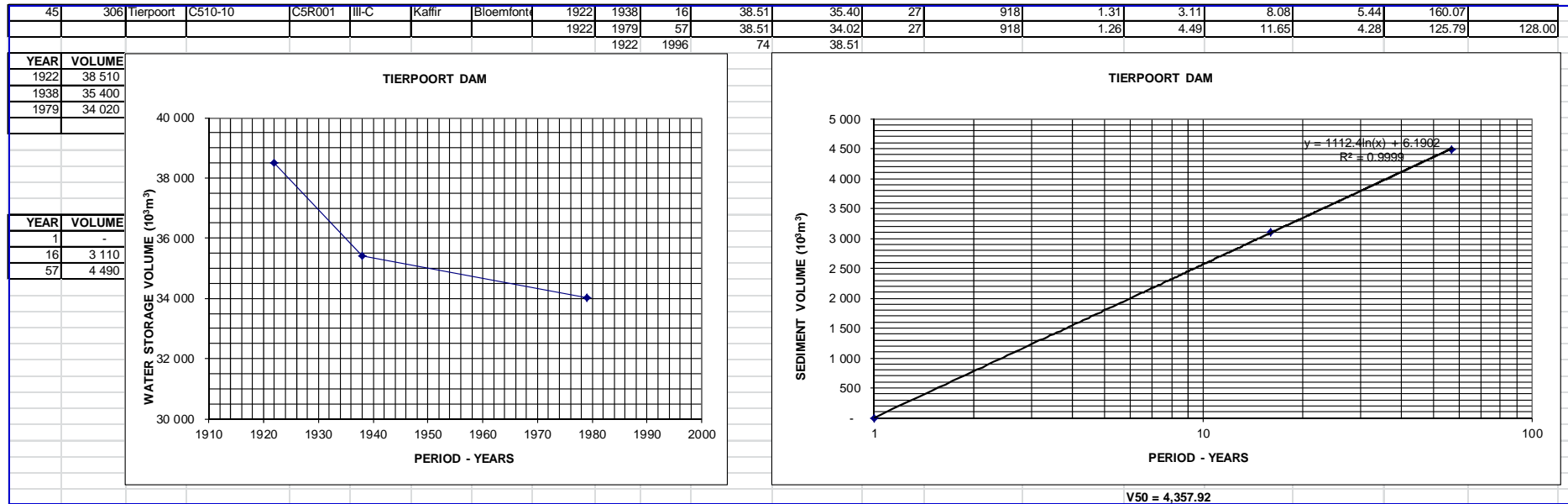
YEAR	VOLUME
1968	63 430
1975	61 340
1988	56 660
2004	57 890



YEAR	VOLUME
1	-
7	2 090
20	6 770
36	5 540

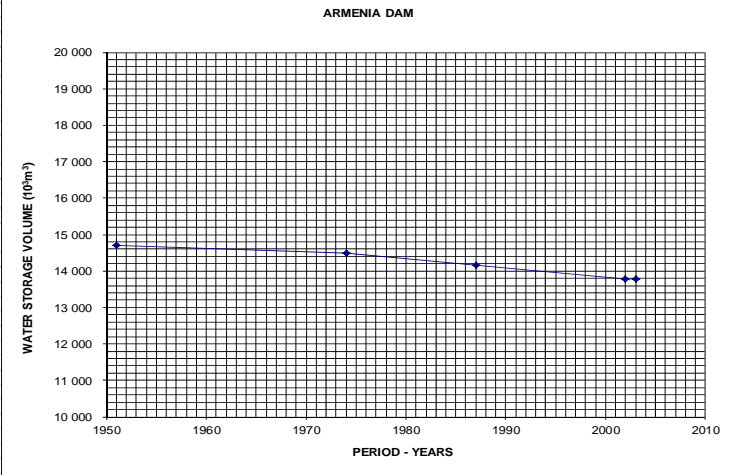


V50 = 7,733.62 - USED PERIOD 1968 TO 1988

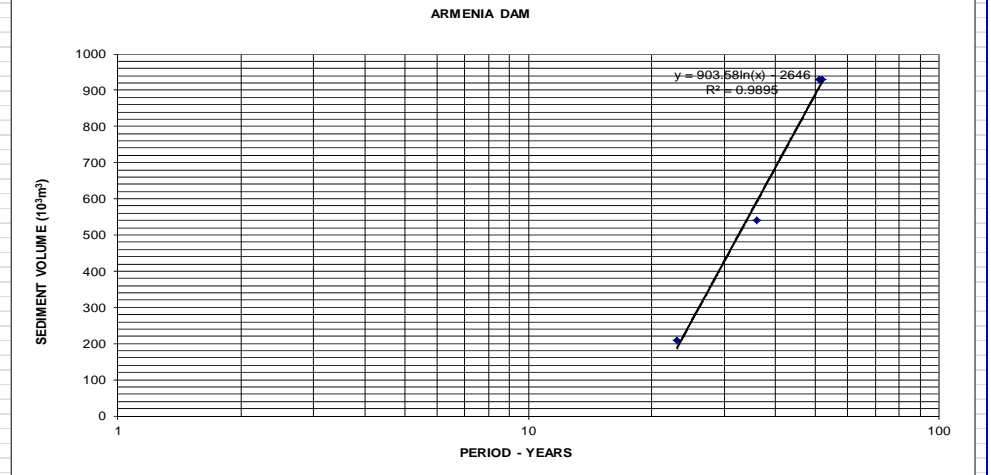


MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number - WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (Km ²)	TRAP EFFICIENCY INDICATOR Vw/MAR	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)	REMARKS
3	302	Armenia	D200-04	D2R002	III-D	Leeu	Ladybrand	1951	1974	23	14.71	14.50	42	260	0.35	0.21	1.43	0.88	91.38		
								1951	1987	36	14.71	14.17	42	260	0.34	0.54	3.70	0.88	91.38		
								1951	2002	51	14.71	13.78	42	260	0.33	0.93	6.34	0.88	91.38		
								1951	2003	52	14.71	13.78	42	260	0.33	0.93	6.34	0.88	91.38		

YEAR	VOLUME
1951	14 710
1974	14 500
1987	14 170
2002	13 780
2003	13 780



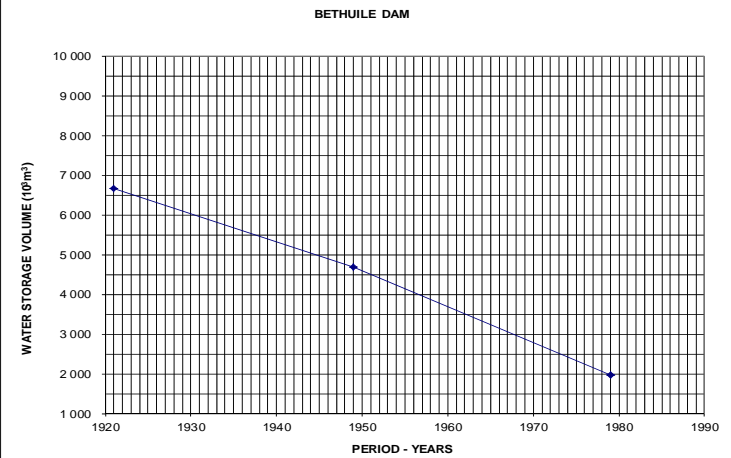
YEAR	VOLUME
1	0
23	210
36	540
51	930
52	930



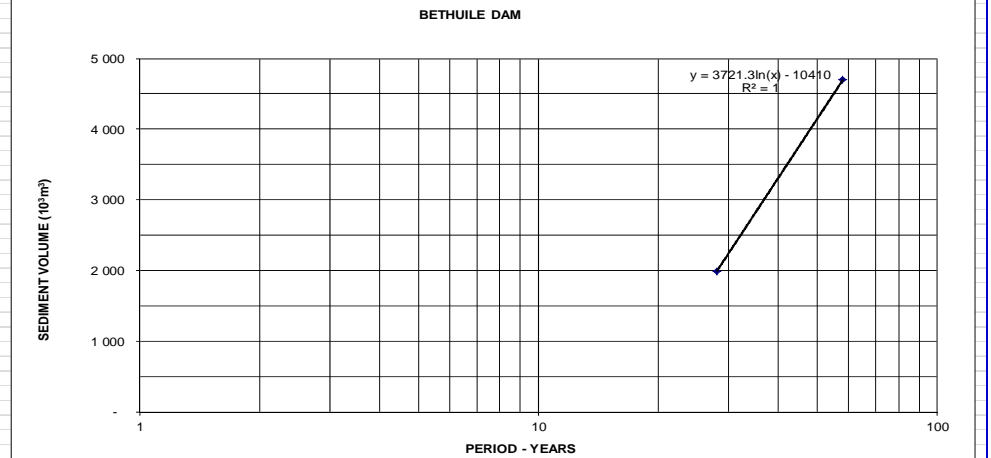
V50 = 888.8

5	349	Bethuille	D350-04	D3R001	III-D	Bethuille	Bethuille	1921	1949	28	6.67	4.68	4	232	1.26	2.00	29.93	2.55	297.25	
								1921	1979	58	6.67	1.97	4	232	0.53	4.70	70.50	4.46	518.57	

YEAR	VOLUME
1921	6 670
1949	4 680
1979	1 970



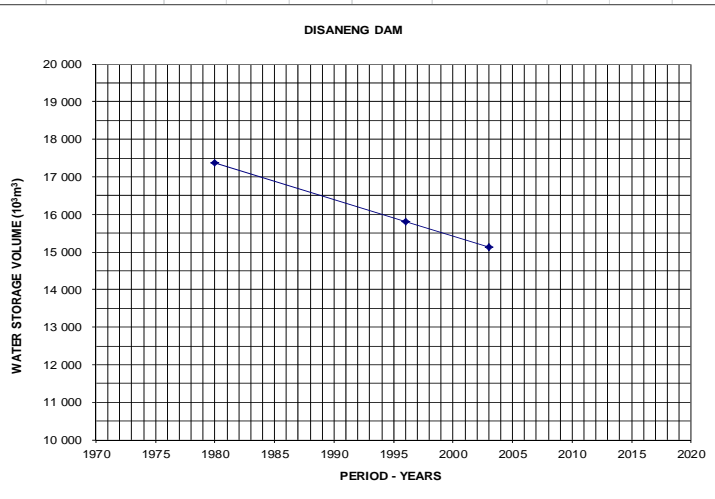
YEAR	VOLUME
1	0
28	1 990
58	4 700



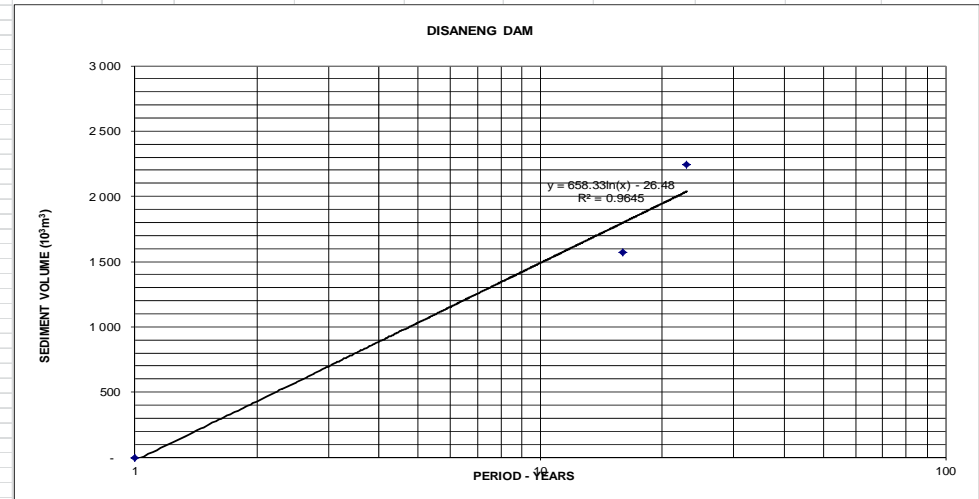
V50 = 4,147.8 (Used period 1949 - 1979)

8	60	Disaneng	D410-02	D4R003	III-D	Molopo	Mmabatho	1980	1996	16	17.37	15.80	0	3817	-	1.57	9.02	2.74	19.38	22.38
								1980	2003	23	17.37	15.13	0	3817	-	2.24	12.90	3.16	22.38	22.38

YEAR	VOLUME
1980	17 370
1996	15 800
2003	15 130



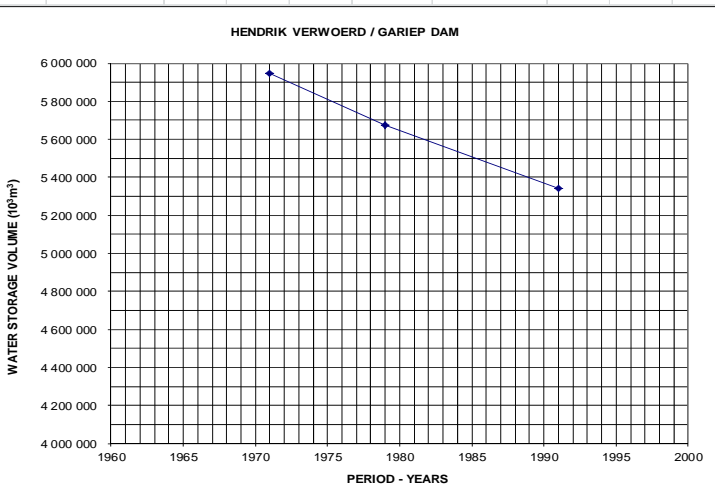
YEAR	VOLUME
1	-
16	1 570
23	2 240



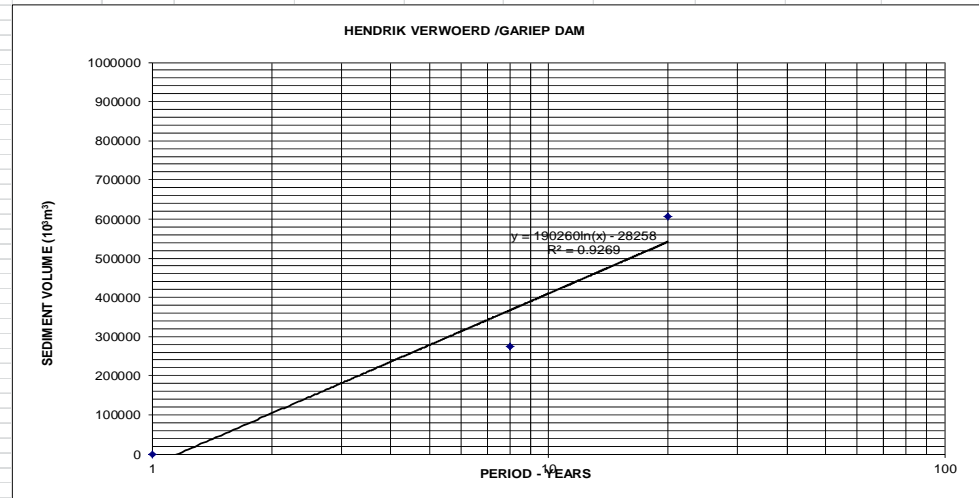
15	347	Hendrik V	D350-02	D3R003	III-D	Orange	OranjeKrag	1971	1979	8	5 948.77	5 673.78	6424	49656	0.88	274.99	4.62	884.69	481.04	392.00
								1971	1991	20	5 948.77	5 342.93	6424	49656	0.83	605.84	10.18	924.44	502.65	392.00

V50 = 2,548.92

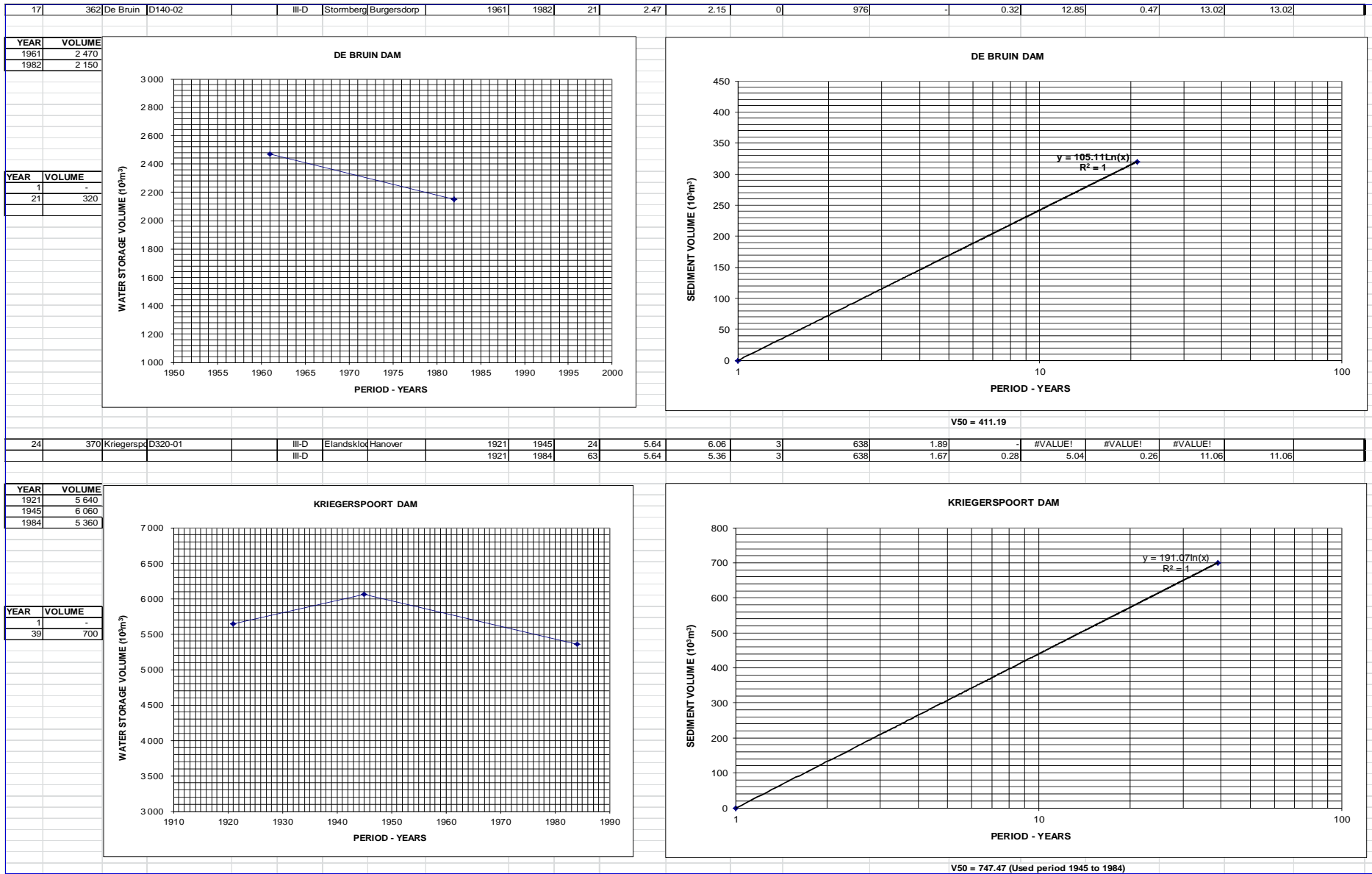
YEAR	VOLUME
1971	5 948 770
1979	5 673 780
1991	5 342 930

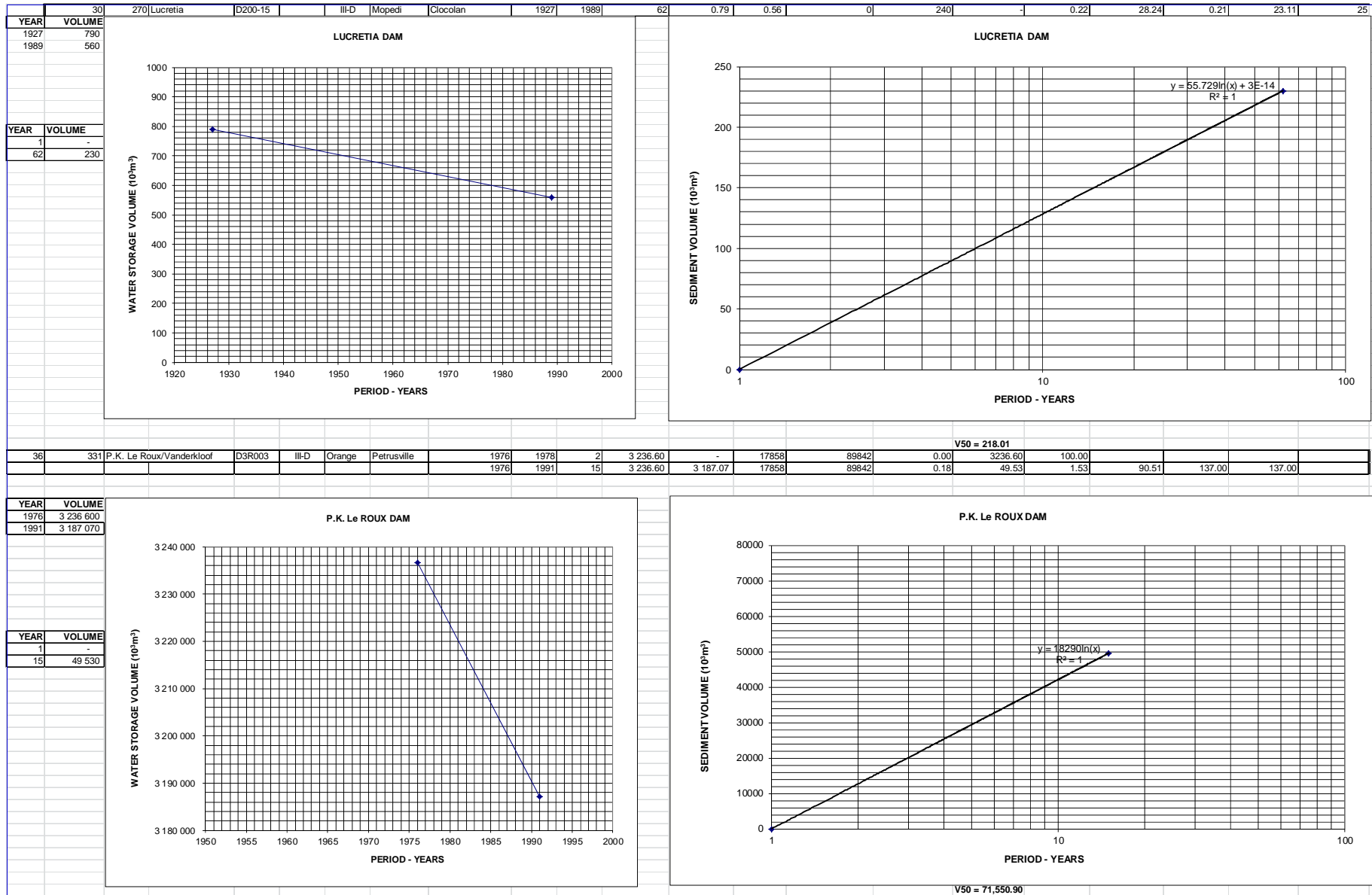


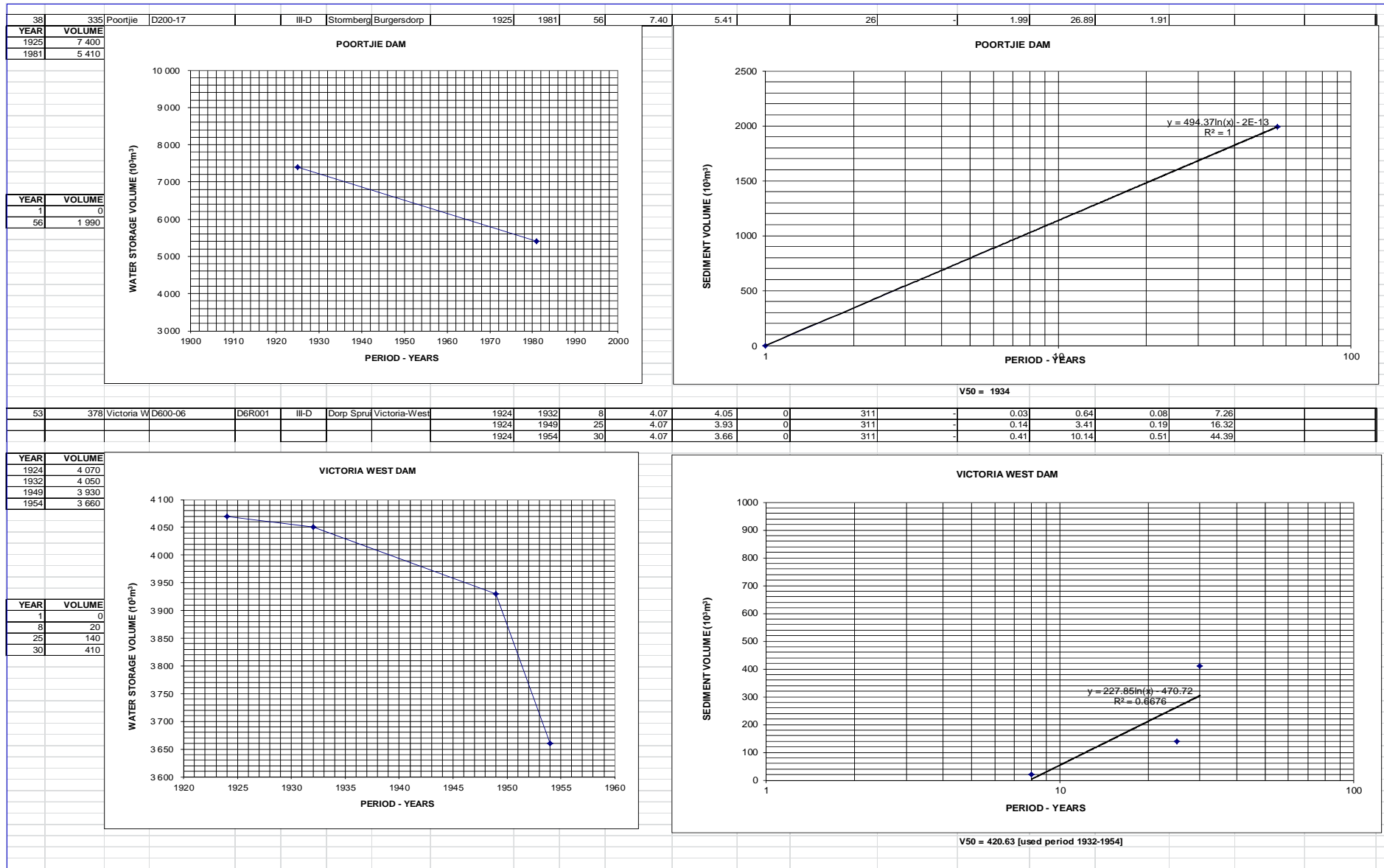
YEAR	VOLUME
1	-
8	274 990
20	605 840

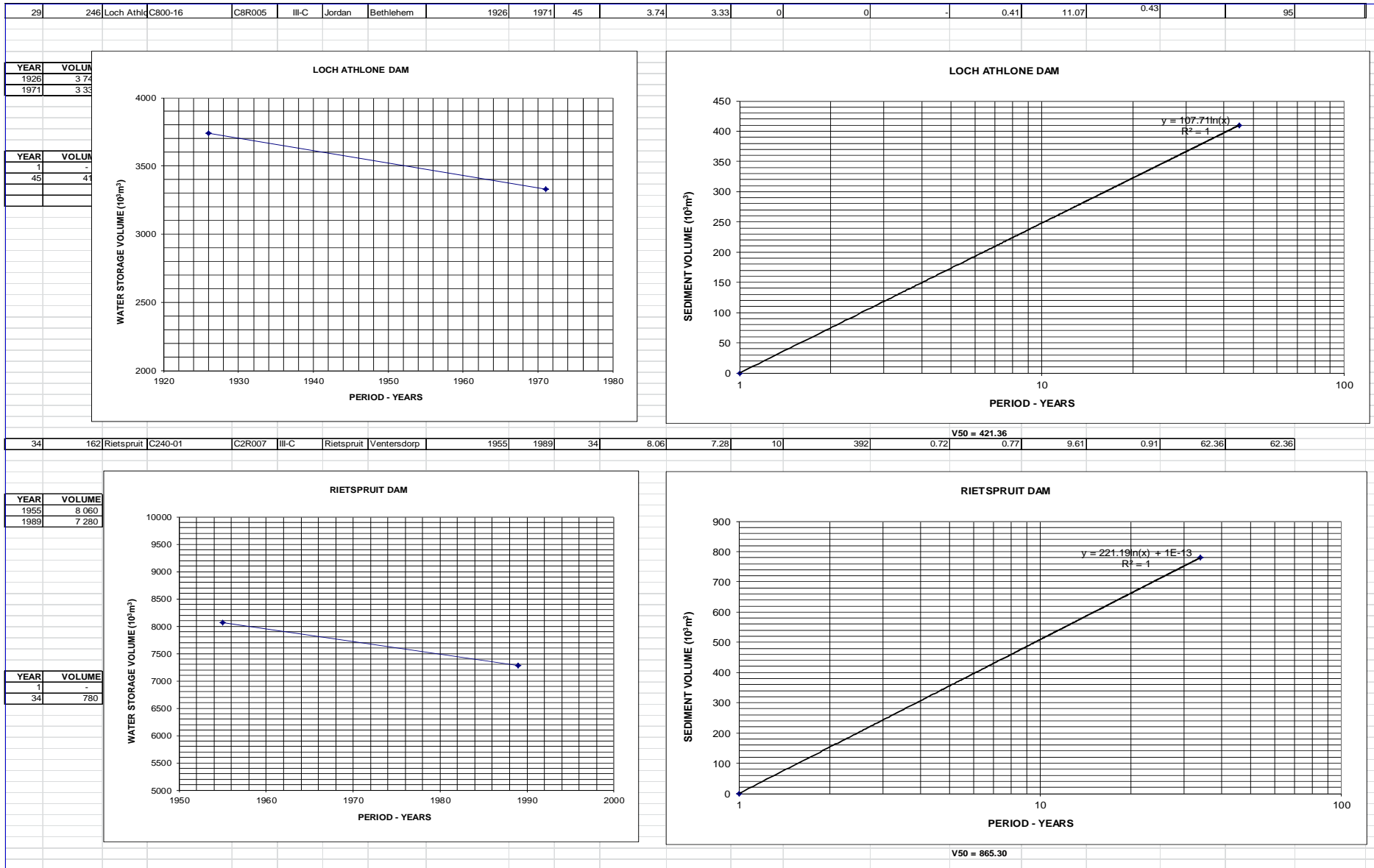


V50 = 716,043.50



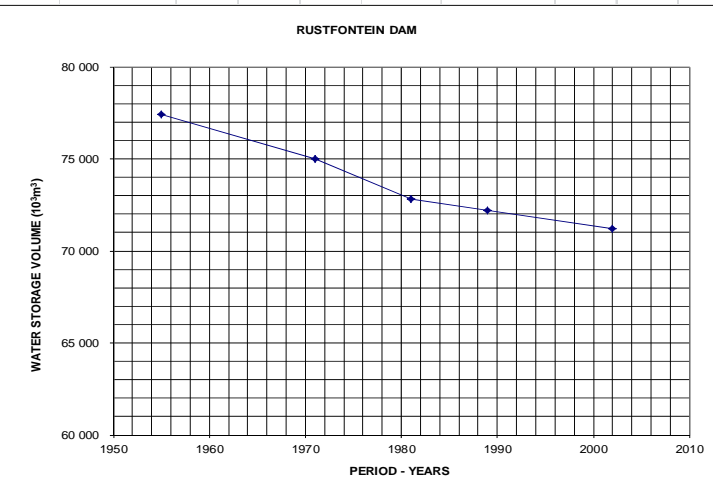




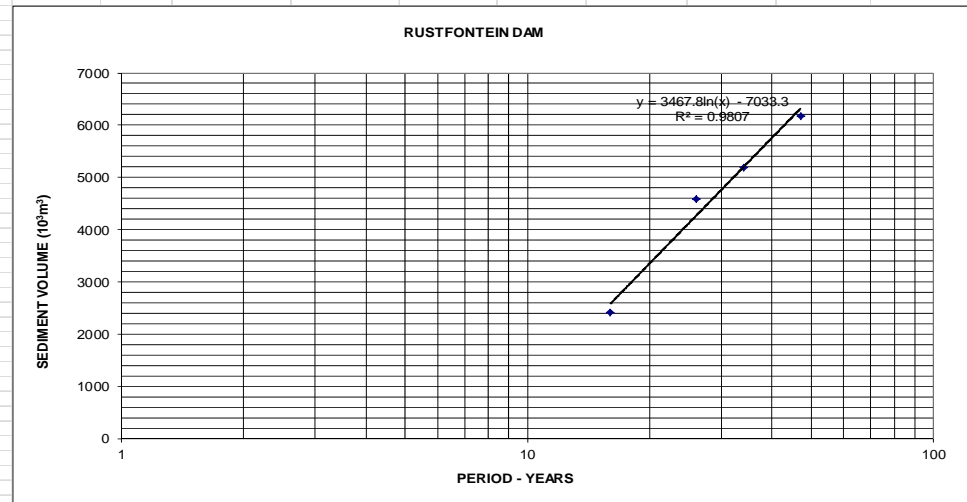


36	299	Rustfontein C520-03	C5R003	III-C	Modder	Bloemfontein	1955	1971	16	77.40	74.99	28	929	2.69	2.41	3.11	4.22	122.52	183.85
							1955	1981	26	77.40	72.82	28	929	2.61	4.57	5.91	6.07	176.31	183.85
							1955	1989	34	77.40	72.21	28	929	2.59	5.19	6.71	6.07	176.48	183.85
							1955	2002	47	77.40	71.22	28	929	2.55	6.18	7.98	6.33	183.85	183.85

YEAR	VOLUME
1955	77 400
1971	74 990
1981	72 820
1989	72 210
2002	71 220



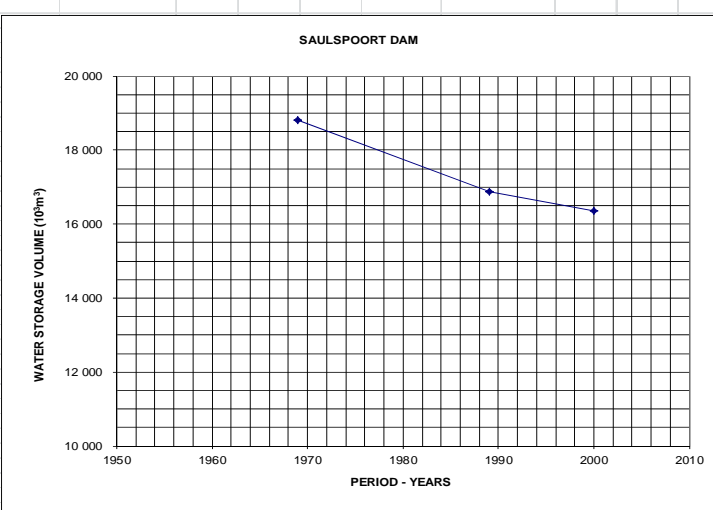
YEAR	VOLUME
1	-
16	2 410
26	4 580
34	5 190
47	6 180



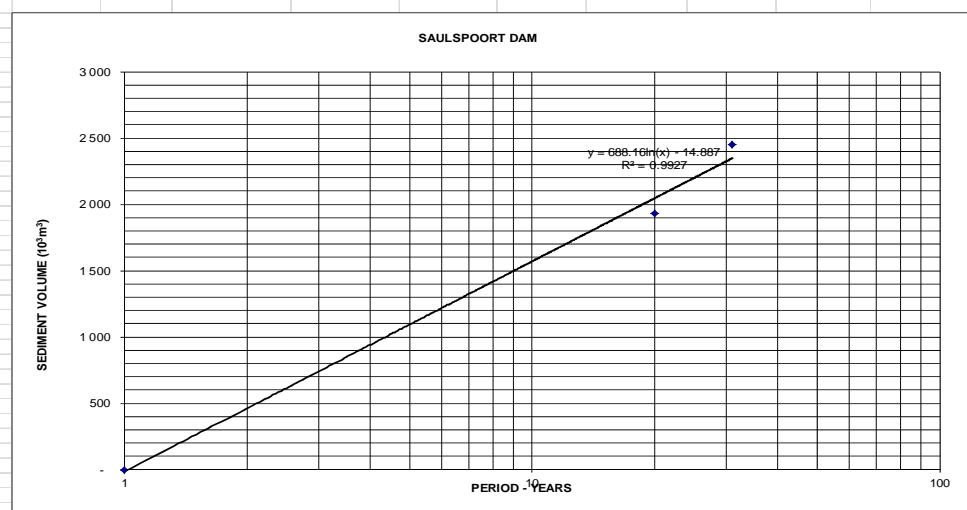
V50 = 6529.68 [period 1971 to 2002]

37	244	Saulspoort C800-14	C8R004	III-C	Nuwejaar	Harrismith	1969	1989	20	18.80	16.87	32	731	0.54	1.93	10.29	2.95	109.00	110.56
							1969	2000	31	18.80	16.35	32	731	0.52	2.46	13.06	2.99	110.56	110.56

YEAR	VOLUME
1969	18 800
1989	16 870
2000	16 350



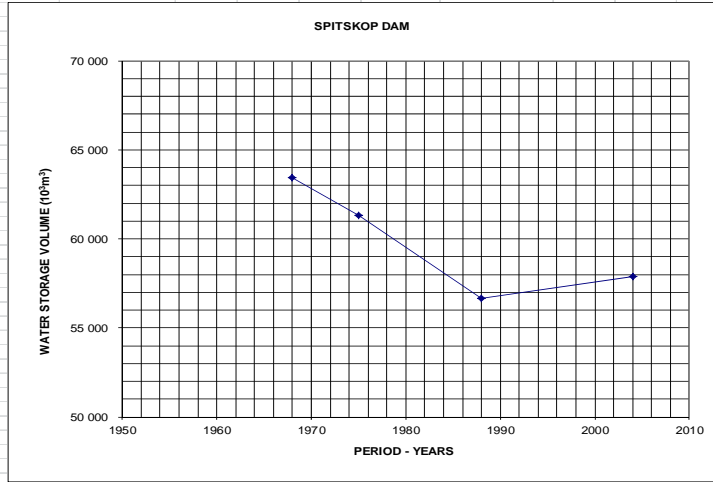
YEAR	VOLUME
1	-
20	1 930
31	2 450



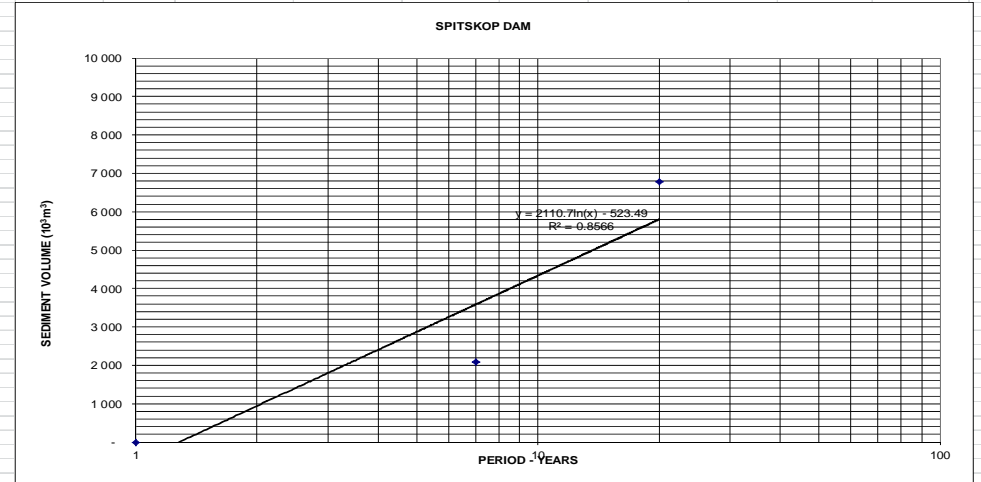
V50 = 2677.21

40	237	Spitskop	C300-01	C3R001	III-C	Harts	Warrenton	1968	1975	7	63.43	61.34	202	14845	0.30	2.10	3.30	8.04	14.62	11.50	Longer period
								1968	1988	20	63.43	56.66	202	14845	0.28	6.77	10.67	10.33	18.78	11.50	
								1968	2004	36	63.43	57.89	202	14845	0.29	5.54	8.74	6.32	11.50	11.50	

YEAR	VOLUME
1968	63 430
1975	61 340
1988	56 660
2004	57 890



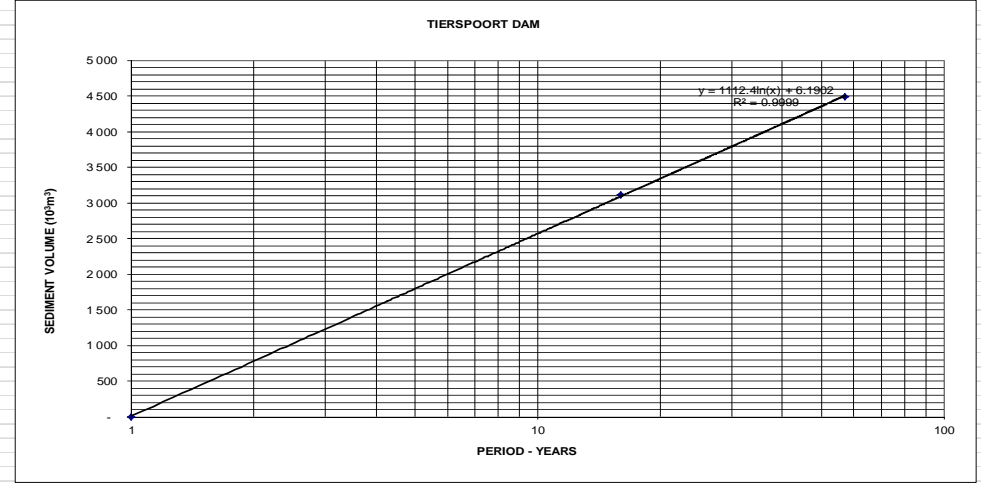
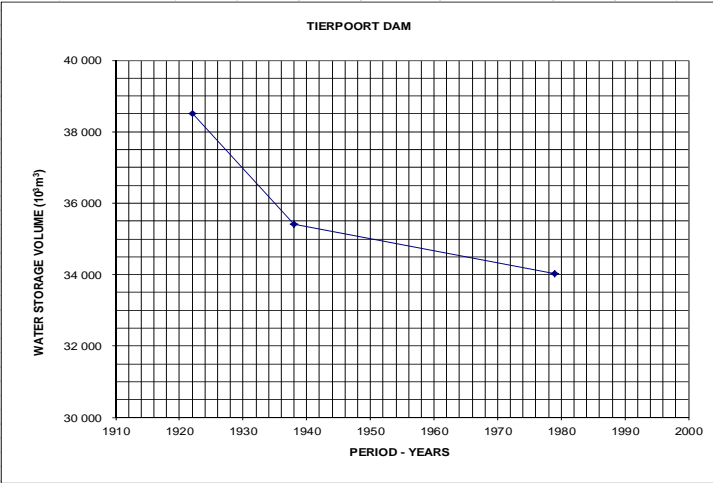
YEAR	VOLUME
1	-
7	2 090
20	6 770



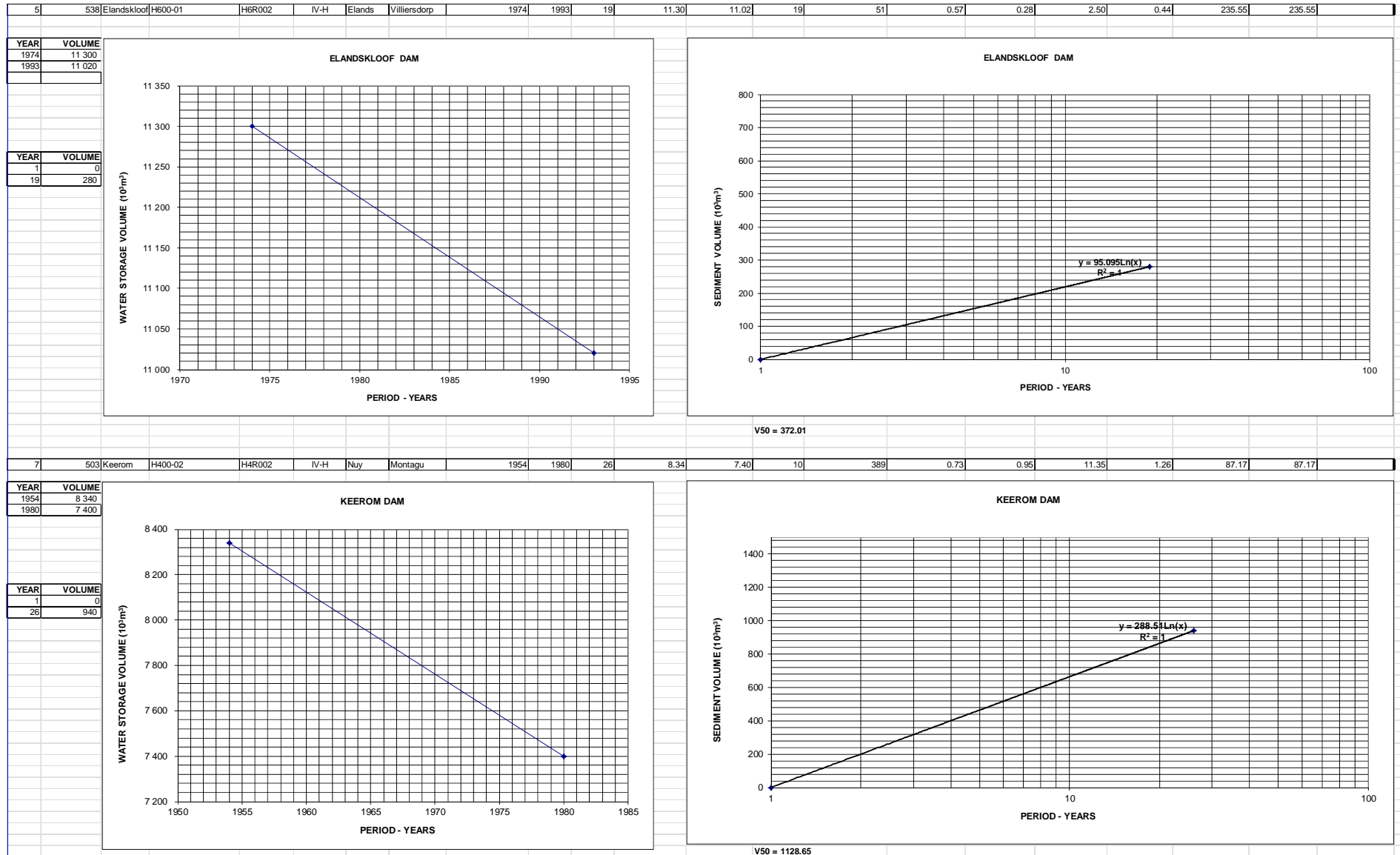
V50 = 7,733.62 [period 1968 to 1988]

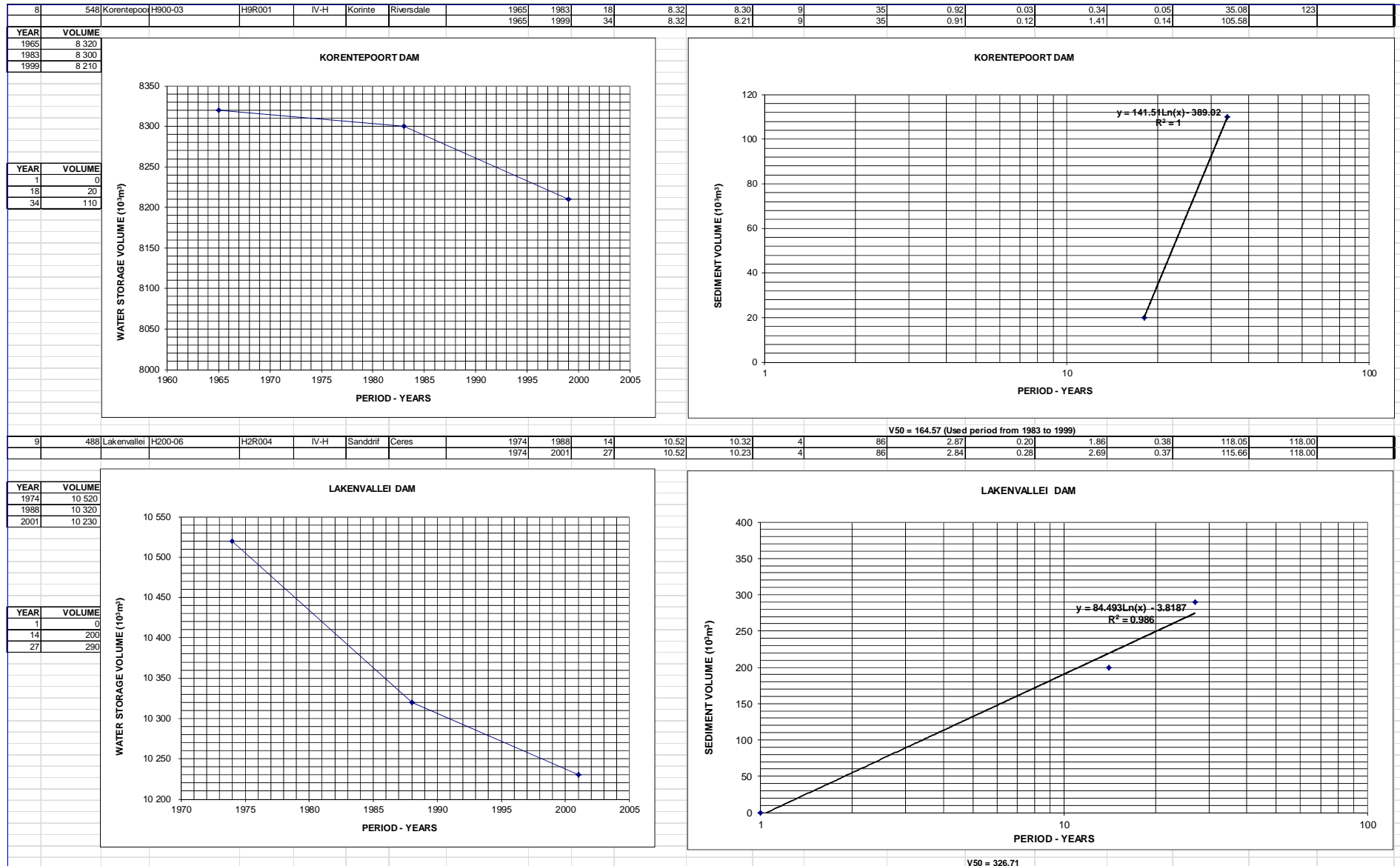
45	306	Tierpoort	C510-10	C5R001	III-C	Kaffir	Bloemfontein	1922	1938	16	38.51	35.40	27	918	1.31	3.11	8.08	5.44	160.07	125.79	Longer period
								1922	1979	57	38.51	34.02	27	918	1.26	4.49	11.65	4.28	125.79	125.79	
								1922	1996	74	38.51					38.51	100.00	33.57	#DIV/0!		

YEAR	VOLUME
1	-
16	3 110
57	4 490



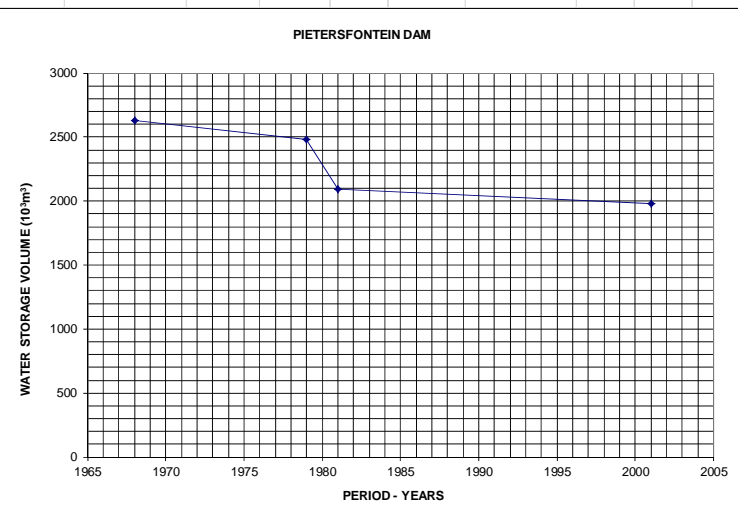
MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number - WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (Km ²)	TRAP EFFICIENCY INDICATOR (Vw/MAR)	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)	REMARKS								
9	520	Wemmersh	G100-13	G1R002	IV-G	Wemmers	Franschoek	1957	1984	27	59.898	58.796	62	86	0.94	1.10	1.84	1.43	450.38	450.38									
<div style="display: flex; justify-content: space-around;"> <div style="width: 45%;"> <p>WEMMERSHOEK DAM</p> <table border="1"> <thead> <tr> <th>YEAR</th> <th>VOLUME</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>0</td> </tr> <tr> <td>27</td> <td>1.102</td> </tr> </tbody> </table> </div> <div style="width: 45%;"> <p>WEMMERSHOEK DAM</p> <p>$y = 334.36\ln(x)$ $R^2 = 1$</p> </div> </div>																						YEAR	VOLUME	1	0	27	1.102		
YEAR	VOLUME																												
1	0																												
27	1.102																												
4	544	Duiwenhoks	H800-03	H8R001	IV-H	Duiwenhol	Heidelberg	1965	1979	14	6.46	6.41	31	147	0.21	0.06	0.91	0.11	20.79	43.0									
<div style="display: flex; justify-content: space-around;"> <div style="width: 45%;"> <p>DUIWENHOKS DAM</p> <table border="1"> <thead> <tr> <th>YEAR</th> <th>VOLUME</th> </tr> </thead> <tbody> <tr> <td>1</td> <td>0</td> </tr> <tr> <td>14</td> <td>50</td> </tr> <tr> <td>34</td> <td>200</td> </tr> </tbody> </table> </div> <div style="width: 45%;"> <p>DUIWENHOKS DAM</p> <p>$y = 48.066\ln(x) - 15.449$ $R^2 = 0.7175$</p> </div> </div>																						YEAR	VOLUME	1	0	14	50	34	200
YEAR	VOLUME																												
1	0																												
14	50																												
34	200																												



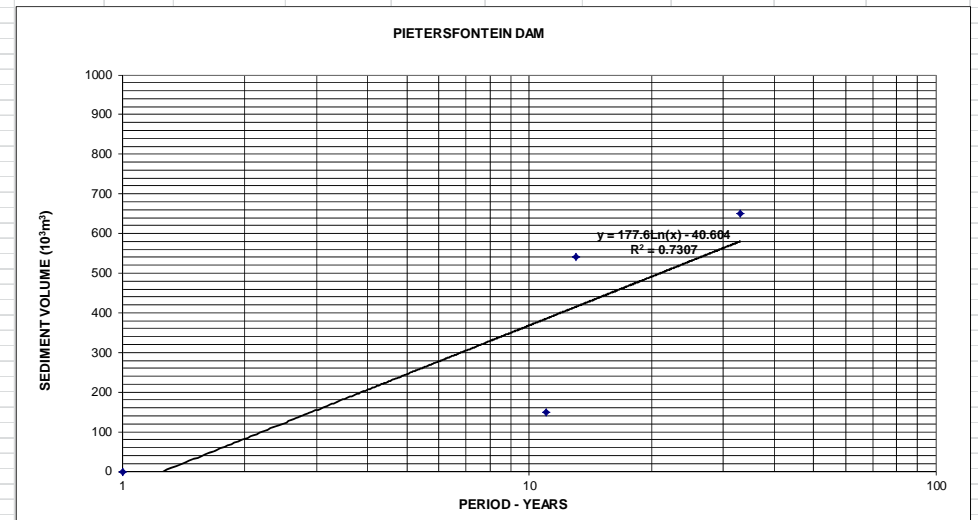


11	506	Pietersfontein	H300-02	H3R002	IV-H	Keisies	Montagu	1968	1979	11	2.63	2.48	8	114	0.30	0.15	5.70	0.35	82.51
								1968	1981	13	2.63	2.09	8	114	0.25	0.54	20.60	1.10	260.18
								1968	2001	33	2.63	1.98	8	114	0.24	0.65	24.59	0.77	181.64

YEAR	VOLUME
1968	2 630
1979	2 480
1981	2 090
2001	1 980



YEAR	VOLUME
1	0
11	150
13	540
33	650

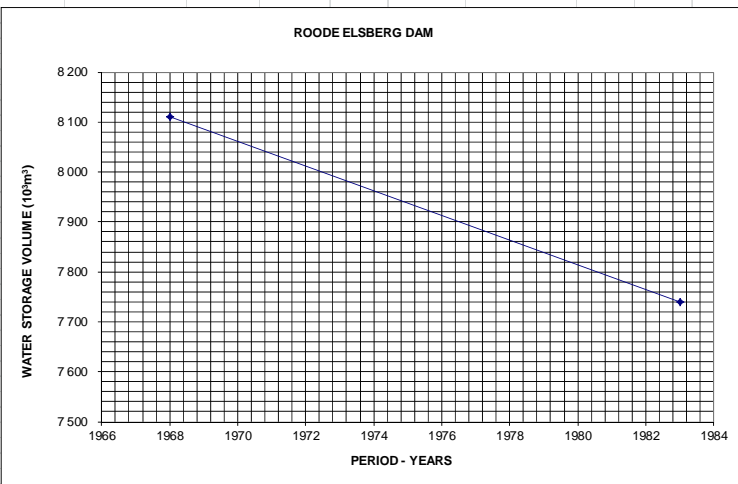


V50 = 820

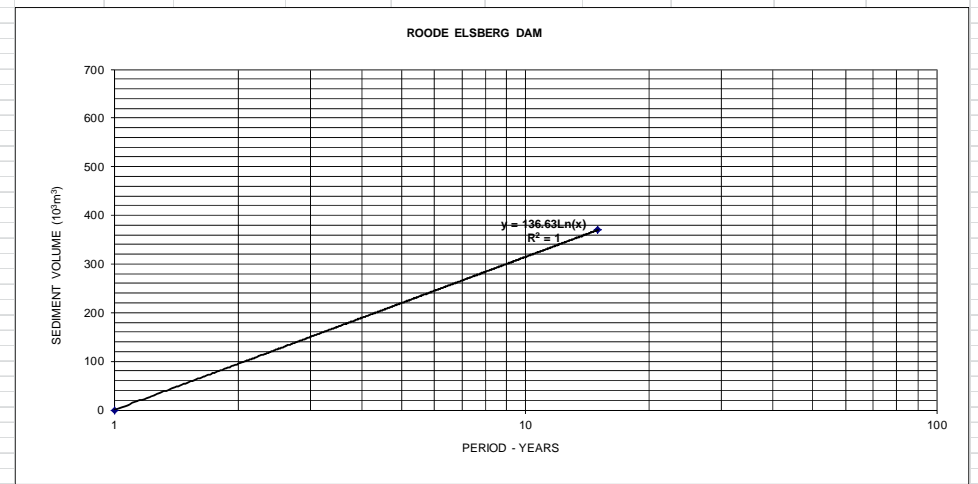
V50 = 654.17

13	496	Roode Elsberg	H200-07	H2R001	IV-H	Sand drif	Worcester	1968	1983	15	8.11	7.74	0	53	#DIV/0!	0.37	4.56	0.68	344.47	344.47
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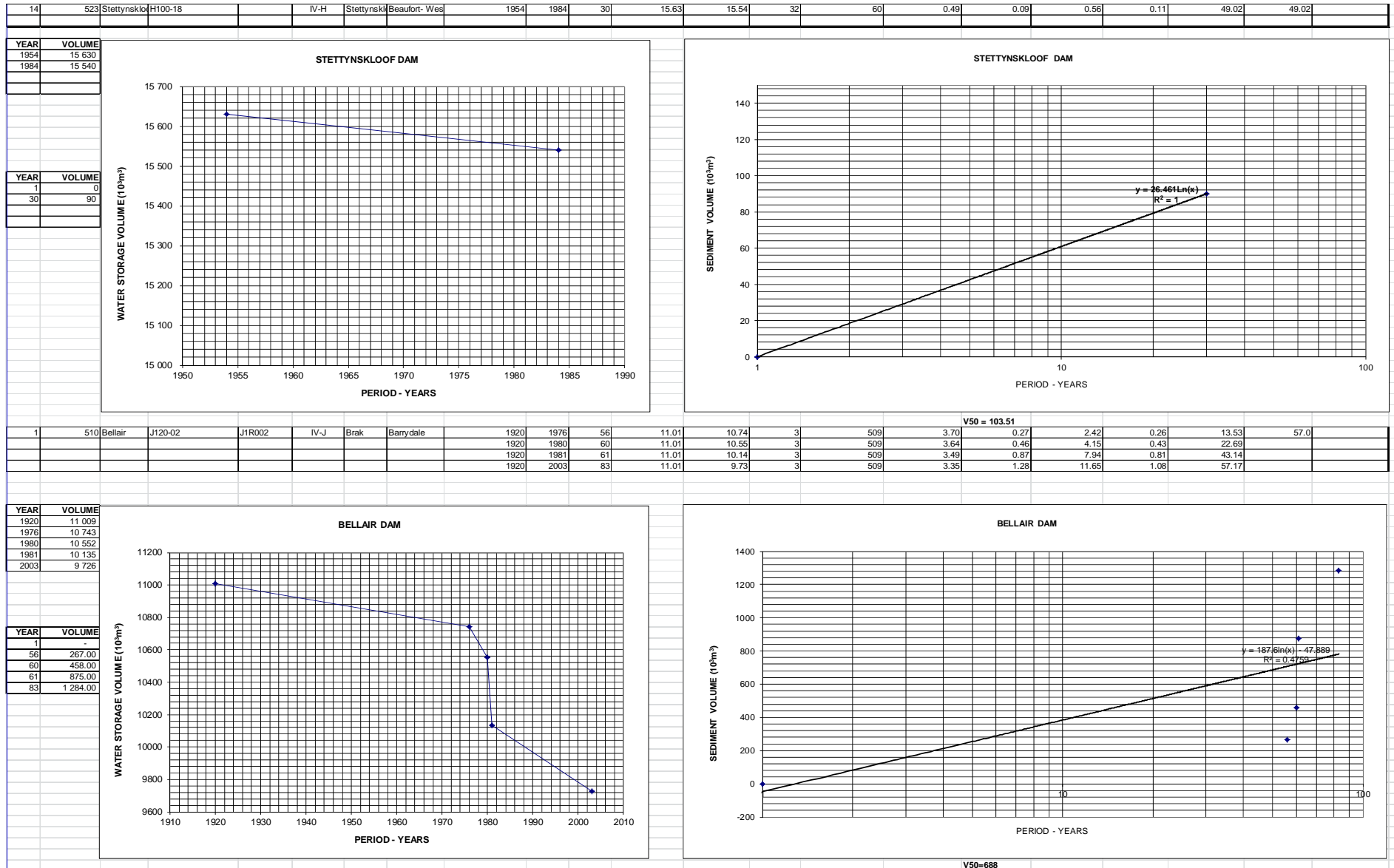
YEAR	VOLUME
1968	8 110
1983	7 740



YEAR	VOLUME
1	0
15	370

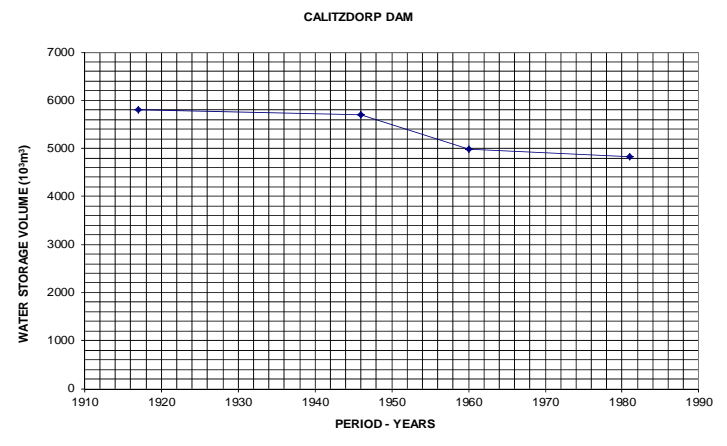


V50 = 534.49

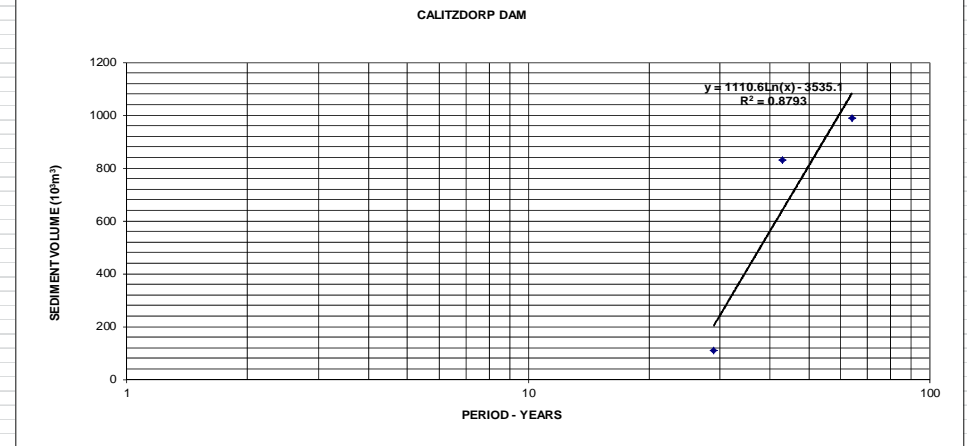


2	498	Calitzdorp	J250-02	J2R001	IV-J	Nels	Calitzdorp	1917	1946	29	5.81	5.70	8	165	0.76	0.11	1.96	0.14	23.46	149.5	Longer period
								1917	1960	43	5.81	4.98	8	165	0.66	0.83	14.28	0.88	144.00	149.5	
								1917	1981	64	5.81	4.82	8	165	0.64	1.00	17.17	0.91	149.45	149.5	

YEAR	VOLUME
1917	5 810
1946	5 700
1960	4 980
1981	4 820



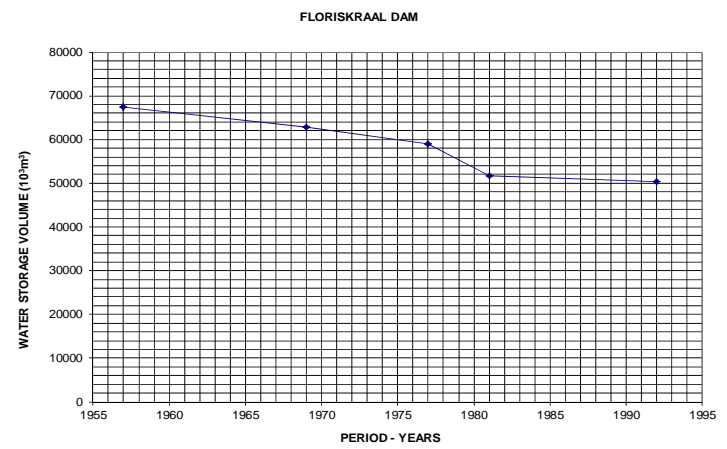
YEAR	VOLUME
1	-
29	110
43	830
64	990



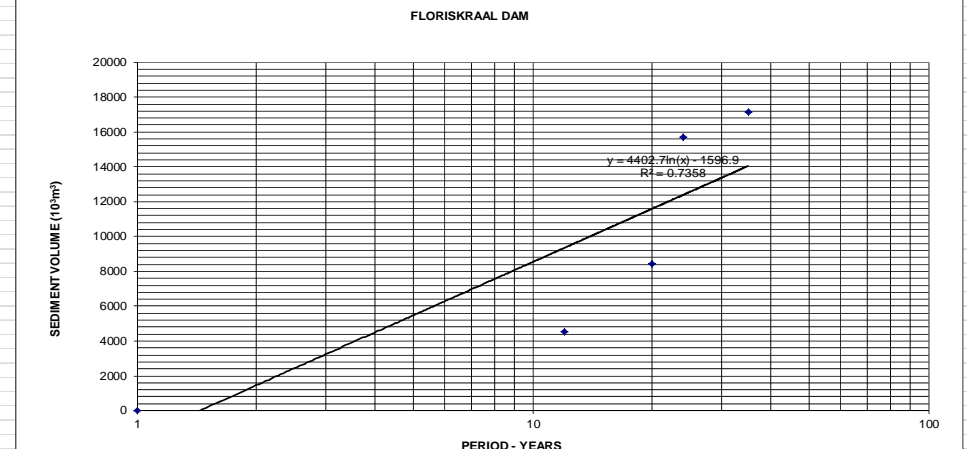
V50 = 840
V50 = 809.59 (Used period 1946 to 1981)

3	476	Floriskraal	J110-01	J1R003	IV-J	Buffels	Laingsburg	1957	1969	12	67.44	62.90	30	4029	2.10	4.54	6.73	9.79	65.63	
								1957	1977	20	67.44	59.02	30	4029	1.97	8.41	12.48	12.84	86.03	
								1957	1981	24	67.44	51.76	30	4029	1.73	15.68	23.25	21.66	145.14	145.0
								1957	1992	35	67.44	50.29	30	4029	1.68	17.15	25.43	19.81	132.74	
													4029							

YEAR	VOLUME
1957	67 440
1969	62 900
1977	59 020
1981	51 760
1992	50 290



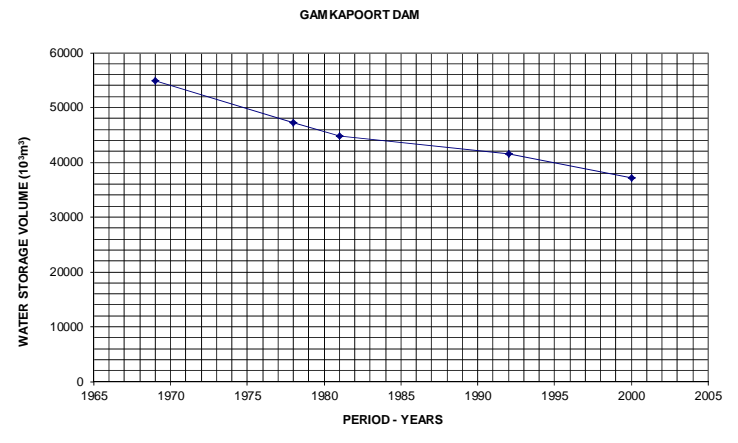
YEAR	VOLUME
1	-
12	4 540
20	8 420
24	15 680
35	17 150



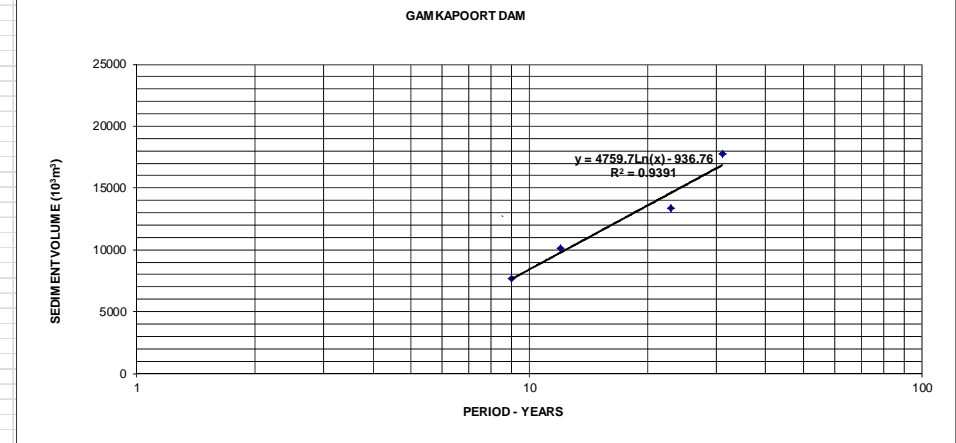
V50 = 15,620

5	477	Gamkaapoort	J250-01	J2R006	IV-J	Gamka	Prince Albert	1969	1978	9	54.94	47.29	193	14535	0.25	7.64	13.91	21.52	39.97	40.14
								1969	1981	12	54.94	44.80	193	14535	0.23	10.14	18.46	21.89	40.66	40.14
								1969	1992	23	54.94	41.59	193	14535	0.22	13.35	24.30	18.85	35.02	40.14
								1969	2000	31	54.94	37.21	193	14535	0.19	17.72	32.26	21.61	40.14	40.14

YEAR	VOLUME
1969	54 940
1978	47 290
1981	44 800
1992	41 590
2000	37 210



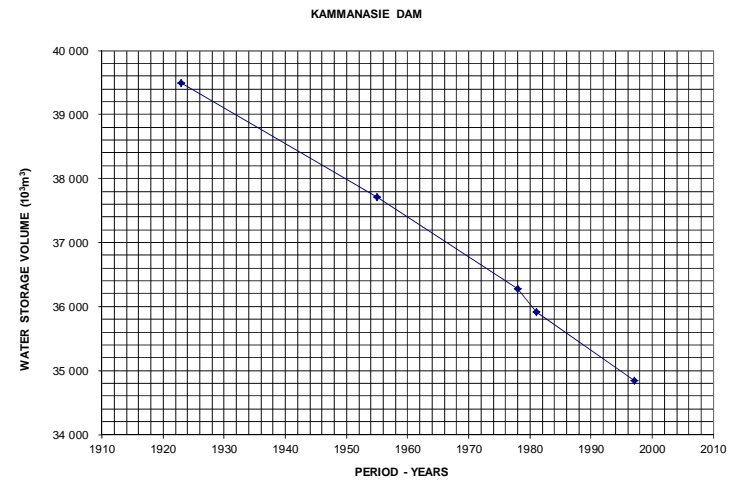
YEAR	VOLUME
1	-
9	7 650
12	10 140
23	13 350
31	17 730



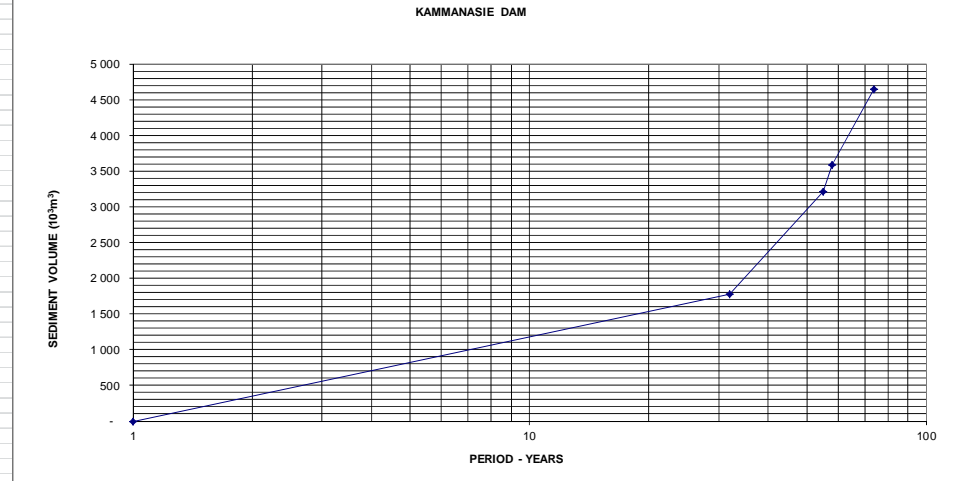
V50 = 17,680.56

6	504	Kammanasie	J340-02	J3R001	IV-J	Kammanasie	Oudtshoorn	1923	1955	32	39.49	37.71	52	1527	0.73	1.78	4.50	2.14	37.80	
								1923	1978	55	39.49	36.28	52	1527	0.70	3.22	8.15	3.11	54.94	53
								1923	1981	58	39.49	35.91	52	1527	0.69	3.58	9.08	3.39	60.03	
								1923	1997	74	39.49	34.84	52	1527	0.67	4.66	11.79	4.06	71.74	

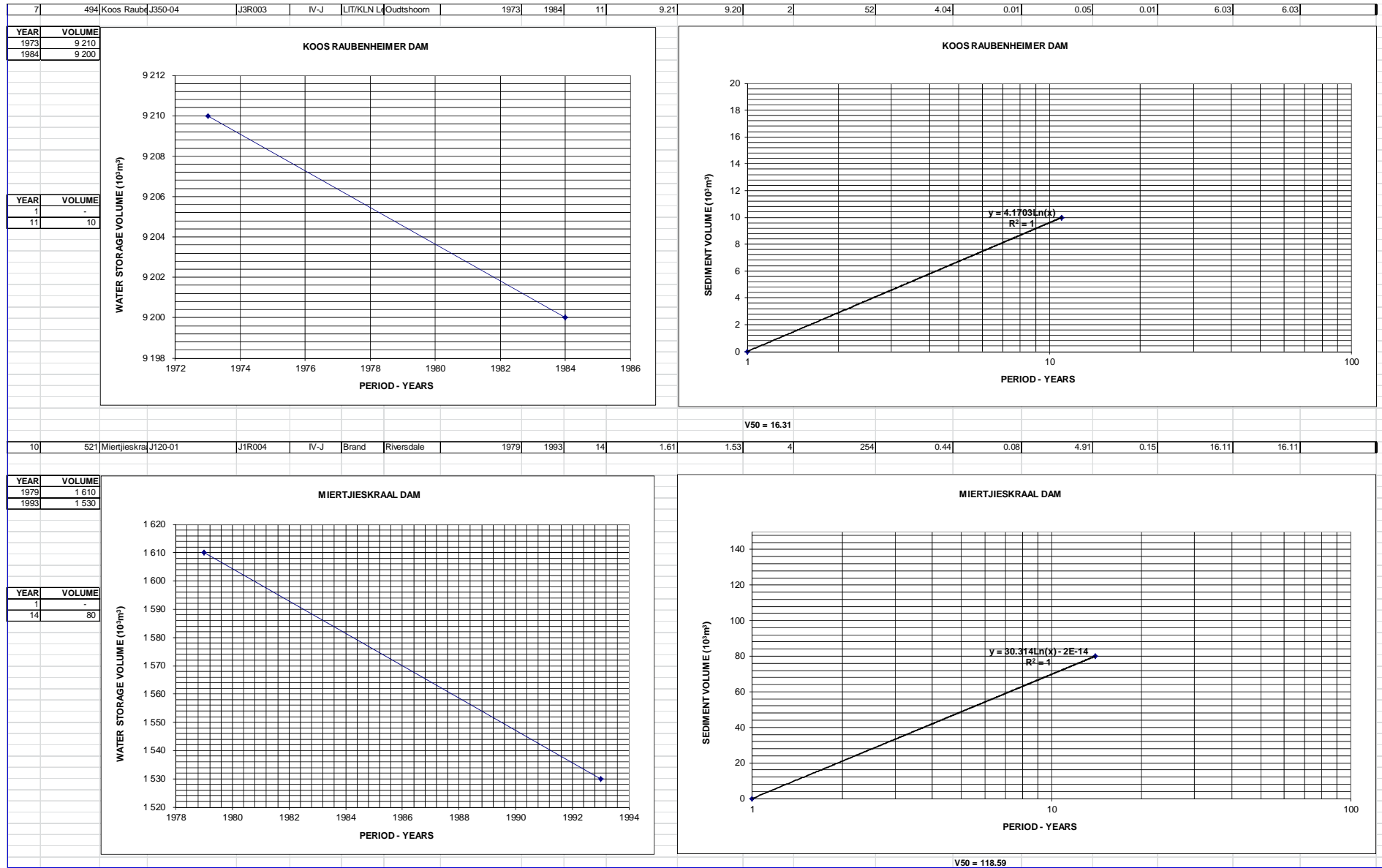
YEAR	VOLUME
1923	39 490
1955	37 710
1978	36 280
1981	35 910
1997	34 840



YEAR	VOLUME
1	-
32	1 780
55	3 210
58	3 580
74	4 650

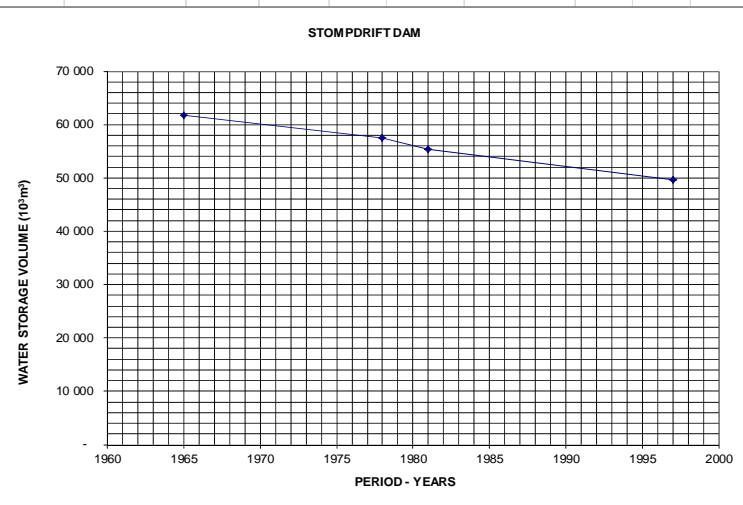


V50 = 3000 (FROM GRAPH)

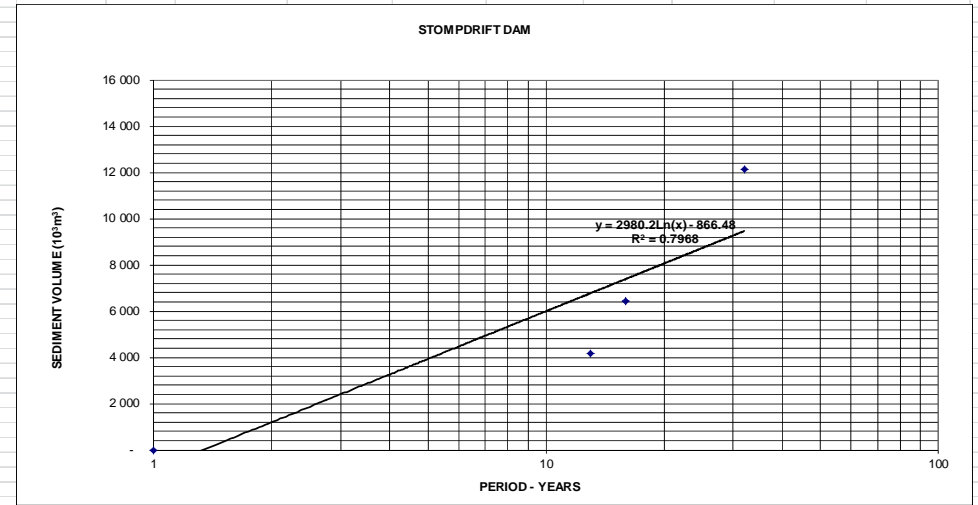


13	499	Stompdrift	J330-01	J3R002	IV-J	Olifants	De Rust	1965	1978	13	61.73	57.55	38	5249	1.51	4.18	6.78	8.48	43.61	75
								1965	1981	16	61.73	55.29	38	5249	1.45	6.44	10.43	11.26	57.94	
								1965	1997	32	61.73	49.58	38	5249	1.30	12.15	19.69	14.60	75.12	

YEAR	VOLUME
1965	61 730
1978	57 550
1981	55 290
1997	49 580

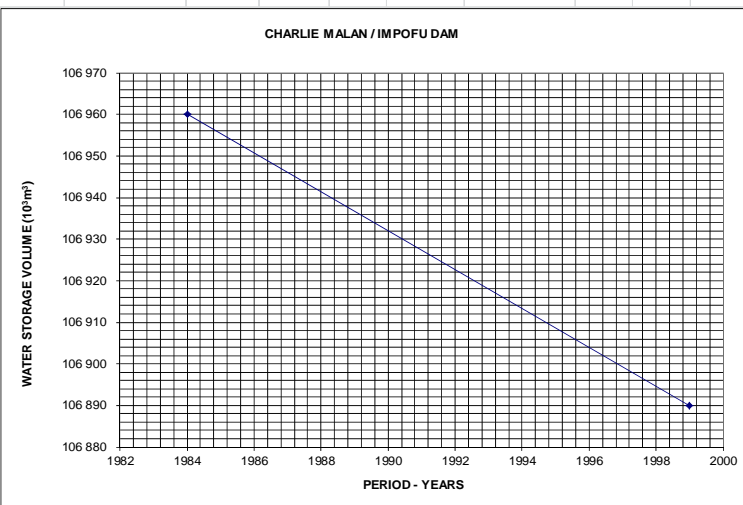


YEAR	VOLUME
1	-
13	4 180
16	6 440
32	12 150

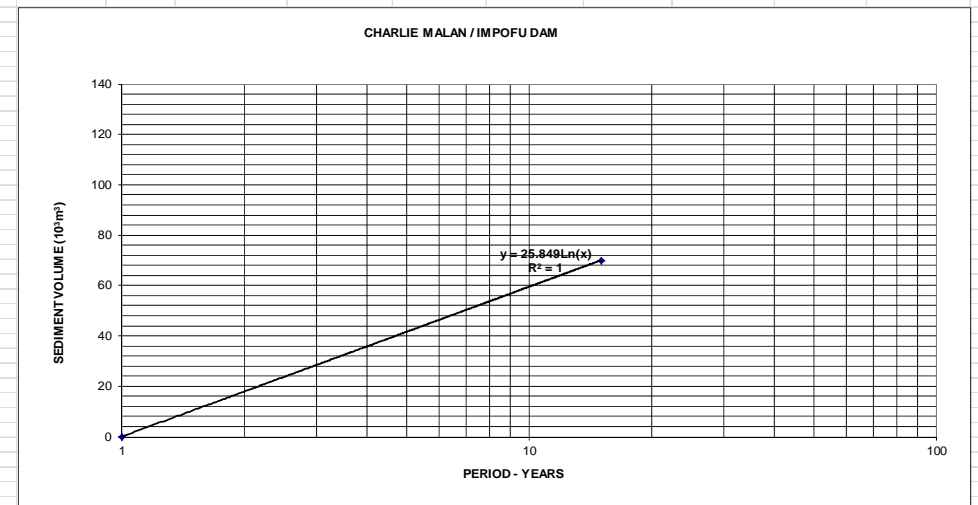


1	566	Charlie Mal	K900-02	K9R002	IV-K	Krom	Humansdorp	1984	1999	15	106.96	106.89	72	871	1.49	0.07	0.07	0.13	4.02	7.0
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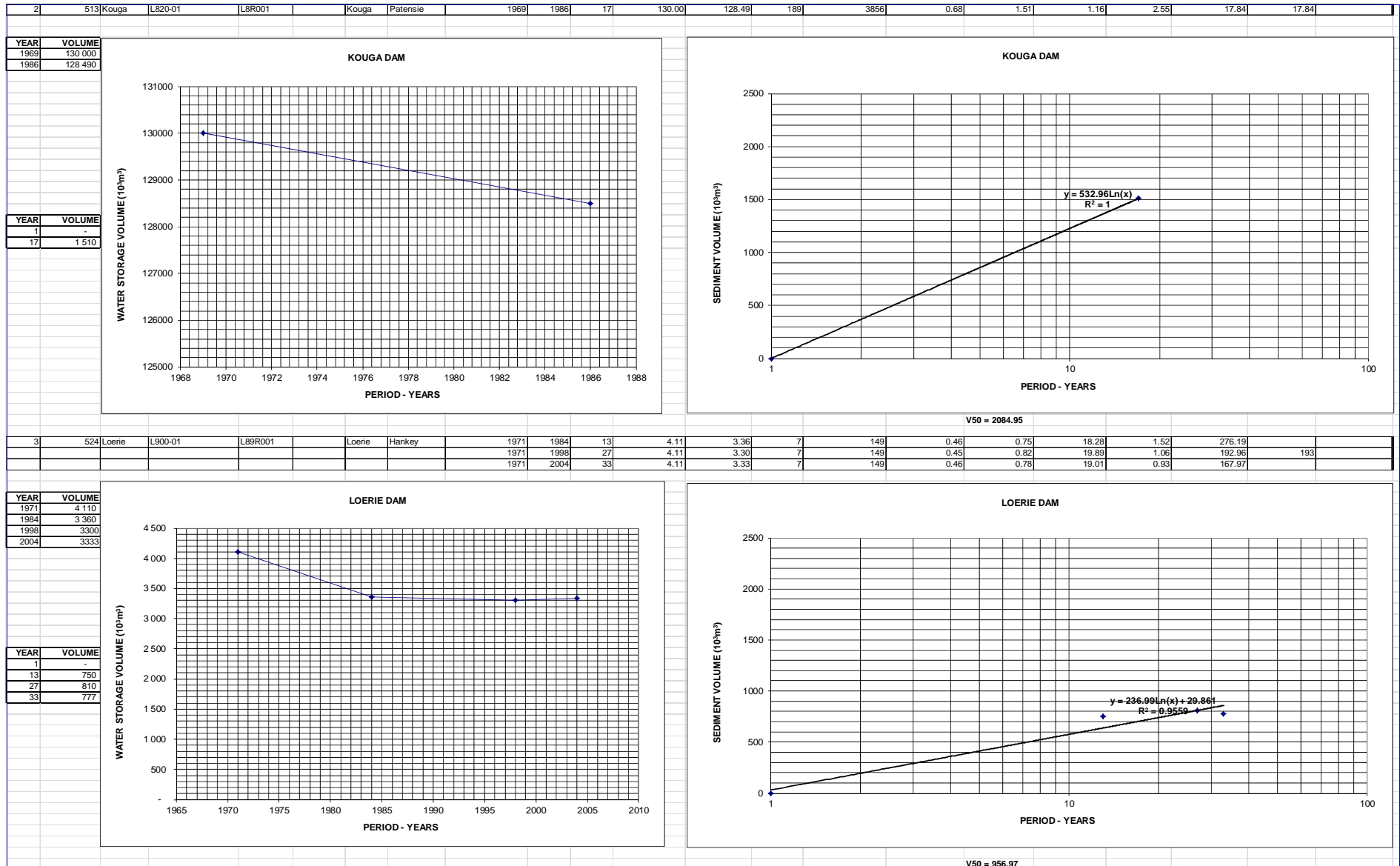
YEAR	VOLUME
1984	106 960
1999	106 890



YEAR	VOLUME
1	-
15	70

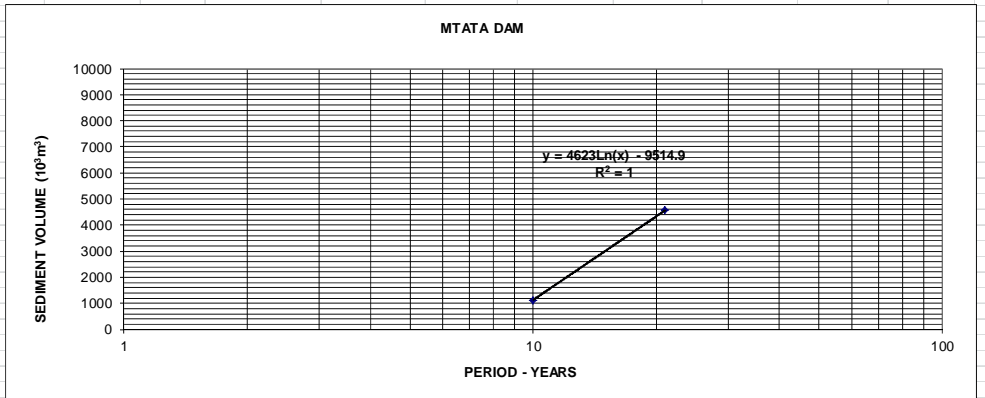
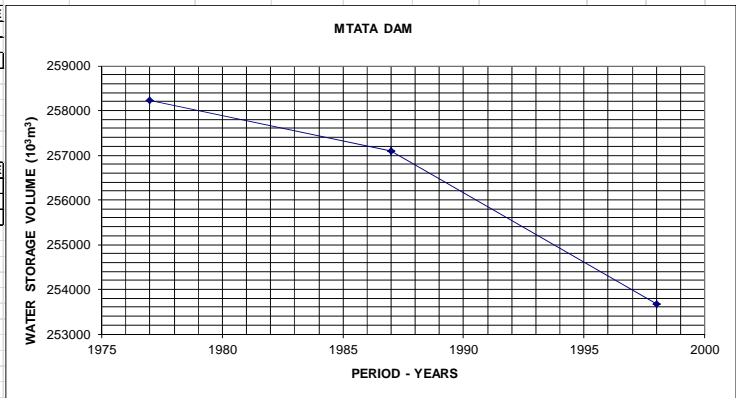


V50 = 101.09



MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number - WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (km ²)	TRAP EFFICIENCY INDICATOR (Vw/MAR)	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)	REMARKS
2	384	Mtata	T200-03	T2R001	V - T	Mtata	Umtata	1977	1987	10	258.23	257.10	218	882	1.18	1.13	0.44	2.86	87.48	262.0	
								1977	1998	21	258.23	253.67	218	882	1.16	4.55	1.76	6.76	206.79	262.0	

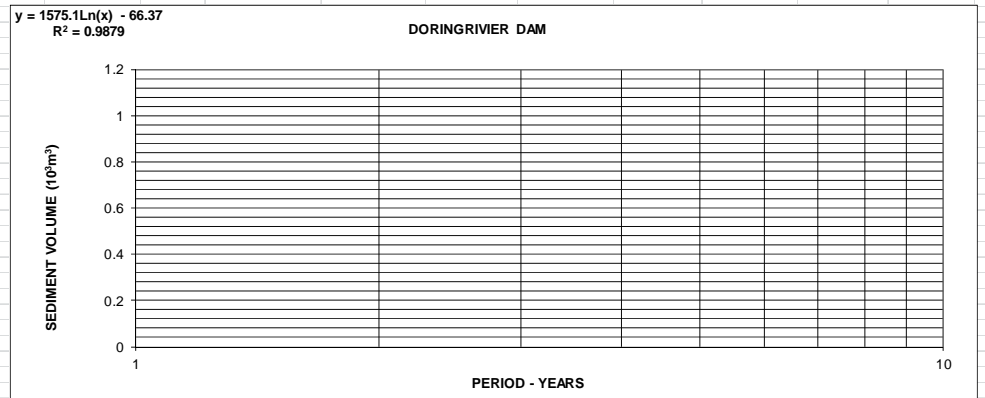
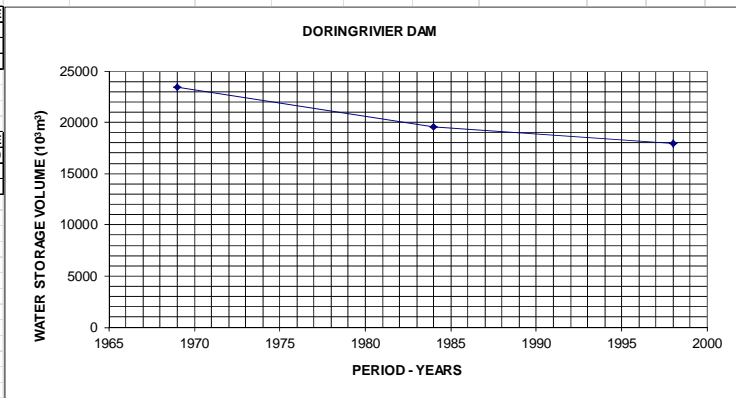
YEAR	VOLUME
1977	258 230
1987	257 100
1998	253 670



V50 = 8,570.38 (Used period from 1987 to 1998)

2	391	Doringrivier	S2R002	S200-01	V - S	Doring	Indwe	1969	1984	15	23.44	19.58	11	309	1.72	3.86	19.73	7.06	616.87	617.00
								1969	1998	29	23.44	17.93	11	309	1.57	5.51	30.73	6.93	605.56	617.00

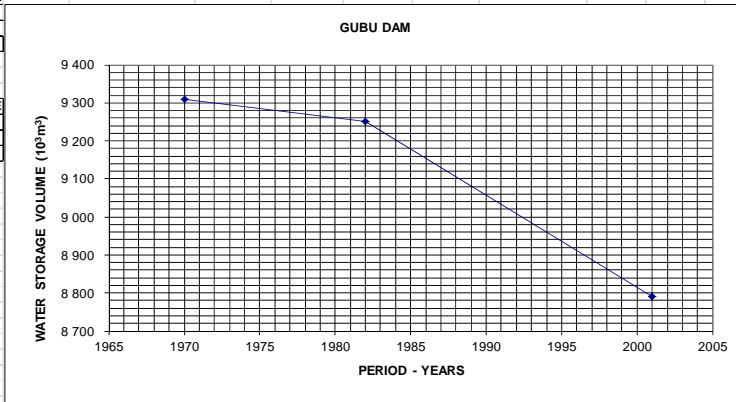
YEAR	VOLUME
1969	23 440
1984	19 580
1998	17 930



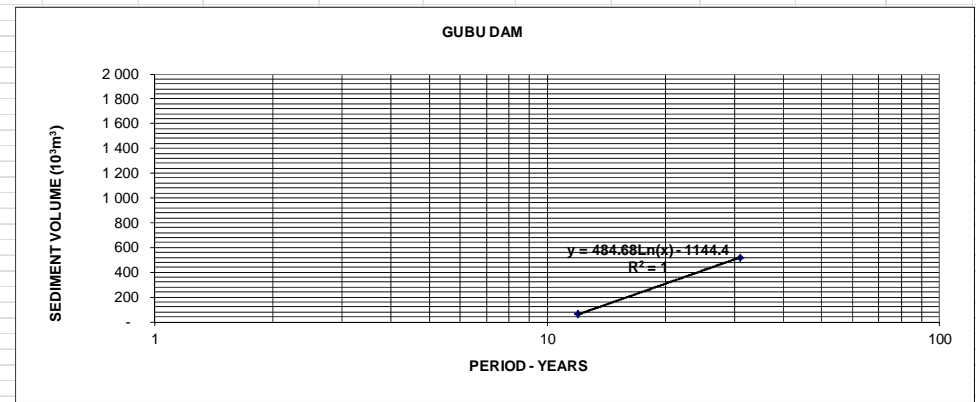
V50 = 6095.45

3	436	Gubu	S6R001	S600-04	V - S	Gubu	Stutterheim	1970	1982	12	9.31	9.25	4	23	2.57	0.06	0.64	0.13	149.50	840.00
								1970	2001	31	9.31	8.79	4	23	2.44	0.53	5.99	0.64	752.89	840.00

YEAR	VOLUME
1970	9 310
1982	9 250
2001	8 790



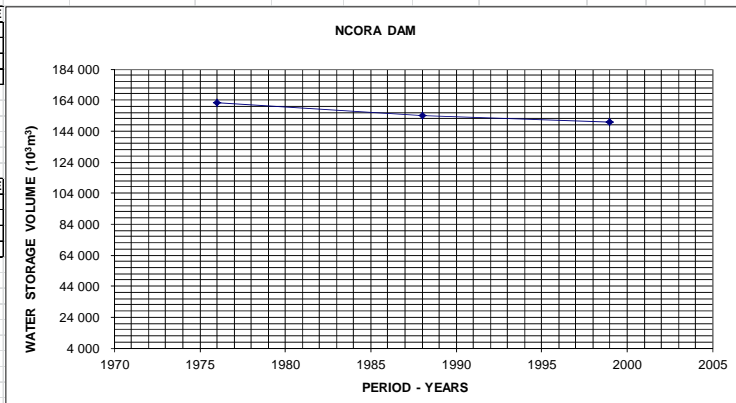
YEAR	VOLUME
1	-
12	60
31	520



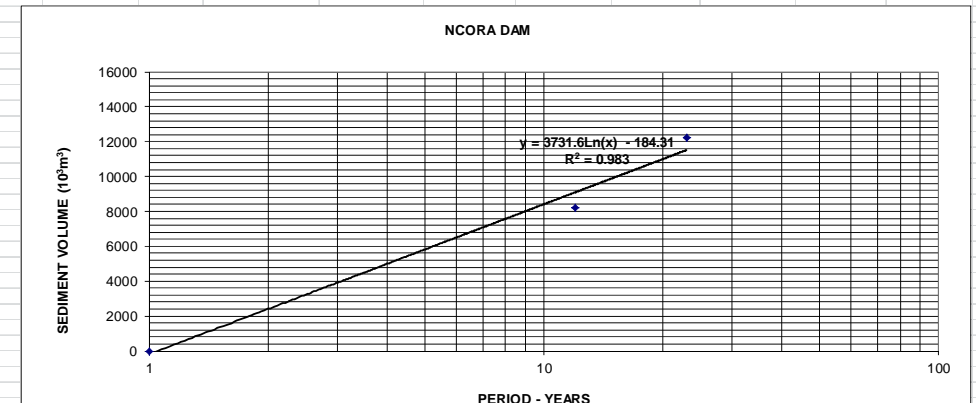
V50 = 751.6 (Used period 1982 to 2001)

6	397	Ncora	S5R001	S500-01	V - S	Tsomo	Cala	1976	1988	12	162.31	154.11	178	1775	0.87	8.19	5.32	17.68	269.00	219.00
								1976	1999	23	162.31	150.09	178	1775	0.84	12.21	8.14	17.25	262.45	219.00

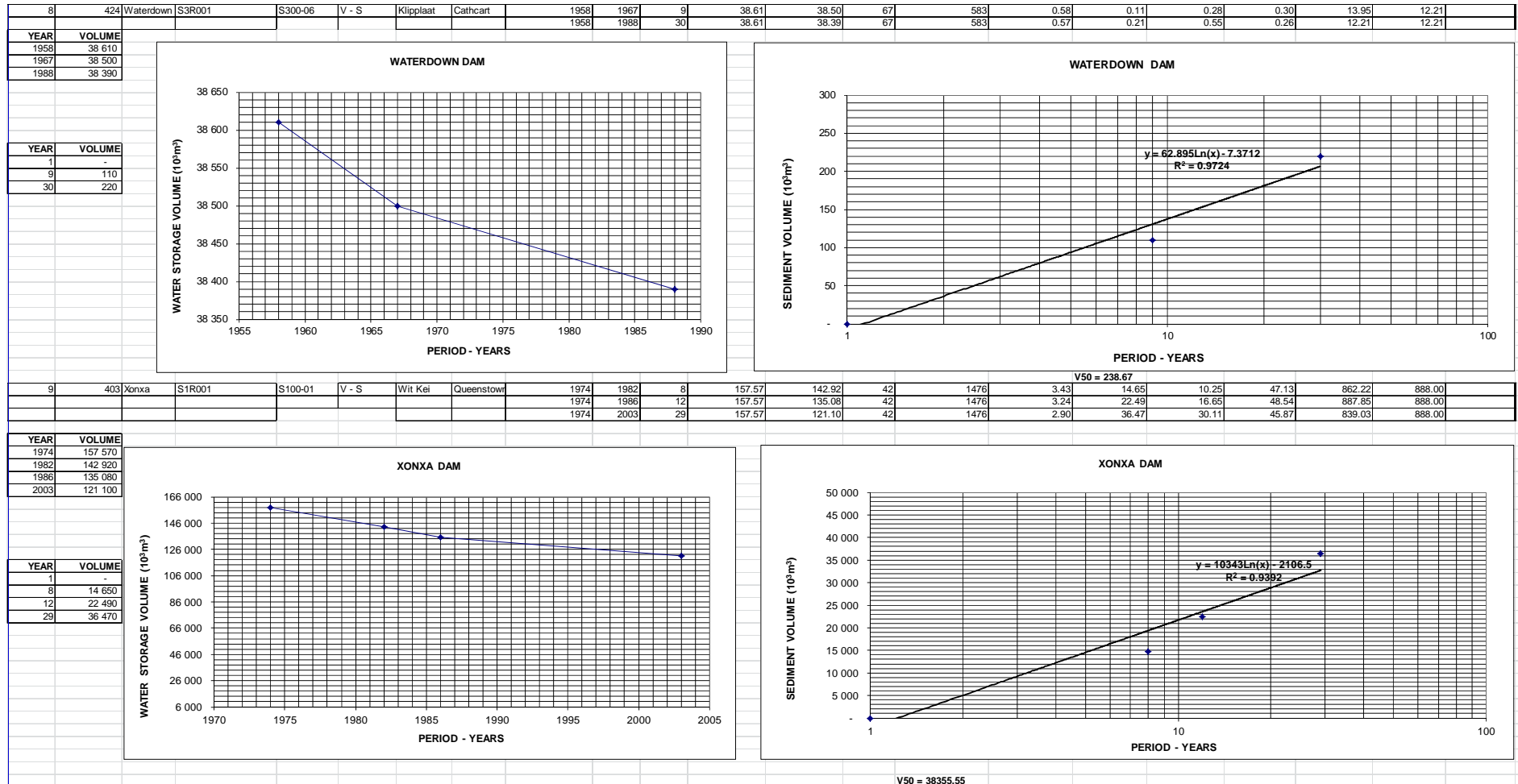
YEAR	VOLUME
1976	162 310
1988	154 110
1999	150 090

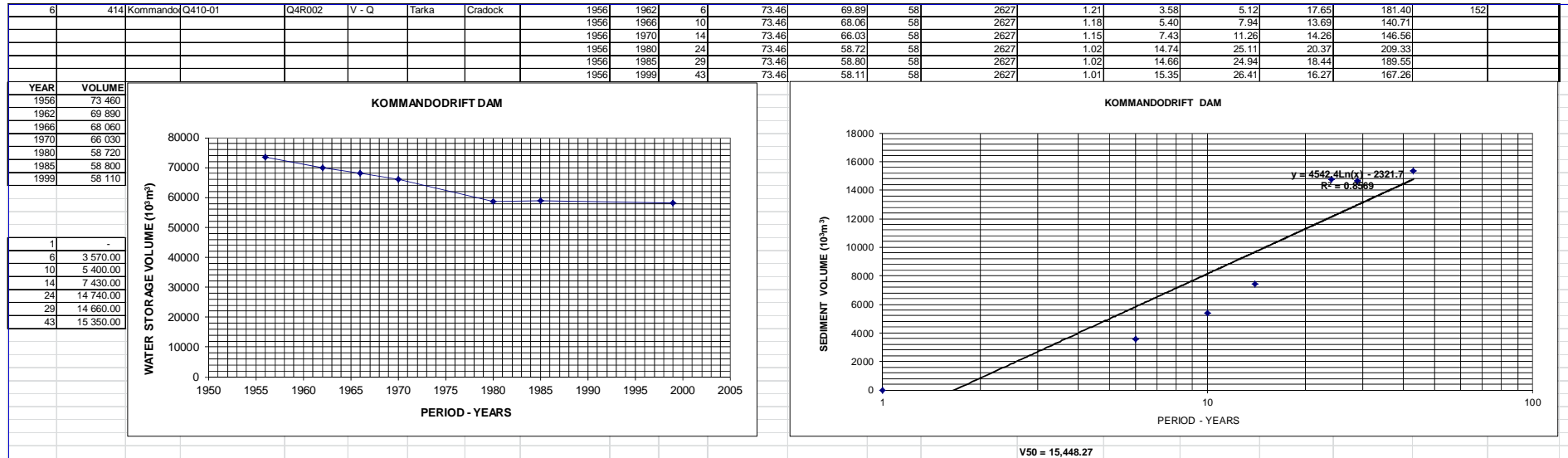


YEAR	VOLUME
1	-
12	8 200
23	12 220



V50 = 14413.79

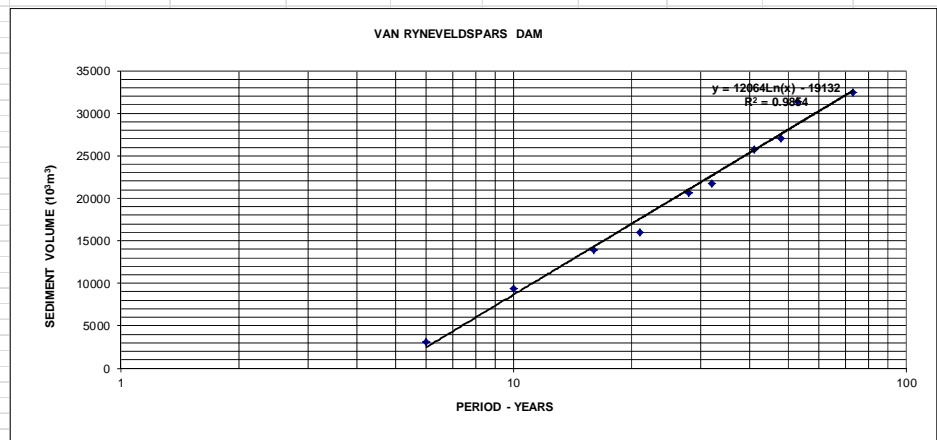
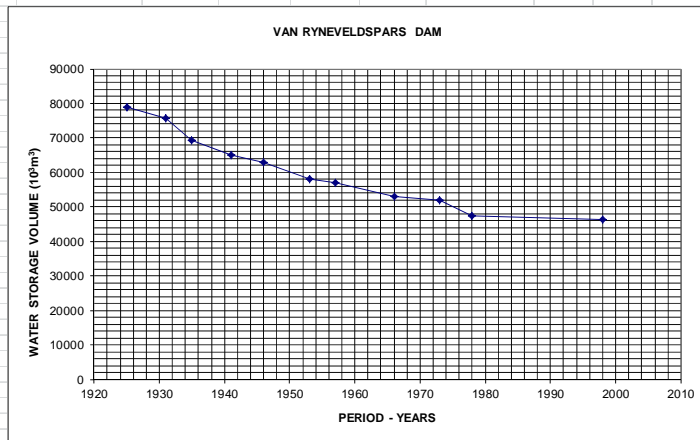




4	420	Van Ryneveld	N120-01	N1R001	V - N	Sondags	Graaff -Rein	1925	1931	6	78.82	75.70	-	3666	-	3.12	4.13	15.41	113.49	207
								1925	1935	10	78.82	69.40	-	3666	-	9.42	13.58	23.87	175.82	
								1925	1941	16	78.82	64.90	-	3666	-	13.92	21.45	24.36	179.44	
								1925	1946	21	78.82	62.80	-	3666	-	16.02	25.51	23.78	175.17	
								1925	1953	28	78.82	58.20	-	3666	-	20.62	35.43	26.38	194.26	
								1925	1957	32	78.82	57.07	-	3666	-	21.75	38.11	26.14	192.51	
								1925	1966	41	78.82	53.06	-	3666	-	25.76	48.55	27.84	205.07	
								1925	1973	48	78.82	51.83	-	3666	-	27.00	52.09	27.42	201.95	
								1925	1978	53	78.82	47.43	-	3666	-	31.40	66.20	30.73	226.31	
								1925	1998	73	78.82	46.37	-	3666	-	32.45	69.99	28.41	209.27	

YEAR	VOLUME
1925	78 820
1931	75 700
1935	69 400
1941	64 900
1946	62 800
1953	58 200
1957	57 070
1966	53 060
1973	51 830
1978	47 430
1998	46 370

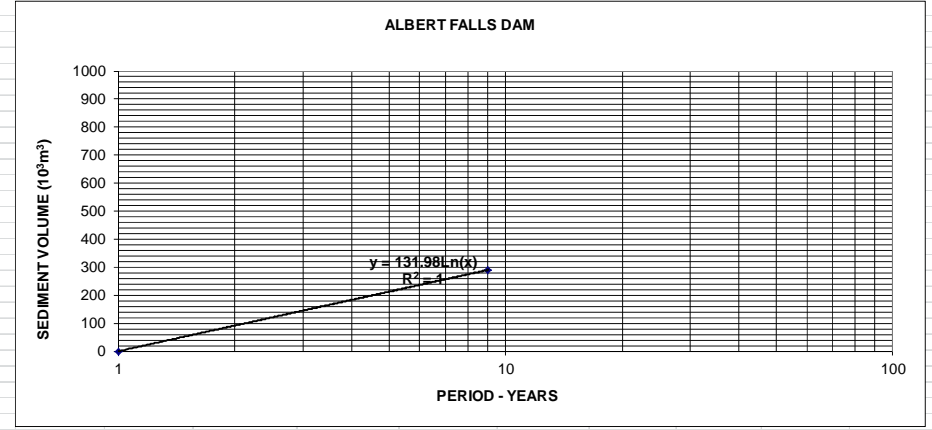
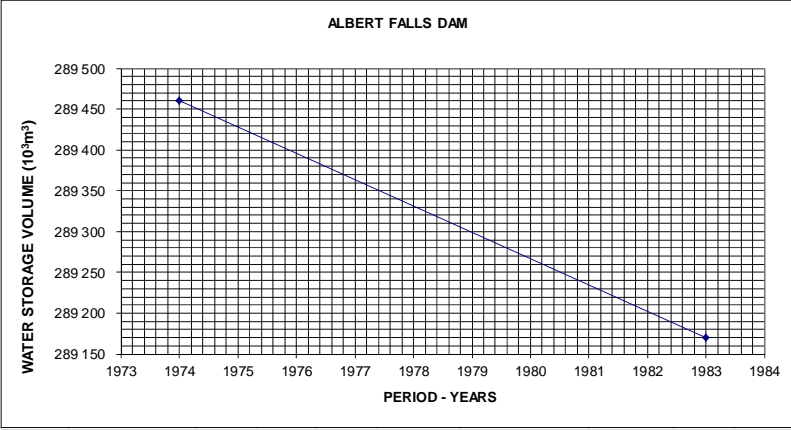
1	-
6	3 120
10	9 420
16	13 920
21	16 020
28	20 620
32	21 750
41	25 760
48	26 990
53	31 390
73	32 450



V50 = 28,062.64 (Used period from 1931 to 1998)

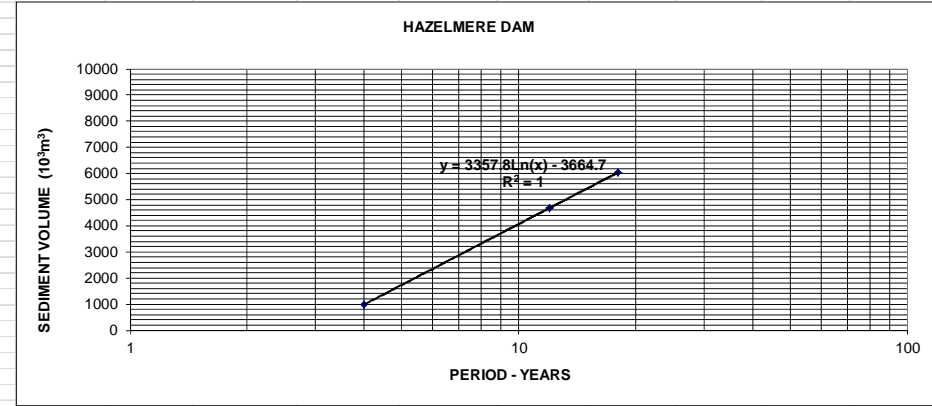
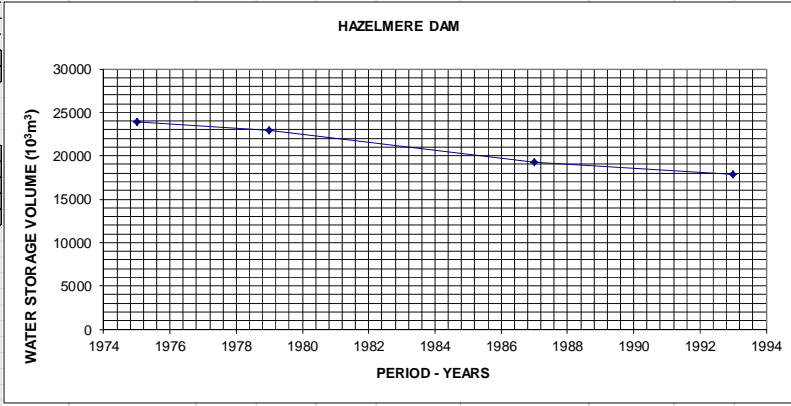
MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number - WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (Km ²)	TRAP EFFICIENCY INDICATOR (Vw/MAR)	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)	REMARKS
1	308	Albert Falls	U200-01	U2R003	6 - U	Mgeni	New Hanover	1974	1983	9	289.46	289.17	360	731	0.80	0.30	0.10	0.83	30.79	30.79	

YEAR	VOLUME
1974	289 460
1983	289 170



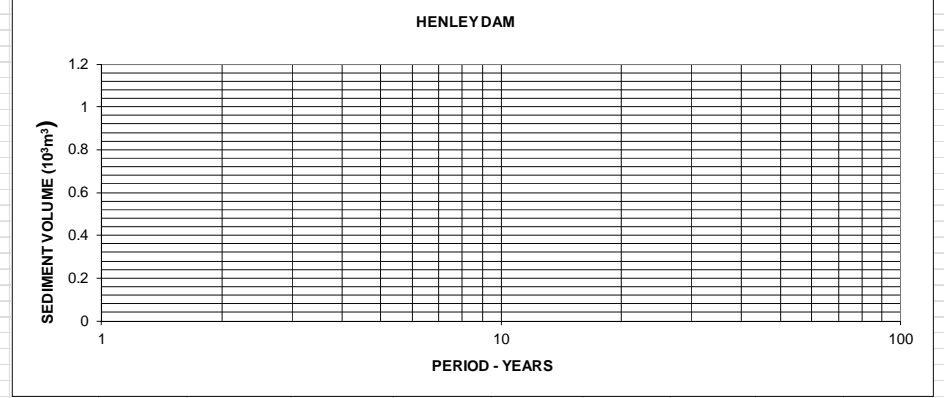
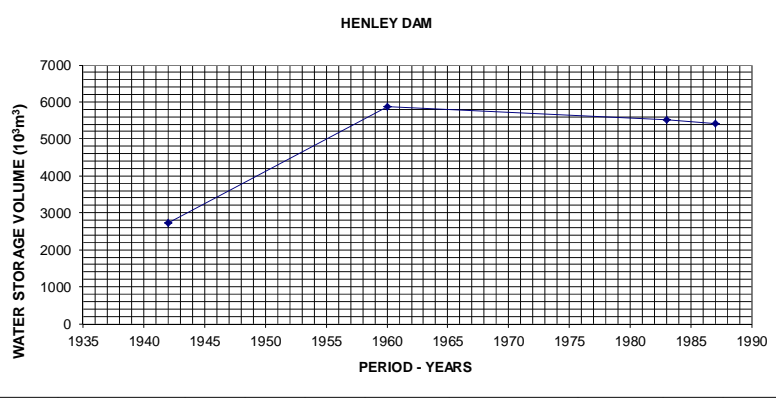
2	314	Hazelmere	U300-01	U3R001	6 - U	Mdloti	Verulam	1975	1979	4	23.90	22.91	66	382	0.35	0.99	4.30	19.64	1388.05	714	
								1975	1987	12	23.90	19.22	66	382	0.29	4.68	24.34	10.10	713.69		
								1975	1993	18	23.90	17.86	66	382	0.27	6.04	33.84	9.81	693.67		

YEAR	VOLUME
1975	23 900
1979	22 310
1987	19 220
1993	17 860



3	315	Henley	U200-09	U2R005	6 - U	Msunduze	Pietermaritzburg	1942	1960	18	2.72	5.87	44	219	0.13					
								1960	1983	23	5.87	5.51	44	219	0.13	0.36	6.46	0.50	62.00	73.99
								1960	1987	27	5.87	5.41	44	219	0.12	0.46	8.53	0.60	73.99	73.99

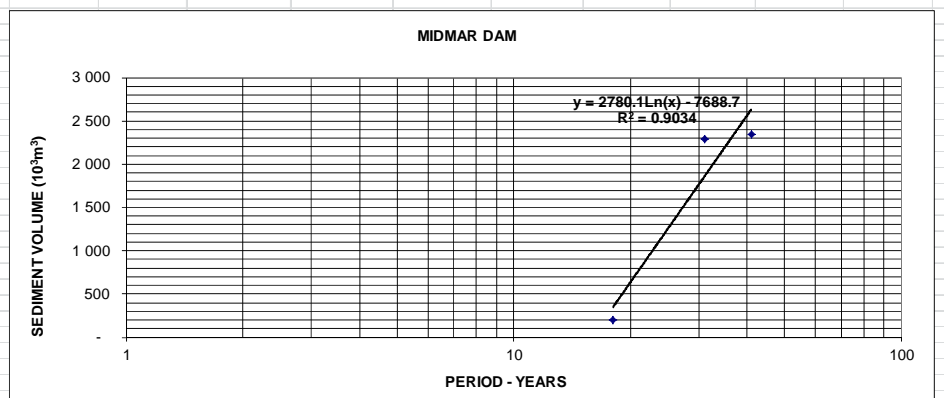
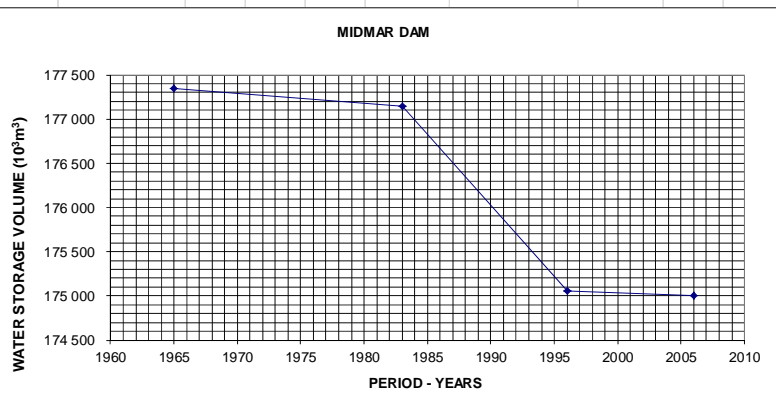
YEAR	VOLUME
1942	2 720
1960	5 870
1983	5 510
1987	5 410



YEAR	VOLUME
1	
18	
23	
27	

4	311	Midmar	U200-03	U2R001	6 - U	Mgeni	Howick	1965	1983	18	177.35	177.15	931	928	0.19	0.20	0.11	0.33	9.59	93
								1965	1996	31	177.35	175.06	931	928	0.19	2.29	1.31	2.79	81.31	
								1965	2006	41	177.35	175.00	931	928	0.19	2.35	1.34	2.54	73.83	

YEAR	VOLUME
1965	177 350
1983	177 150
1996	175 060
2006	175 000

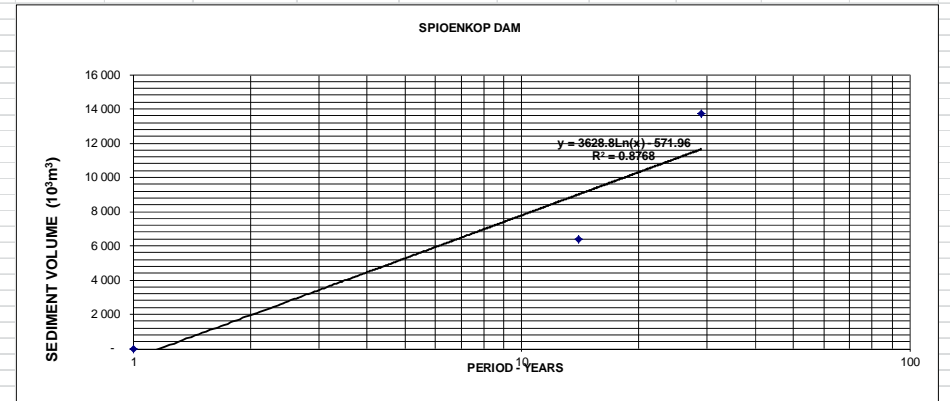
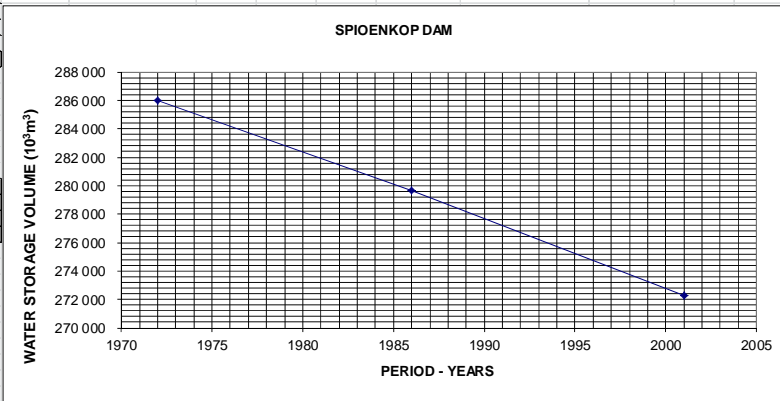


YEAR	VOLUME
1	-
18	200
31	2 290
41	2 350

V50=3,187.12 (Used period 1983 to 2006)

4	261	Spioenkop	V100-01	V1R001	6 - V	Tugela	Ladysmith	1972	1986	14	285.99	279.63	817	803	0.34	6.37	2.28	12.22	410.76	581.000
								1972	2001	29	285.99	272.27	817	803	0.33	13.73	5.04	17.27	580.64	

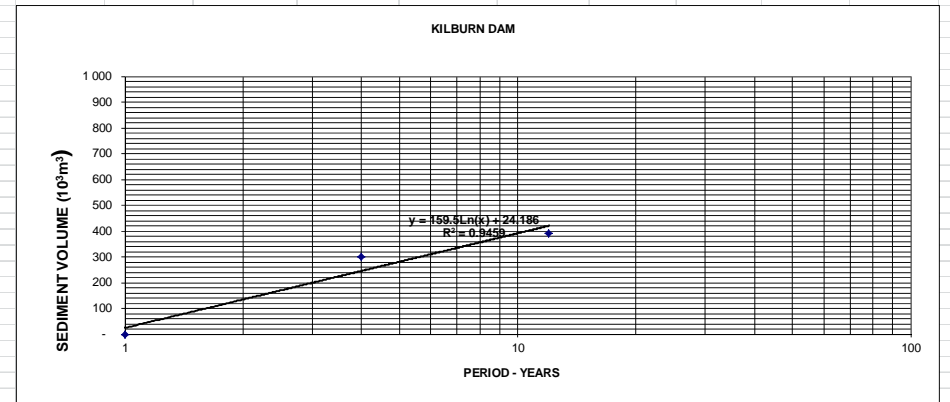
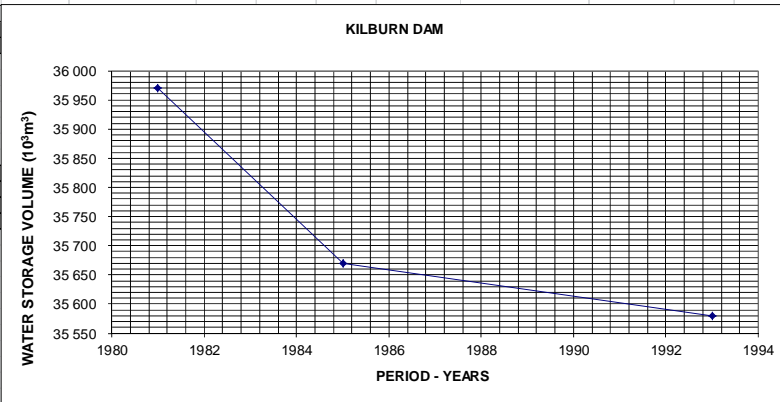
YEAR	VOLUME
1972	285 990
1986	279 630
2001	272 270



V50=13,623.99

5	257	Kilburn	V1R004	6 - V	Mnjani	Bergville	1981	1985	4	35.97	35.67	10	30	3.51	0.30	0.84	6.00	5395.58	
							1981	1993	12	35.97	35.58	10	30	3.51	0.39	1.09	0.84	755.69	755.69

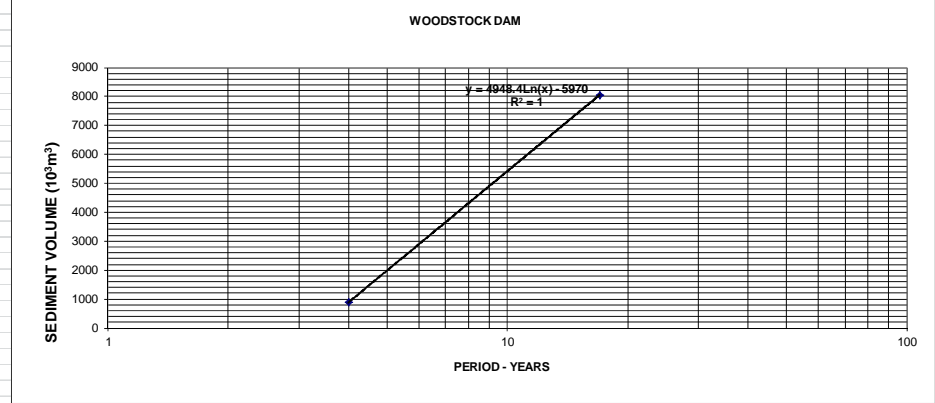
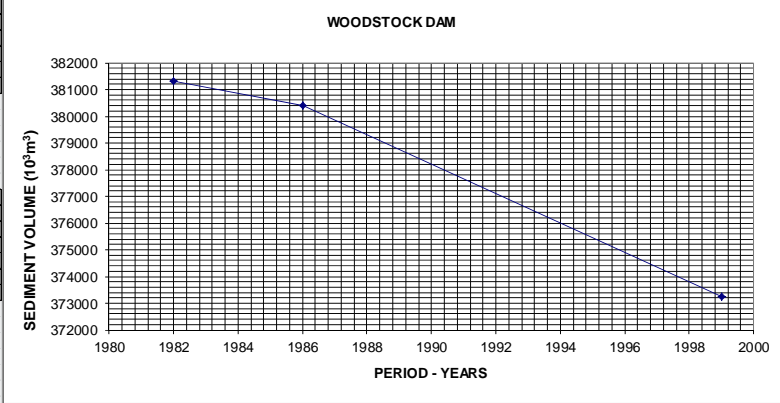
YEAR	VOLUME
1981	35 970
1985	35 670
1993	35580



V50 = 648.15

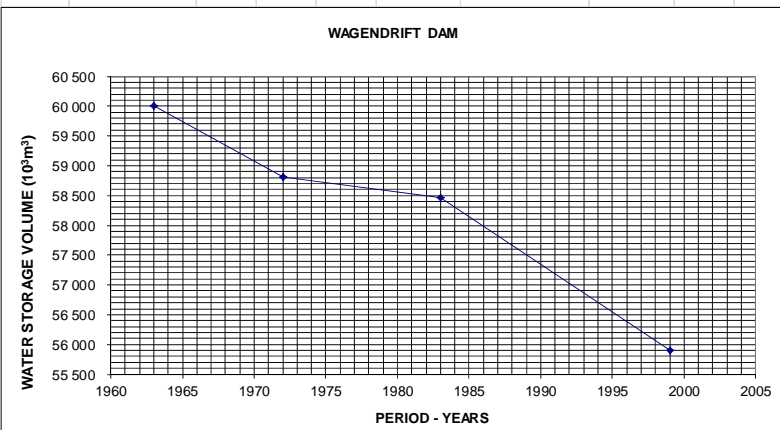
6	263	Woodstock	V100-02	V1R003	6 - V	Tugela	Bergville		1982	1986	4	381.31	380.42	10	875	37.48	0.89	0.23	17.69	545.75	318.000
									1982	1999	17	381.31	373.26	10	875	36.78	8.05	2.16	13.54	417.80	

YEAR	VOLUME
1982	381 310
1986	380 420
1999	373 260

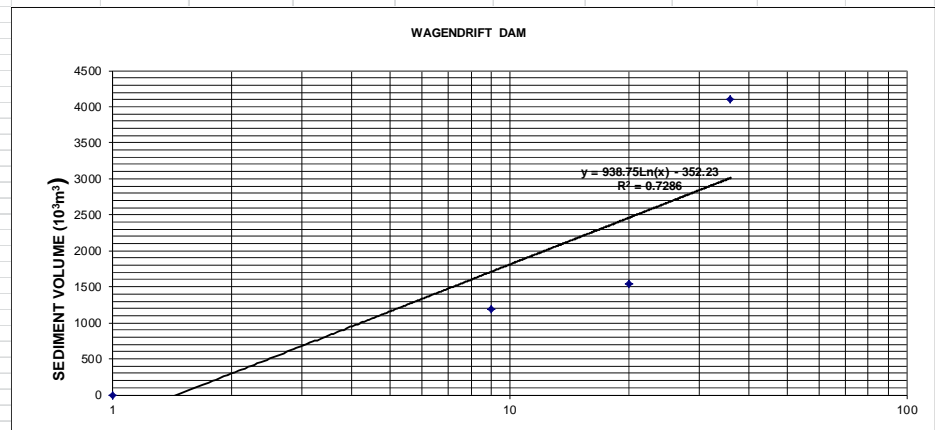


8	278	Wagendrift	V700-01	V7R001	6 - V	Boesmans	Estcourt		1963	1972	9	60.00	58.81	222	755	0.26	1.20	2.03	3.37	120.34	167.000
									1963	1983	20	60.00	58.46	222	755	0.26	1.55	2.64	2.36	84.31	
									1963	1999	36	60.00	55.90	222	755	0.25	4.10	7.34	4.68	167.35	

YEAR	VOLUME
1963	60 000
1972	58 810
1983	58 460
1999	55 900



YEAR	VOLUME
1	-
9	1 190
20	1 540
36	4 100

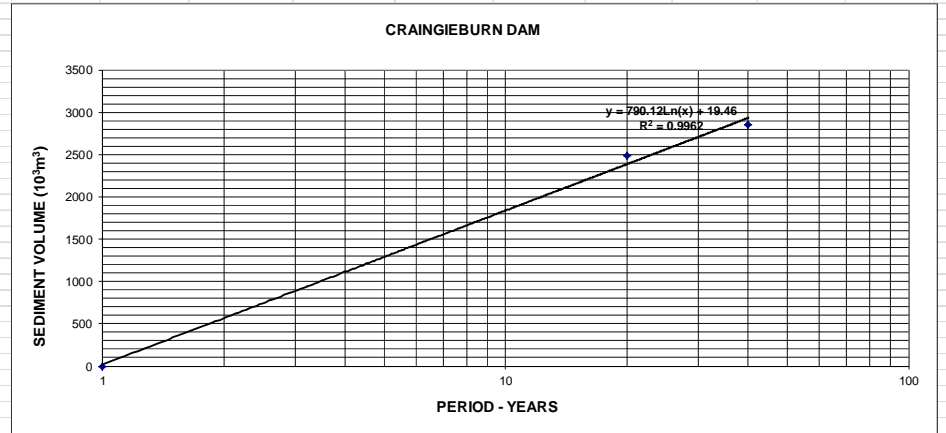
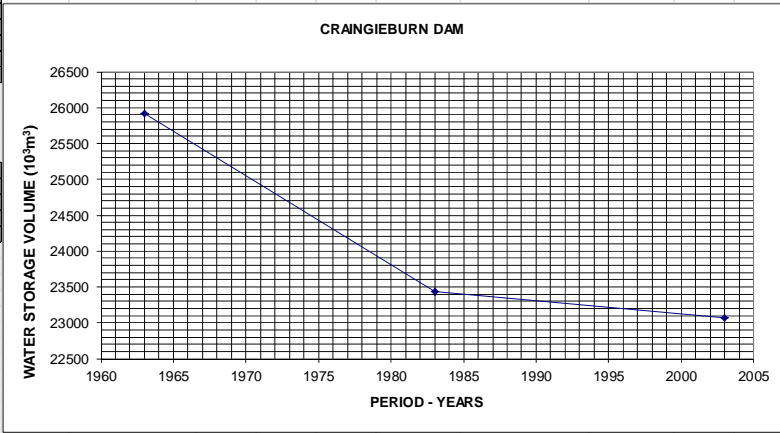


V50 = 13,388.25

V50 = 3,320.18

9	292	Craingieburn	V200-02	V2R001	6 - V	Mnyamul	Greytown	1963	1983	20	25.92	23.43	27	156	0.86	2.48	10.60	3.79	656.01	656.000
								1963	2003	40	25.92	23.07	27	156	0.85	2.85	12.35	3.11	538.14	

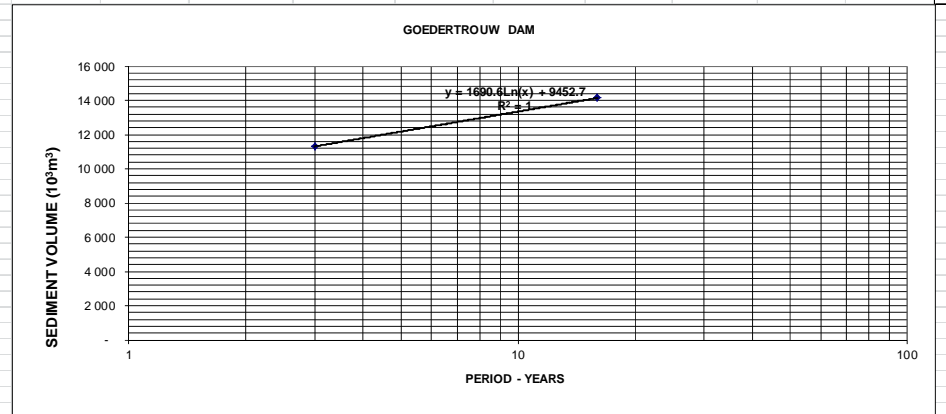
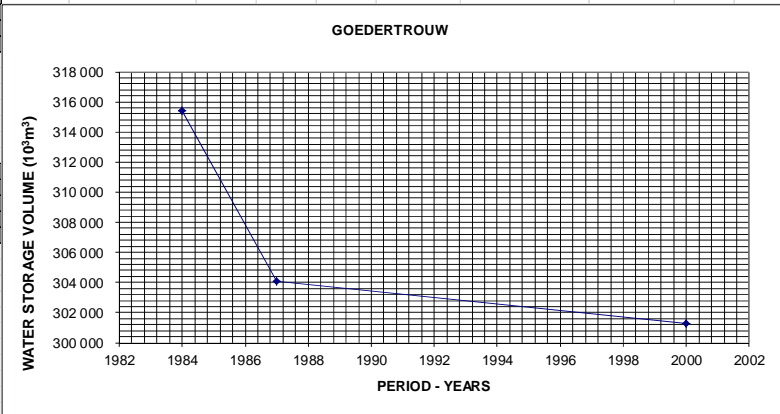
YEAR	VOLUME
1963	25 920
1983	23 430
2003	23 070



V50 = 3,110.42

1	626	Goedertrou	W1R001	W120-01	6 - W	Mhlatuze	Eshowe	1984	1987	3	315.42	304.11	133	1275	2.28	11.32	3.59			
								1984	2000	16	315.42	301.28	133	1275	2.26	14.15	4.48	24.75	524.21	524.2

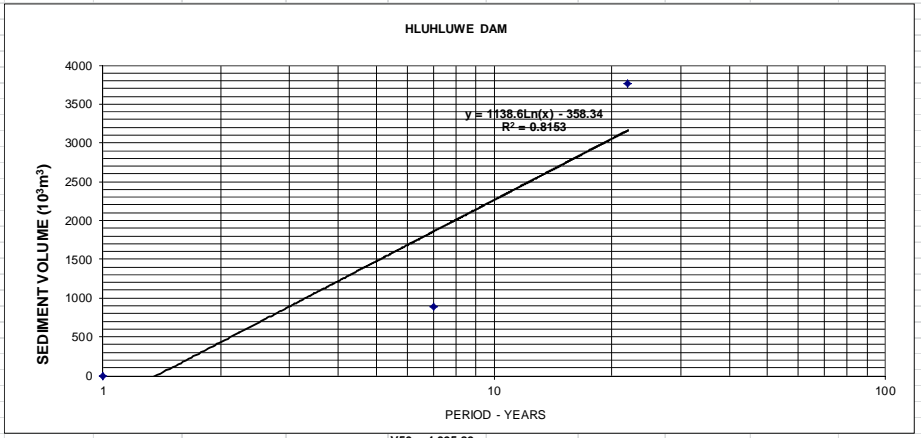
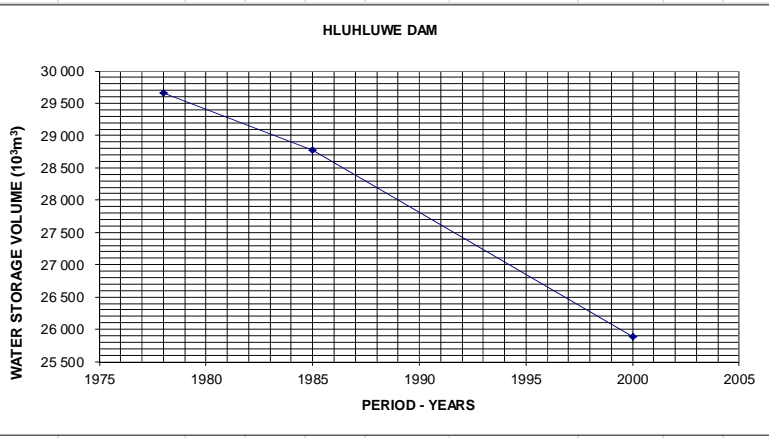
YEAR	VOLUME
1984	315 420
1987	304 110
2000	301 280



V50 = 16,066.37 (Used period 1987 to 2000)

2	242	Hluhluwe	W3R001	W300-03	6 - W	Hluhluwe	Hluhluwe	1978	1985	7	29.66	28.77	38	726	0.76	0.88	2.98	3.39	126.14	202.6
								1978	2000	22	29.66	25.89	38	726	0.68	3.77	12.70	5.45	202.63	202.6

YEAR	VOLUME
1978	29 660
1985	28 770
2000	25 890

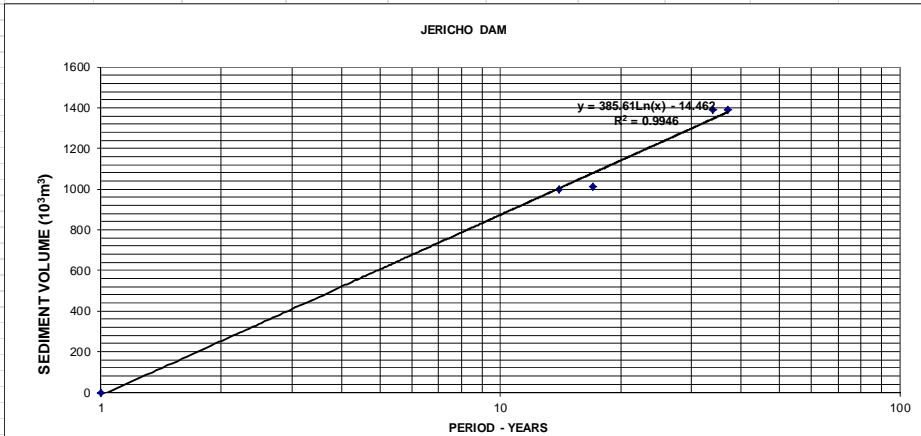
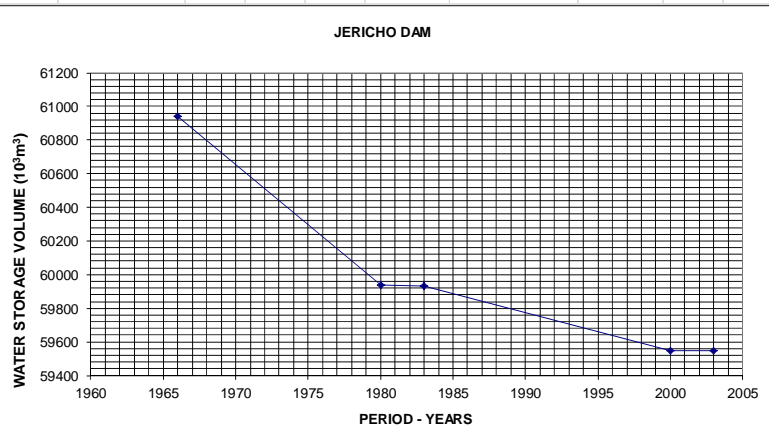


YEAR	VOLUME
1	-
7	890
22	3 770

V50 = 4,095.89

3	190	Jericho	W5R001	W530-03	6 - W	Mpama	Amsterdam	1966	1980	14	60.94	59.94	24	211	2.49	1.00	1.64	1.92	245.25	245.0
								1966	1983	17	60.94	59.93	24	211	2.49	1.01	1.66	1.70	217.70	
								1966	2000	34	60.94	59.55	24	211	2.47	1.39	2.29	1.63	208.66	
								1966	2003	37	60.94	59.55	24	211	2.47	1.39	2.29	1.57	201.18	

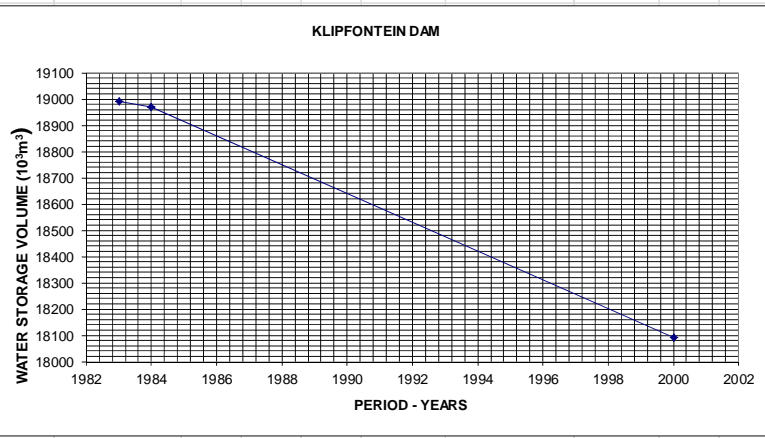
YEAR	VOLUME
1966	60 940
1980	59 940
1983	59 930
2000	59 550
2003	59 550



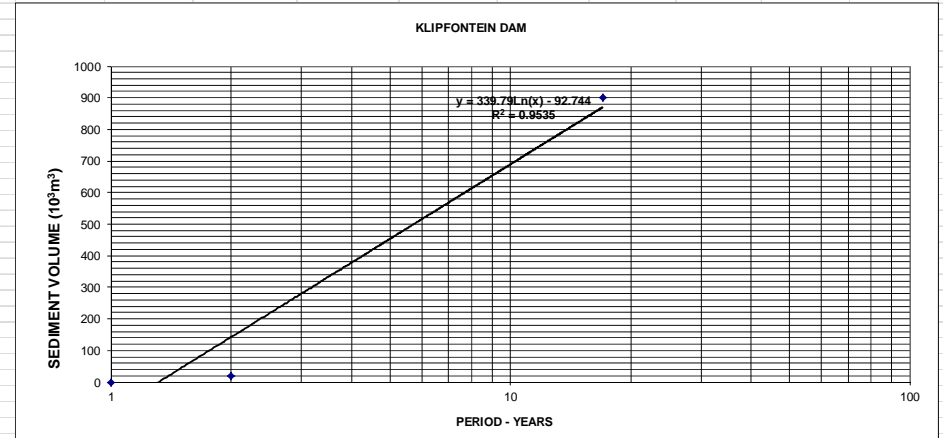
V50 = 1,494.01

4	230	Klipfontein	W2R001	W210-12	6 - W	Wit-Mlolozi Vryheid	1983	1984	1	18.99	18.97	49	281	0.39	0.02	0.12		121.0
							1983	2000	17	18.99	18.09	49	281	0.37	0.91	4.77	1.52	146.33

YEAR	VOLUME
1983	18 990
1984	18 970
2000	18 090



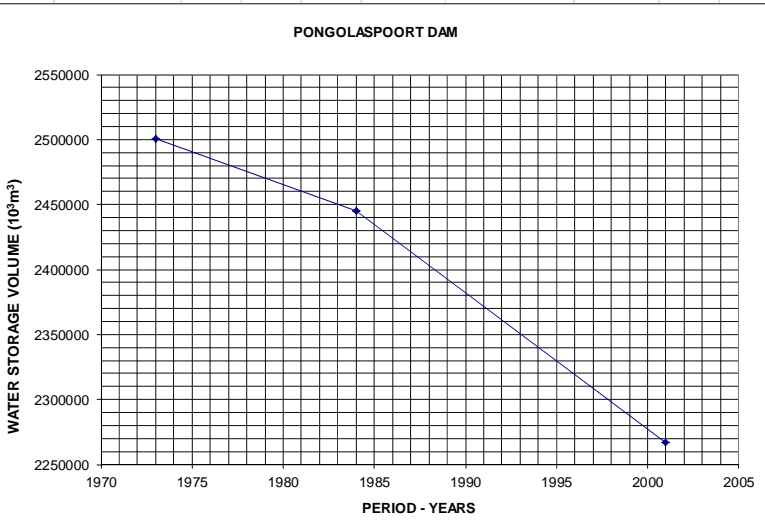
YEAR	VOLUME
1	-
2	20
17	900



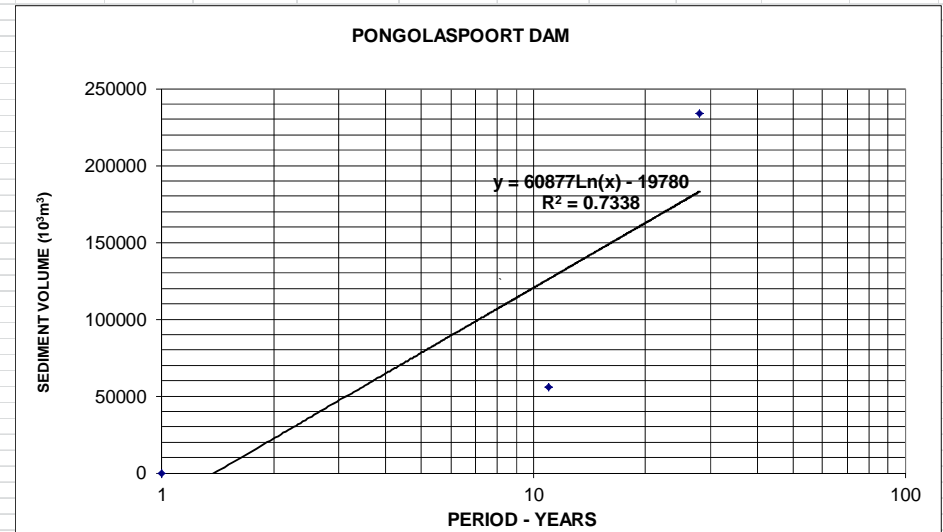
V50 = 1,236.52

9	210	Pongolaspo	W4R001	W440-01	6 - W	Phongolo Pongola	1973	1984	11	2500.91	2445.26	1136	7782	2.15	55.66	2.23	129.26	448.48	1038.0
							1973	2001	28	2500.91	2267.07	1136	7782	1.99	233.85	9.35	299.08	1037.69	

YEAR	VOLUME
1973	2 500 910
1984	2 445 260
2001	2 267 070



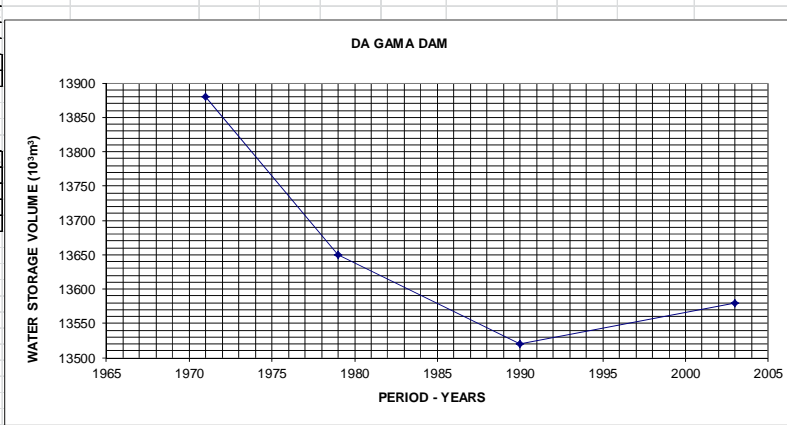
YEAR	VOLUME
1	-
11	55 650
28	233 840



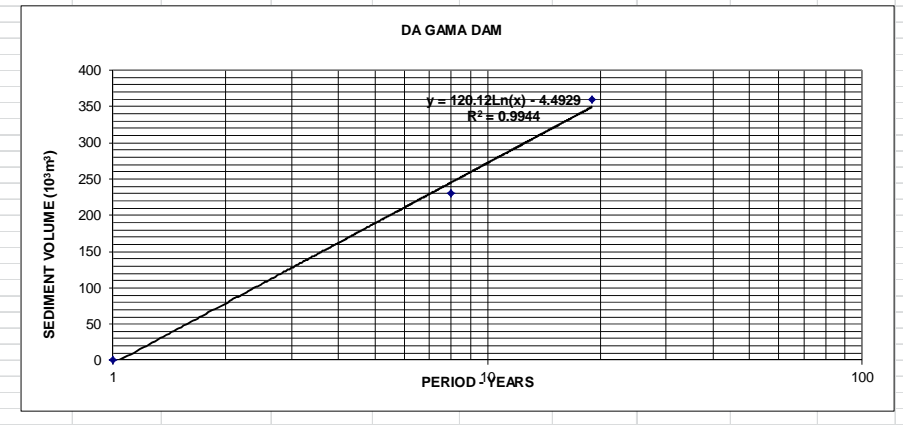
V50 = 218,372.22

MAP NO	GIS No	Dam Name	Dam Number - Dam List	Dam Number - WR90	WR 90 Region	River Name	Nearest Town	From (Year)	To (Year)	No of years	INITIAL STORAGE CAPACITY (10 ⁶ m ³)	FINAL STORAGE CAPACITY (10 ⁶ m ³)	MAR (10 ⁶ m ³)	EFFECTIVE CATCHMENT AREA (Km ²)	TRAP EFFICIENCY INDICATOR Vw/MAR	SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT STORAGE LOSS (%)	50 YEAR SEDIMENT VOLUME (10 ⁶ m ³)	SEDIMENT YIELD (t/Km ² .a)	SELECTED SEDIMENT YIELD (t/Km ² .a)	REMARKS
	3	83 Da Gama	X3R001	X300-02	6 - X	Witwaters	Witriver	1971	1979	8	13.88	13.88	13.65	18	18	60	0.77	0.23	1.71	0.75	338.77
								1971	1990	19	13.88	13.52	13.52	18	60	0.76	0.36	2.69	0.57	257.52	
								1971	2003	32	13.88	13.58	13.58	18	60	0.76	0.31	2.25	0.37	164.95	

YEAR	VOLUME
1971	13 880
1979	13 650
1990	13 520
2003	13 580



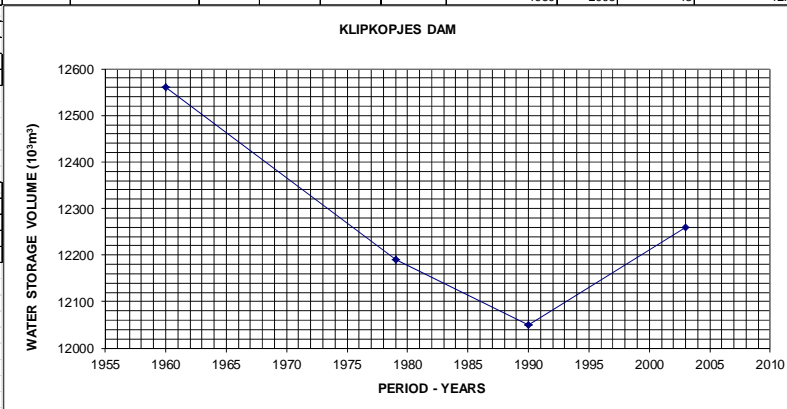
YEAR	VOLUME
1	230
8	360
19	300
32	300



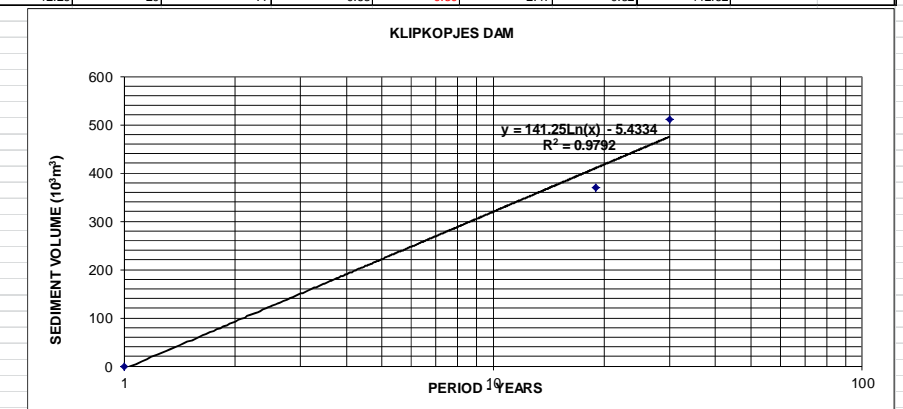
V50 = 465 (Period from 1979 to 2003)

4	85 Klipkopje	X2R003	X200-23	6 - X	Whitewit	Witriver	1960	1979	19	12.56	12.19	20	77	0.62	0.37	3.02	0.58	203.14	
							1960	1990	30	12.56	12.05	20	77	0.62	0.50	4.18	0.62	218.69	
							1960	2003	43	12.56	12.26	20	77	0.63	0.30	2.47	0.32	112.62	

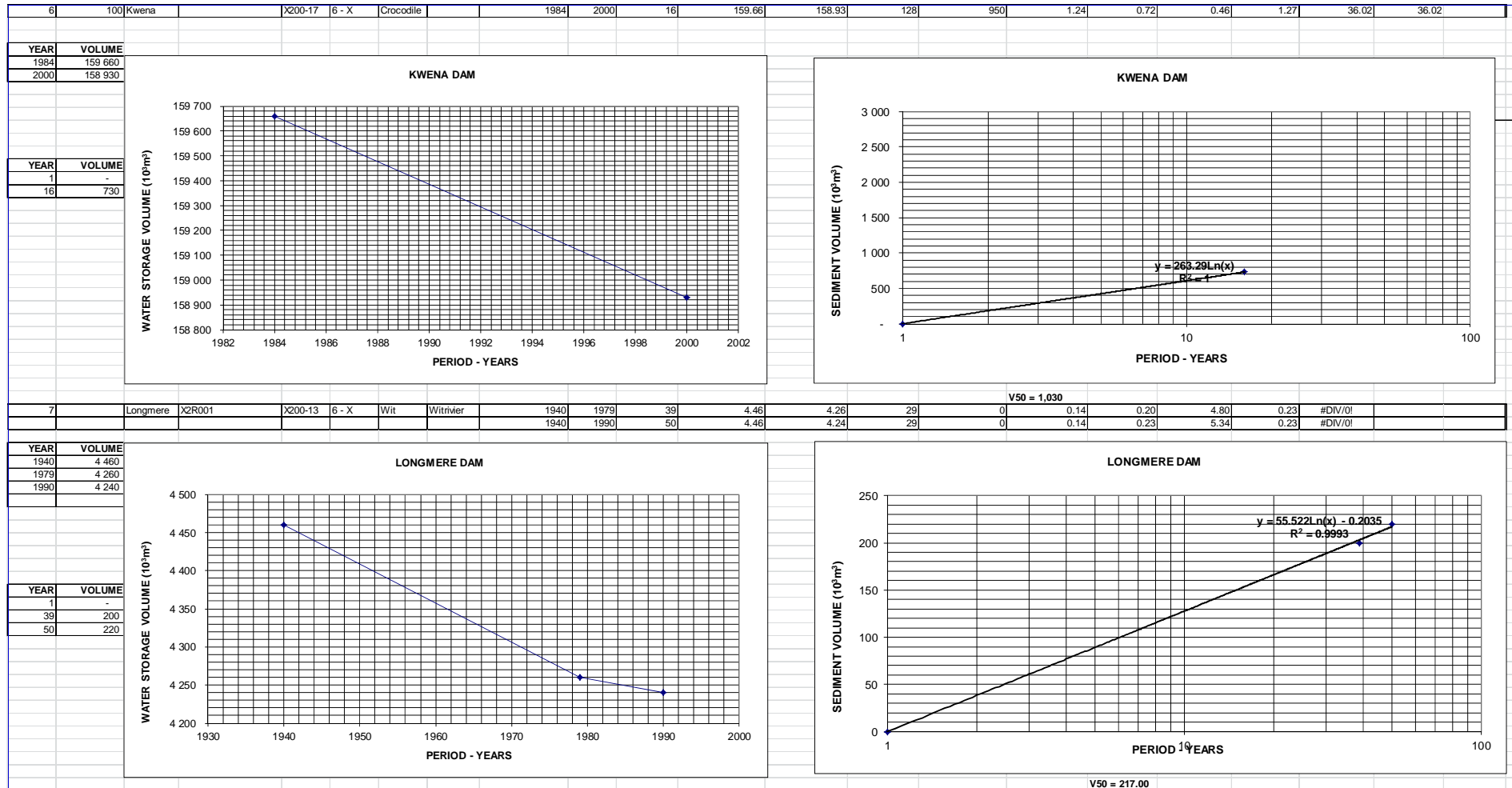
YEAR	VOLUME
1960	12 560
1979	12 190
1990	12 050
2003	12 260



YEAR	VOLUME
1	-
19	370
30	510
43	300

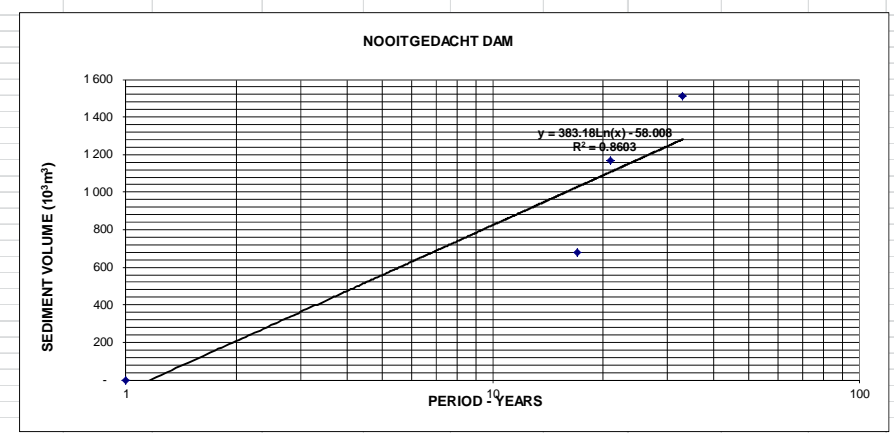
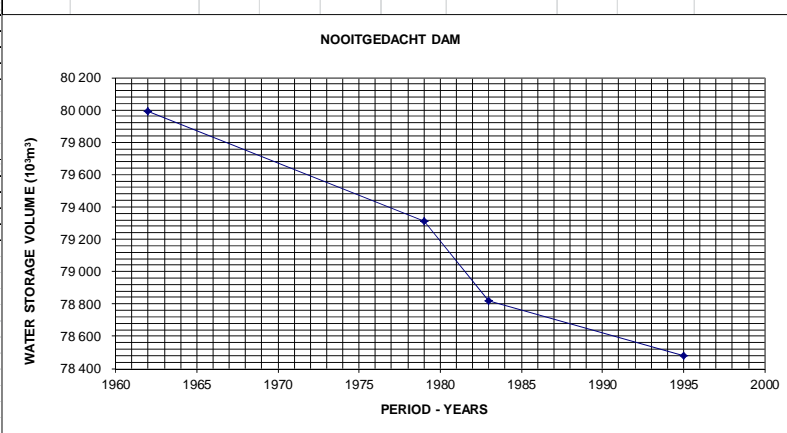


V50 = 547.14 (Used period 1960 to 1990)



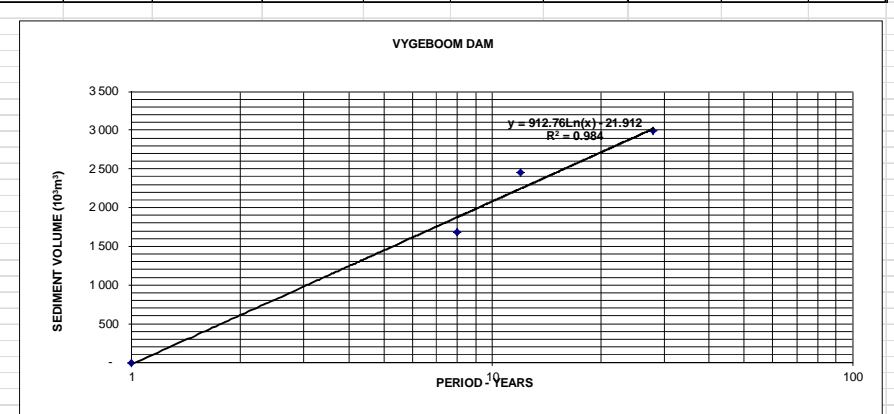
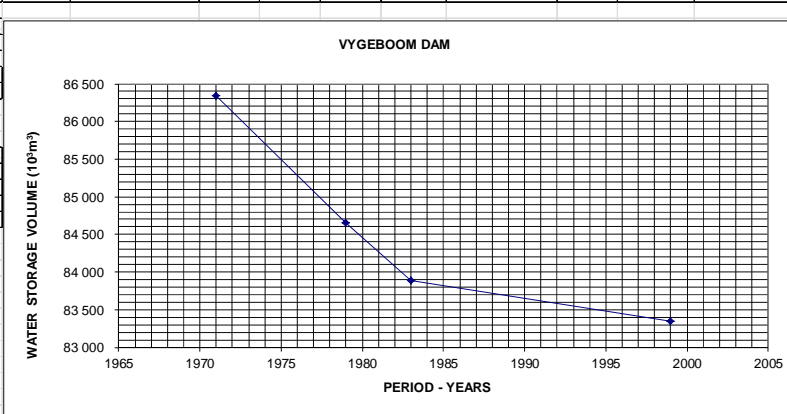
9	142	Nooitgedacht	X1R001	X100-09	6 - X	Komati	Carolina	1962	1979	17	79.99	79.31	64	1581	1.24	0.68	0.85	1.14	19.40	30.53	Longer period
								1962	1983	21	79.99	78.82	64	1581	1.23	1.16	1.47	1.72	29.45	30.53	
								1962	1995	33	79.99	78.48	64	1581	1.22	1.51	1.92	1.79	30.53	30.53	

YEAR	VOLUME
1962	79 990
1979	79 310
1983	78 820
1995	78 480

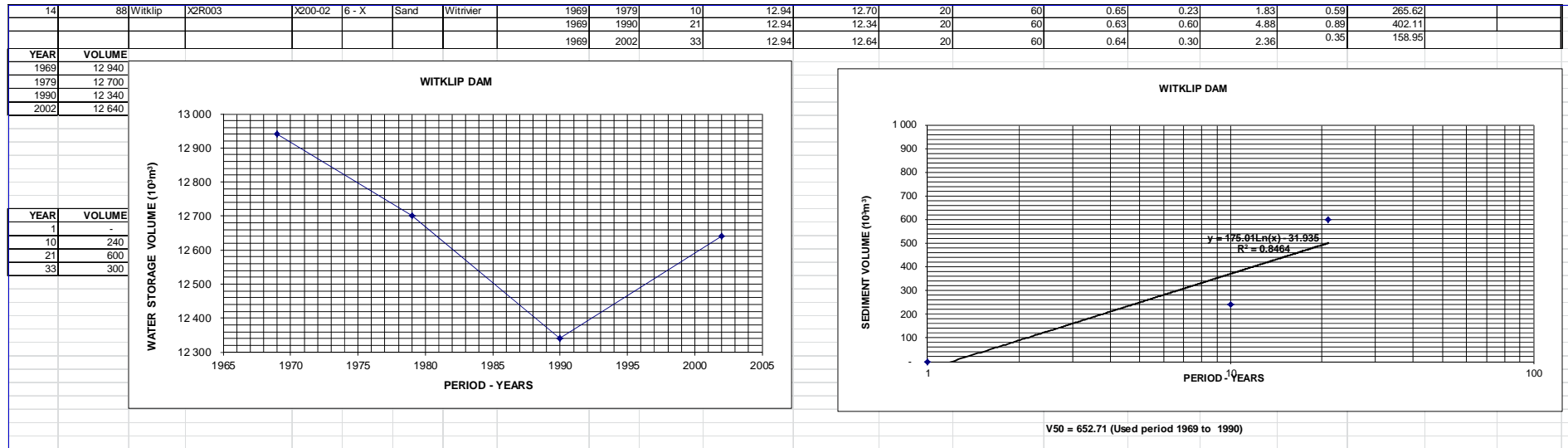


13	135	Vygeboom	X1R003	X100-02	6 - X	Komati	Badplass	1971	1979	8	86.34	84.66	268	1536	0.32	1.68	1.98	5.40	94.96	67.12
								1971	1983	12	86.34	83.89	268	1536	0.31	2.45	2.92	5.29	93.00	67.12
								1971	1999	28	86.34	83.35	268	1536	0.31	2.99	3.58	3.82	67.12	67.12

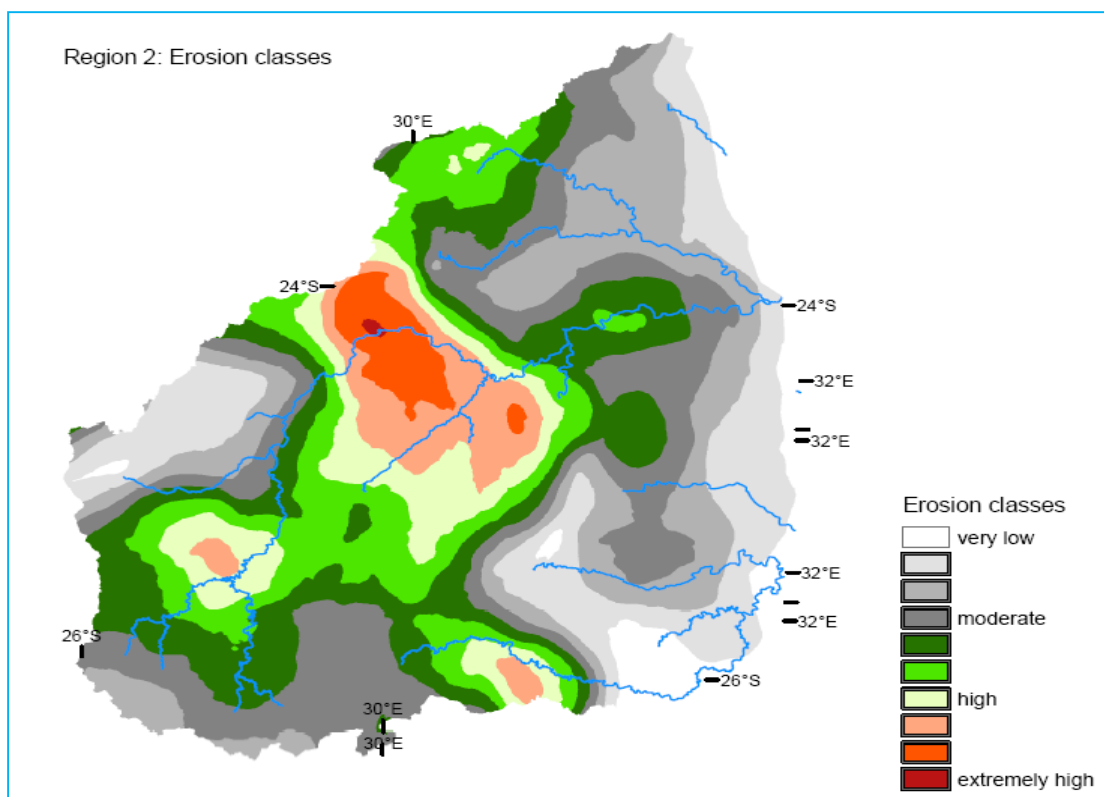
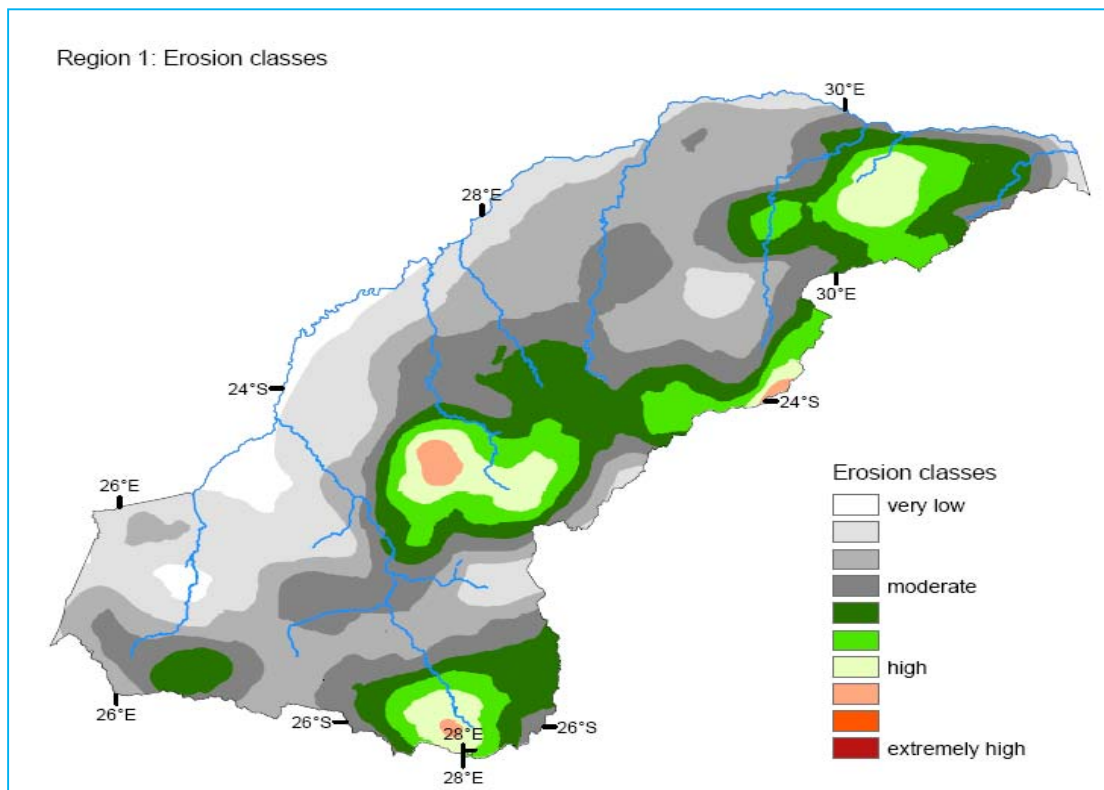
YEAR	VOLUME
1971	86 340
1979	84 660
1983	83 890
1999	83 350

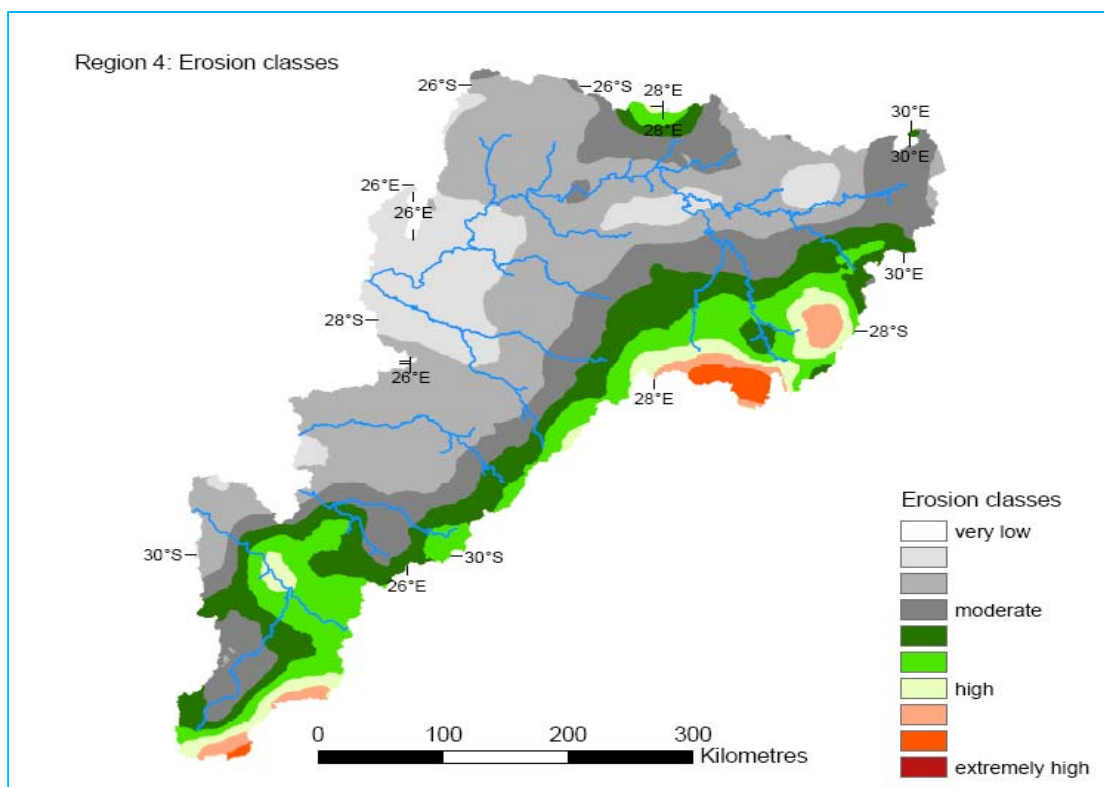
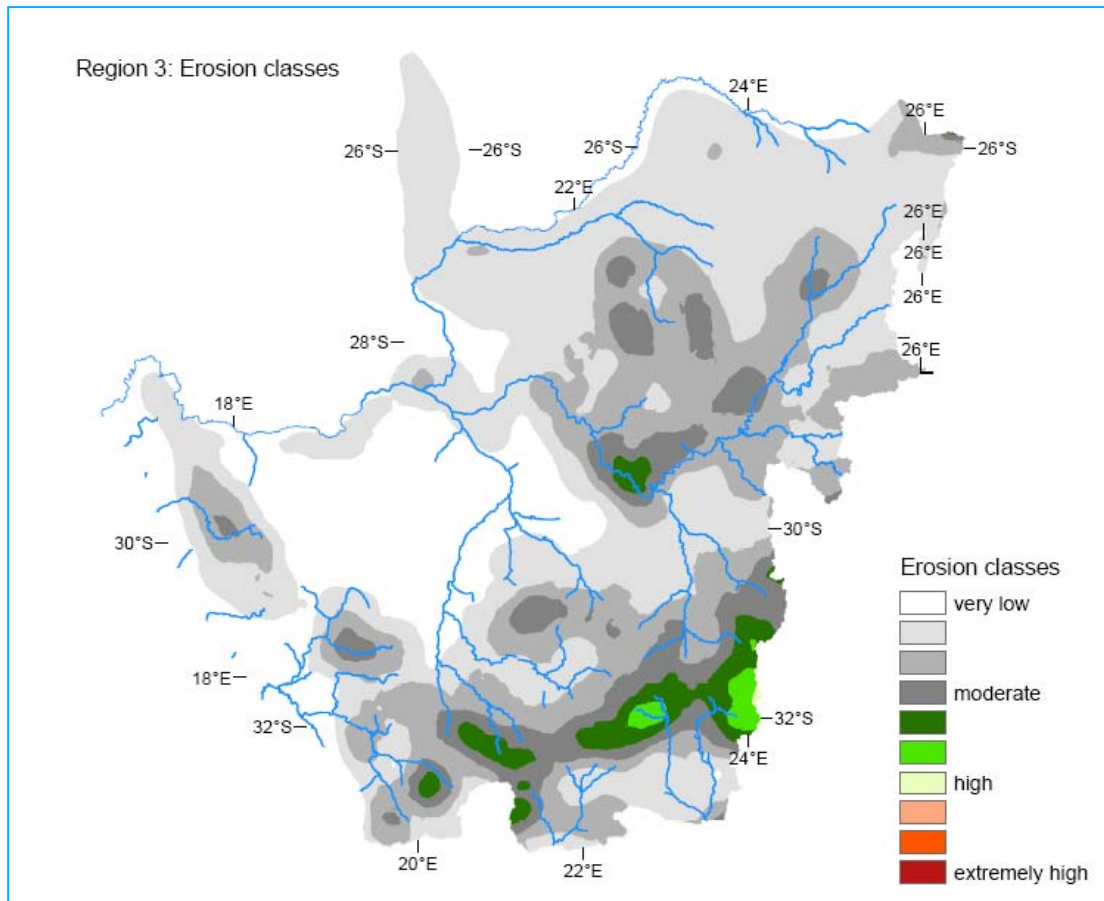


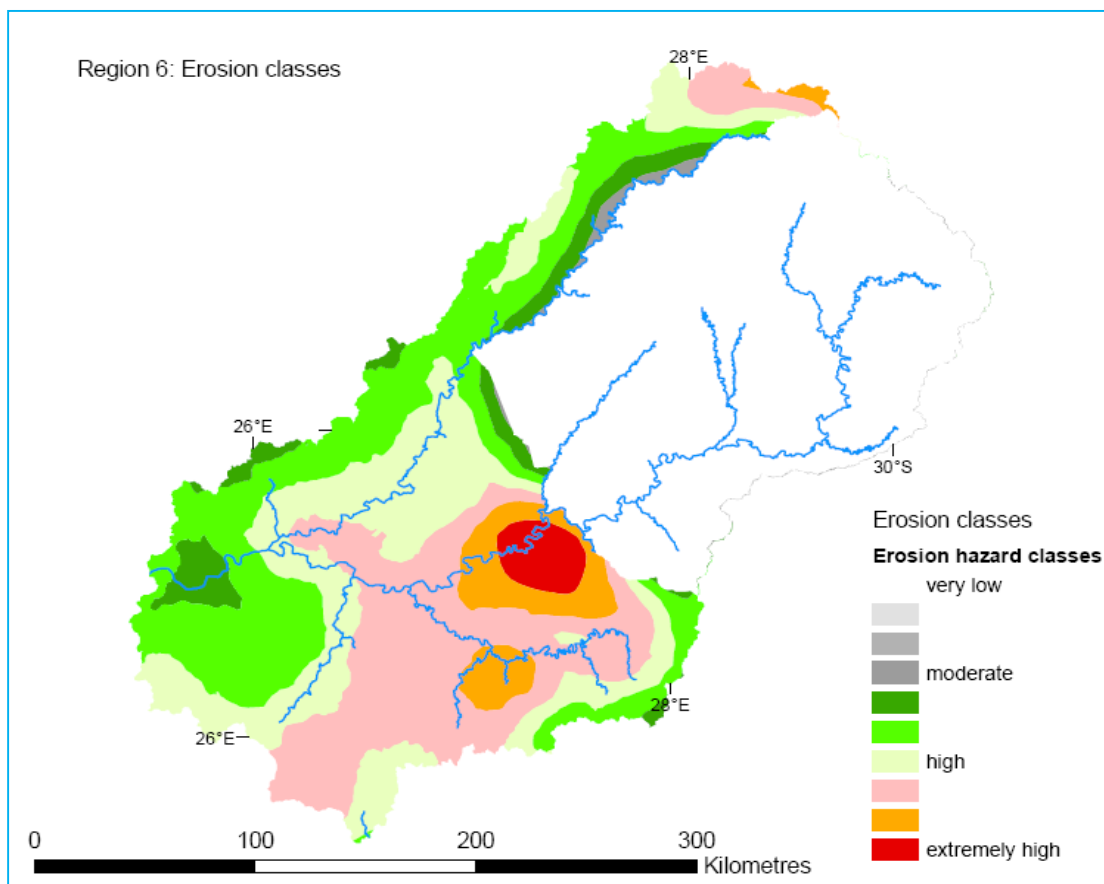
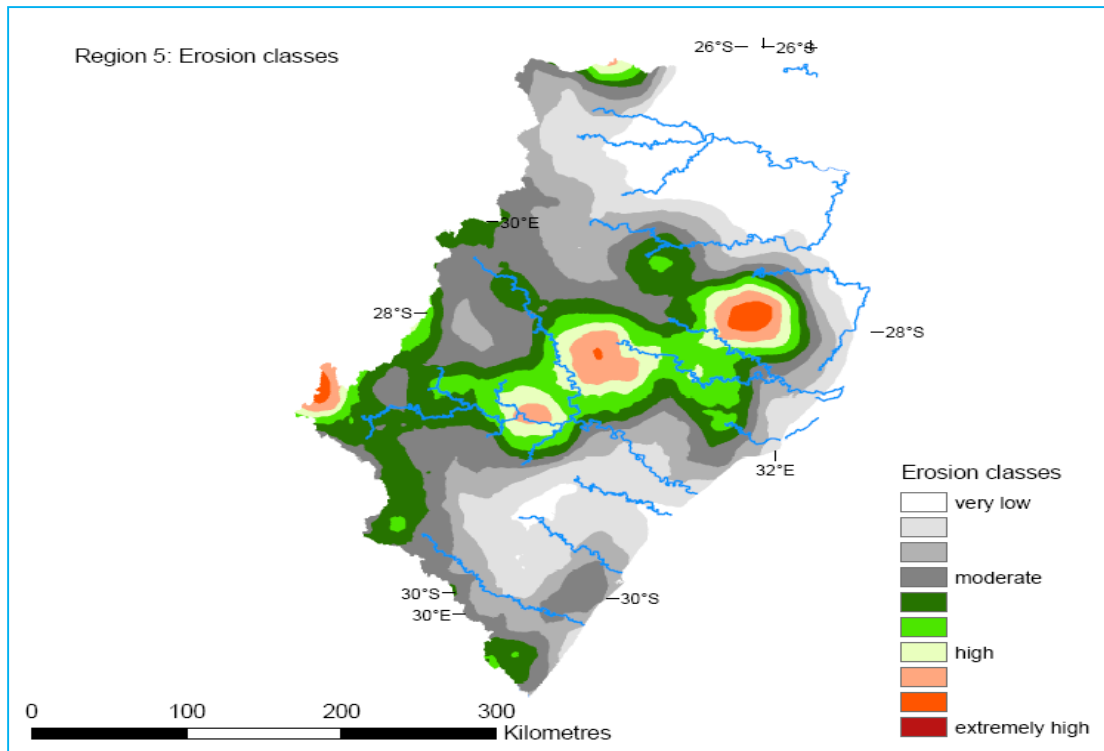
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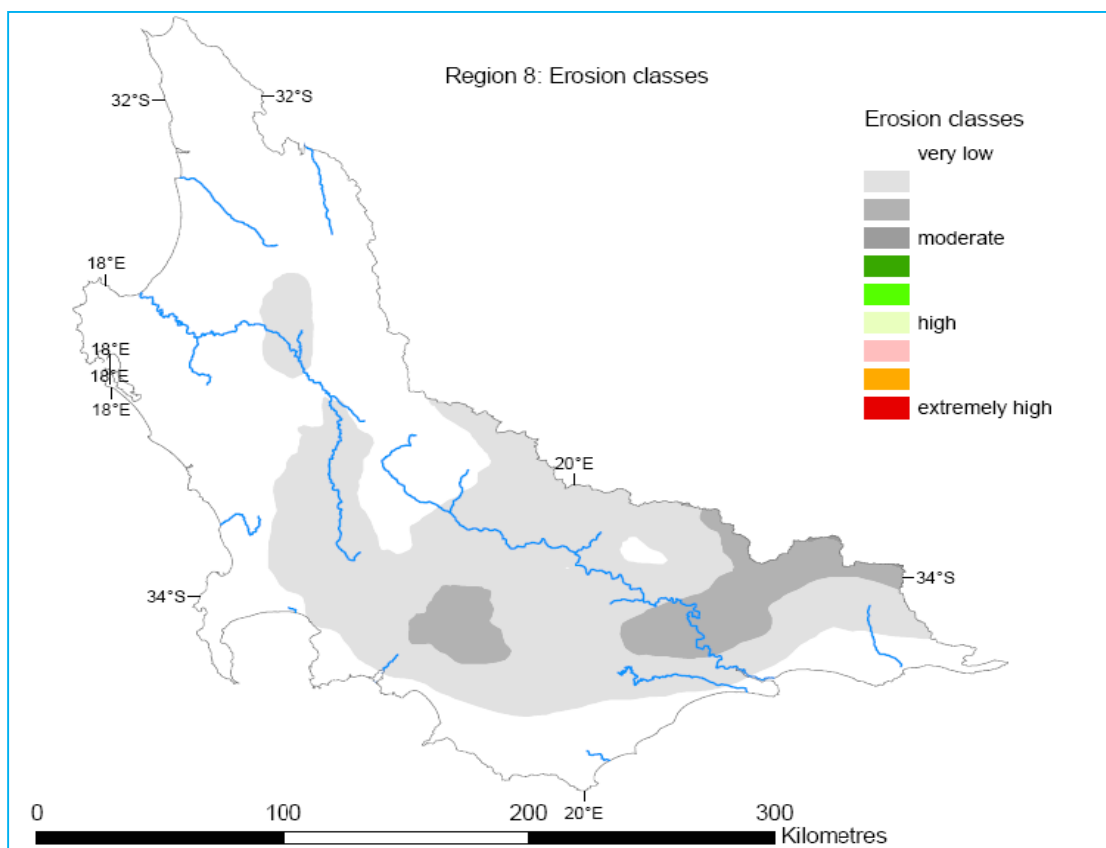
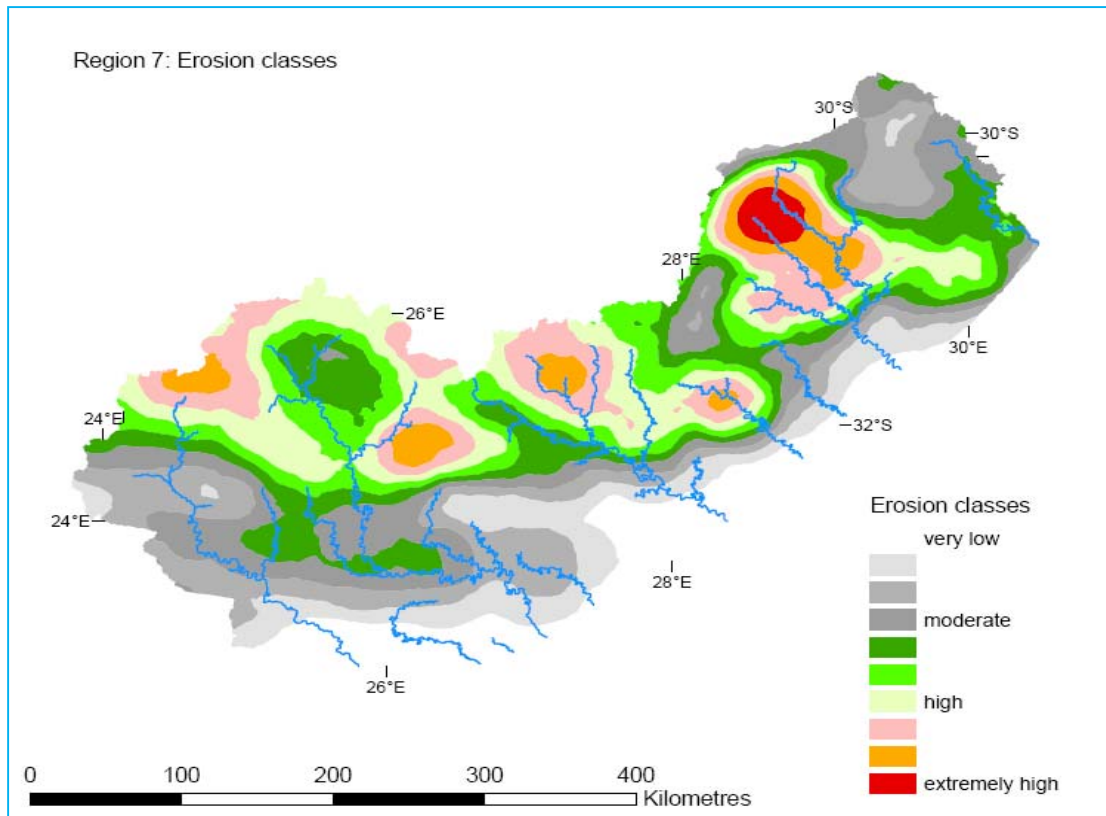


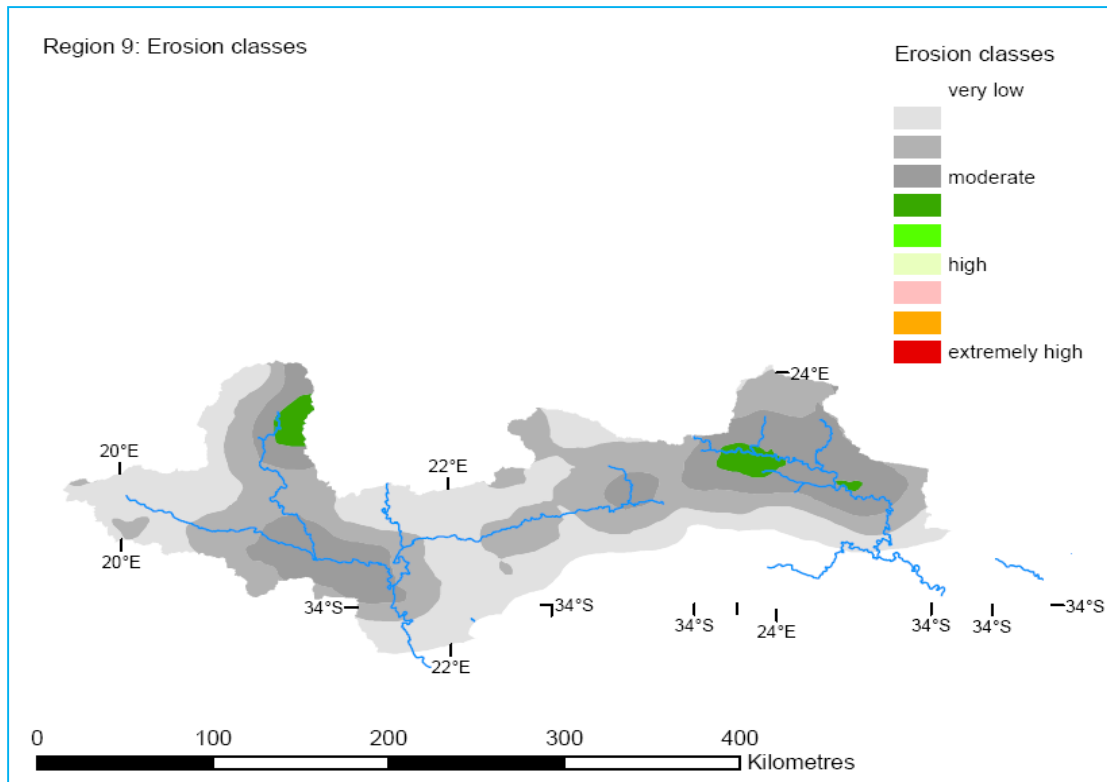
**APPENDIX B SOIL EROSION HAZARD CLASSES FOR
EACH SEDIMENT YIELD REGION**











APPENDIX C FINAL ADOPTED SEDIMENT YIELD VALUES

Name	Station No	Sediment Yield (t/km ² .a)	Effective Catchment Area (km ²)	Region
Albasini Dam	A9R001	84	501	1
Bospoort Dam	A2R006	152	580	1
Buffelspoort Dam	A2R005	126	116	1
Cross Dam		129	302	1
Doomdraai Dam	A6R001	167	387	1
Gert Combrink Dam	A6R004	15	176	1
Hans Strijdom Dam		9	4329	1
Hartebeespoort Dam	A2R001	110	3474	1
Klein-Maricopoort Dam	A3R002	24	828	1
Klipvoor Dam	A2R012	13	4708	1
Koster Dam	A2R011	27	289	1
Kromellenboog Dam	A3R003	120	607	1
Kudube Dam (Leeukraal)	A2R016	15	389	1
Lehujwane Dam	A3R005	105	201	1
Madikwe Dam		63	313	1
Marico-Bosveld Dam	A3R001	63	948	1
Ngotwana Dam	A1R001	41	504	1
Olifantsnek Dam	A2R003	101	499	1
Rietvlei Dam	A2R004	35	490	1
Roodeplaat Dam	A2R009	95	689	1
Vaalkop Dam	A2R014	53	3918	1
Blyderivierspoort Dam	B6R003	25	1235	2
Bronkhorstspuit Dam	B2R001	77	1244	2
Buffelkloof Dam	B4R004	25	279	2
Da Gama Dam	X3R001	339	44	2
Ebenezer Dam	B8R001	156	126	2
Hans Merensky Dam	B8R002	27	89	2
Klaserie Dam	B7R001	122	168	2
Klipkoppie Dam	X2R002	219	77	2
Kwena Dam	X2R005	36	950	2
Longmere Dam	X2R001	226	32	2
Loskop Dam	B3R002	48	3973	2

Name	Station No	Sediment Yield (t/km ² .a)	Effective Catchment Area (km ²)	Region
Magoebaskloof Dam	B8R003	73	81	2
Middel Letaba	B8R007	520	1051	2
Nooitgedag Dam	X1R001	31	1583	2
Ohrigstad Dam	B6R001	40	85	2
Rietfontein Dam		53	86	2
Rietspruit Dam	C2R007	62	392	2
Rust de Winter Dam	B3R001	25	1127	2
Trichardsfontein Dam	B1H022	72	11	2
Tzaneen Dam	B8R005	248	284	2
Vlugkraal Dam	B4R002	46	14	2
Vygeboom Dam	X1R003	93	1541	2
Witklip Dam	X2R003	402	60	2
Corumana		330	6271	2
Massingir		245	63350	2
Disaneng Dam	D4R003	22	3817	3
Gamkapoort Dam	J2R006	41	14535	3
Leeu-Gamka Dam	J2R002	26	2030	3
Oukloof Dam	J2R003	48	155	3
Spitskop Dam	C3002	11	14845	3
Victoria West Dam	D6R001	44	311	3
Upington		205	117932	3
Allemanskraal Dam	C4R001	411	2405	4
Armenia Dam	D2R002	96	260	4
Bloemhof Dam	C9R002	75	30601	4
Boskop Dam	C2R001	11	2172	4
Erfenis Dam	C4R002	163	4188	4
Grootdraai Dam	C1R002	63	7057	4
Jericho Dam	W5R001	245	211	4
Kalkfontein Dam	C5R002	100	8664	4
Klerkskraal Dam	C2R003	18	1272	4
Klipdrif Dam	C2R005	15	875	4

Name	Station No	Sediment Yield (t/km ² .a)	Effective Catchment Area (km ²)	Region
Koppies Dam	C7R001	126	2145	4
Kriegerspoort Dam		32	638	4
Krugersdrif Dam	C5R004	104	4453	4
Loch Athlone Dam	C8R005	95	122	4
Lucretia Dam		25	374	4
P.K. Le Roux Dam/ Vanderkloof	D3R003	137	17858	4
Rusfontein Dam	C5R003	184	868	4
Saulspoort Dam	C8R004	111	731	4
Tierpoort Dam	C5R001	128	918	4
Vaal Dam	C1R001	163	25678	4
Barrage - Vaal		85	31145	4
Leewkraal		100	9936	4
Oranjerivierbrug		630	22834	4
Paardeberg		312	14175	4
Sannaspos		304	931	4
Standerton		193	7958	4
Upington		205	16911	4
Wilge		32	1455	4
Albert Falls Dam	U2R003	31	731	5
Chelmsford Dam	V3R001	236	838	5
Craigie Burn Dam	V2R001	656	156	5
Goedertrouw Dam	W1R001	524	1275	5
Hammarsdale Dam		100	48	5
Hazelmere Dam	U3R001	714	382	5
Henley Dam	U2R005	74	219	5
Hluhluwe Dam	W3R001	203	725	5
Jericho Dam	W5R001	245	211	5
Kilburn Dam	V1R004	756	30	5
Klipfontein Dam	W2R001	121	281	5
Midmar Dam	U2R001	93	931	5
Pongolapoort Dam	W4R001	1038	10927	5
Spioenkop Dam	V1R001	581	803	5

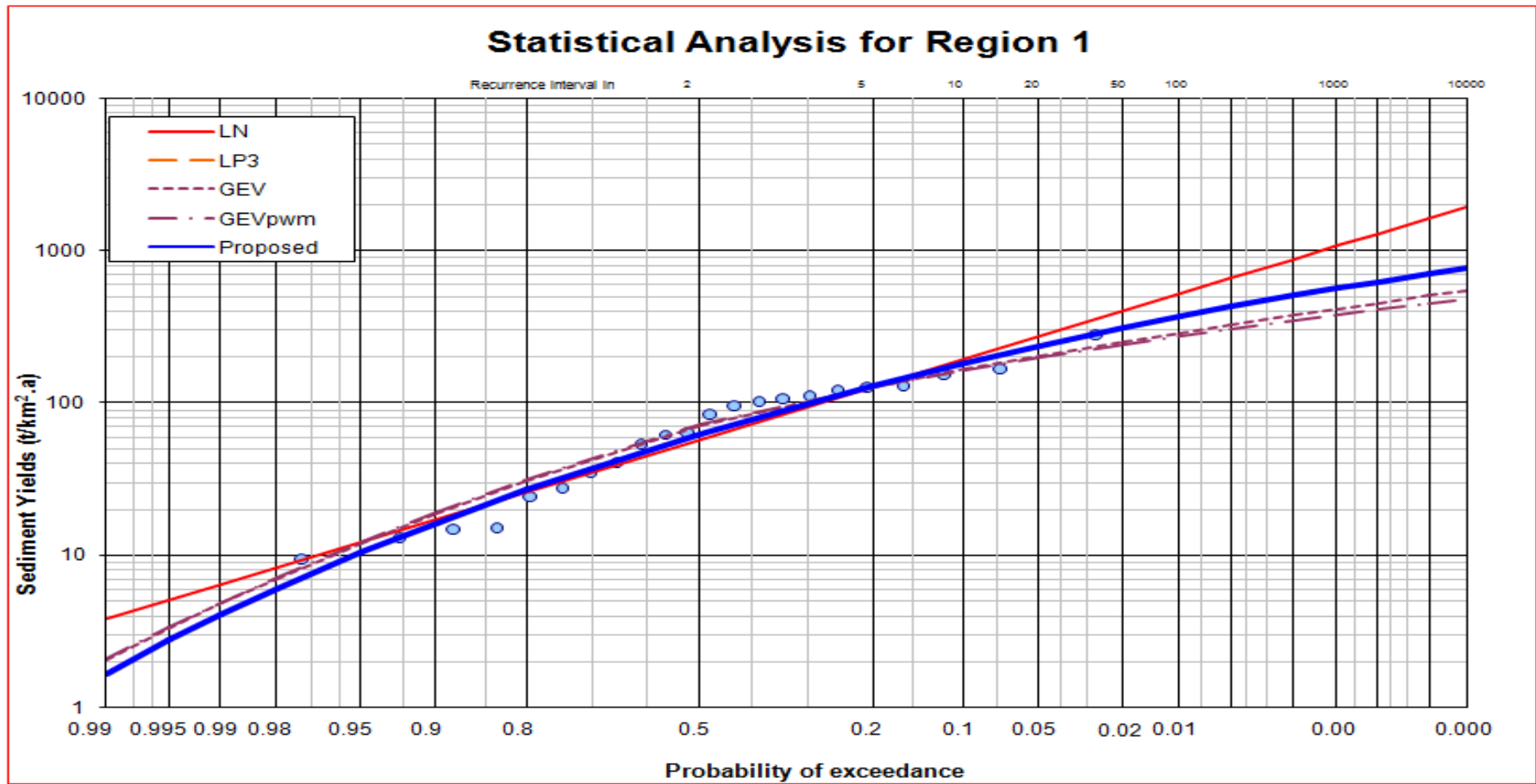
Name	Station No	Sediment Yield (t/km ² .a)	Effective Catchment Area (km ²)	Region
Wagendrift Dam	V7R001	167	755	5
Woodstock Dam	V1R003	318	875	5
Colenso		571	4198	5
Intulembi		133	8806	5
Bethulie Dam	D3R001	519	232	6
Gariiep Dam	D3R002	392	28091	6
J.L. De Bruin Dam		13	976	6
Aliwal-North		623	13465	6
Bethulie	D3H002	778	14105	6
Caledon River @ Lesotho		1141	934	6
Caledon River @ Slabbertswag	D2H016	832	659	6
Jammersdrift		621	4448	6
Bridle Drift Dam	R2R003	1509	252	7
Darlington Dam	N2R001	210	10397	7
Doringrivier Dam	S2R002	617	310	7
Elandskuil Dam	C2R006	158	22	7
Grassridge Dam	Q1R001	236	3507	7
Gubu Dam	S6R001	840	16	7
Katrivier Dam	Q9R001	306	262	7
Kommandodrift Dam	Q4R002	152	2627	7
Laing Dam	R2R001	95	834	7
Loerie Dam	L9R001	193	149	7
Maden Dam		49	31	7
Mtata Dam	T2R001	262	882	7
Nahoon Dam	R3R001	106	478	7
Ncora Dam	S5R001	219	1775	7
Nuwejaars Dam		4	519	7
Poortjie Dam		156	26	7
Van Ryneveldspas Dam	N1R001	207	3666	7
Waterdown Dam	S3R001	12	583	7
Xilinx Dam	S7R002	378	209	7

Name	Station No	Sediment Yield (t/km ² .a)	Effective Catchment Area (km ²)	Region
Xonxa Dam	S1R001	888	1476	7
Buffelsfontein	Q8H001	589	173	7
Doornhoek	S3H002	558	811	7
GrootMakte		279	803	7
Hougham Abramson		209	13305	7
Jansenville		136	1921	7
Roberts Kraal		19	974	7
Bellair Dam	J1R002	57	509	8
Clanwilliam Dam	E1R002	206	1954	8
Duiwenhoks Dam	H8R001	43	147	8
Elandskloof Dam	H6R002	236	51	8
Keerom Dam	H4R002	87	389	8
Korentepoort Dam	H9R001	123	35	8
Lakenvallei Dam	H2R002	118	86	8
Miertjieskraal Dam	J1R004	16	254	8
Pietersfontein Dam	H3R002	260	114	8
Poortjieskloof Dam	H3R001	156	86	8
Roode Elsberg Dam	H2R001	344	53	8
Stettynskloof Dam		49	60	8
Wemmershoek Dam	G1R002	450	86	8
Goudmyn/Rooiburg		10	1	8
Nieuwkloof		69	397	8
Calitzdorp Dam	J2R001	149	165	9
Churchill Dam	K9R001	10	354	9
Floriskraal Dam	J1R003	145	4029	9
Impofu Dam	K9R002	7	486	9
Kammanassie Dam	J3R001	53	1527	9
Kouga Dam	L8R001	18	3856	9
Prinsrivier Dam	J1R001	129	753	9
Raubenheimer Dam	J3R003	6	52	9
Stompdrift Dam	J3R002	75	5249	9

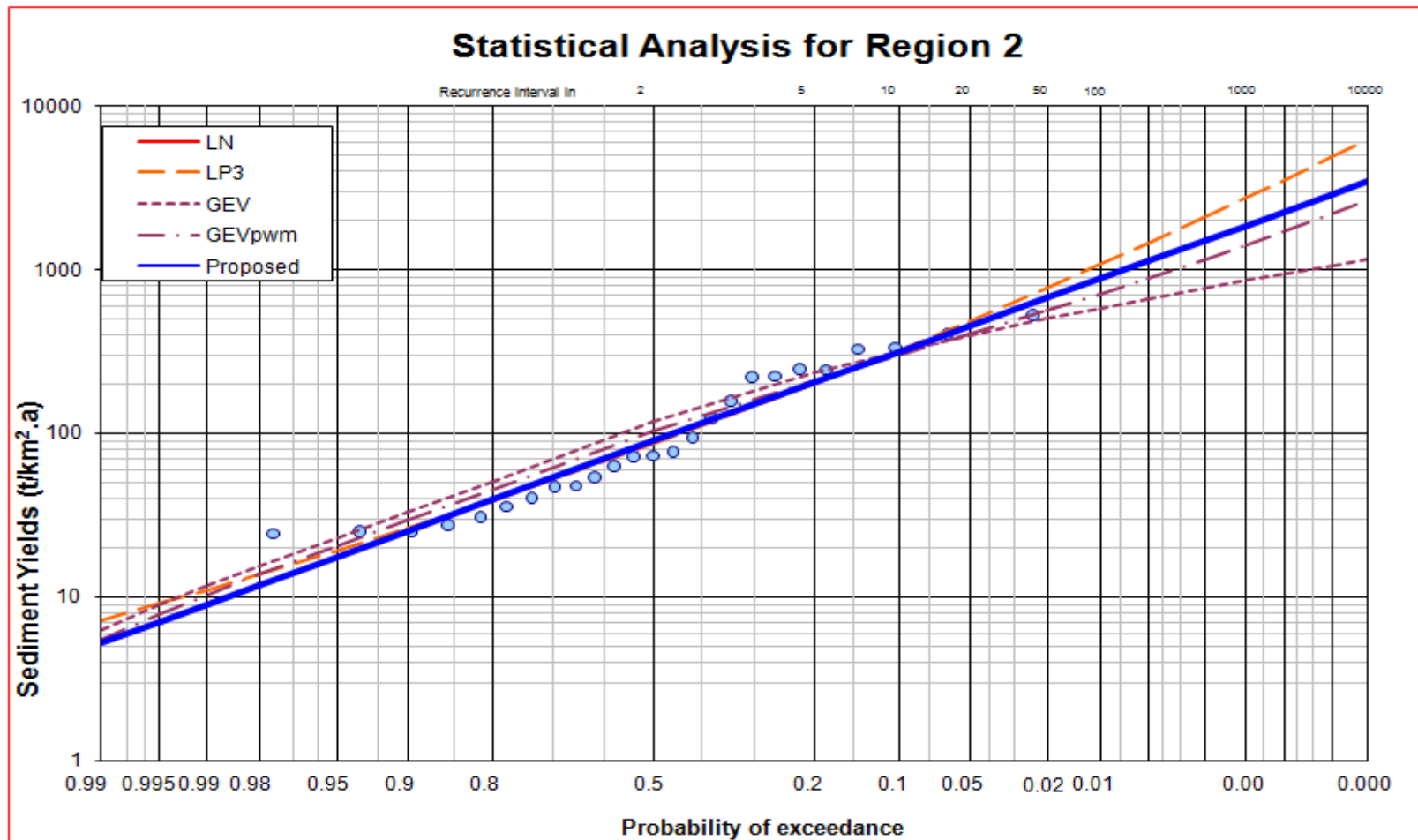
APPENDIX D DETERMINATION OF SEDIMENT POTENTIAL FACTORS

Station Name	Total Area (km ²)	Erosion Hazard Class										Observed Sediment Yield (t/km ² .a)	Weighted Erosion Hazard Class	Dominant Erosion Hazard Class
		1	2	3	4	5	6	7	8	9	10			
Calitzdorp Dam	165	0	165	0	0	0	0	0	0	0	0	149	2.00	2
Churchill Dam	354	354	0	0	0	0	0	0	0	0	0	10	1.00	1
Floriskraal Dam	4,029	0	1122	1390	1035	482	0	0	0	0	0	145	3.22	3
Impofu Dam	485	485	0	0	0	0	0	0	0	0	0	7	1.00	1
Kammanassie Dam	1,526	259	1045	222	0	0	0	0	0	0	0	53	1.98	2
Kouga Dam	3,856	2733	1025	98	0	0	0	0	0	0	0	18	1.32	1
Prinsrivier Dam	752	0	494	258	0	0	0	0	0	0	0	129	2.34	2
Raubenheimer Dam	51	0	36	15	0	0	0	0	0	0	0	6	2.29	2
Stompdrift Dam	5,248	38	1518	3145	547	0	0	0	0	0	0	75	2.80	3

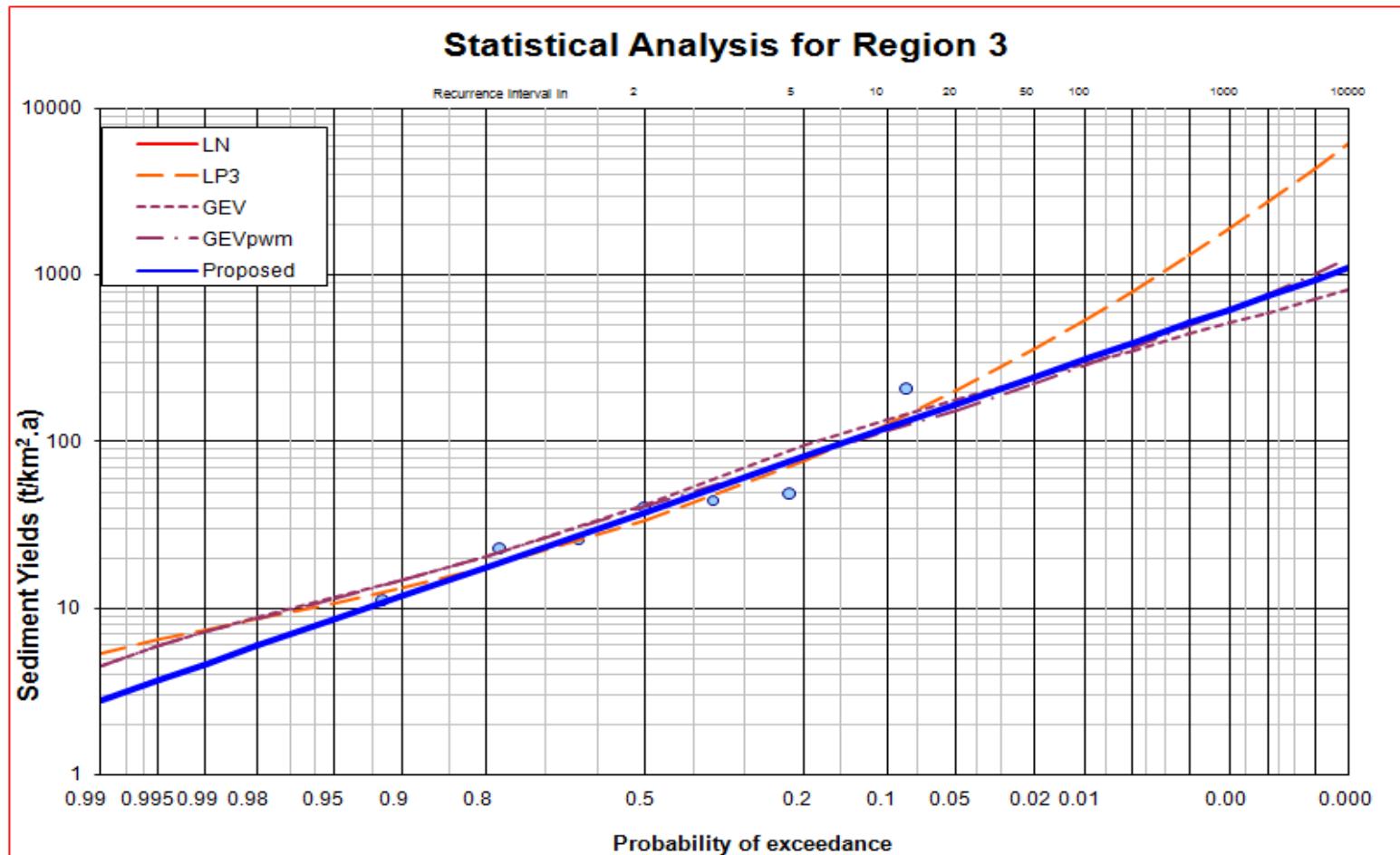
APPENDIX E REGIONAL GRAPHS FOR STATISTICAL ANALYSIS



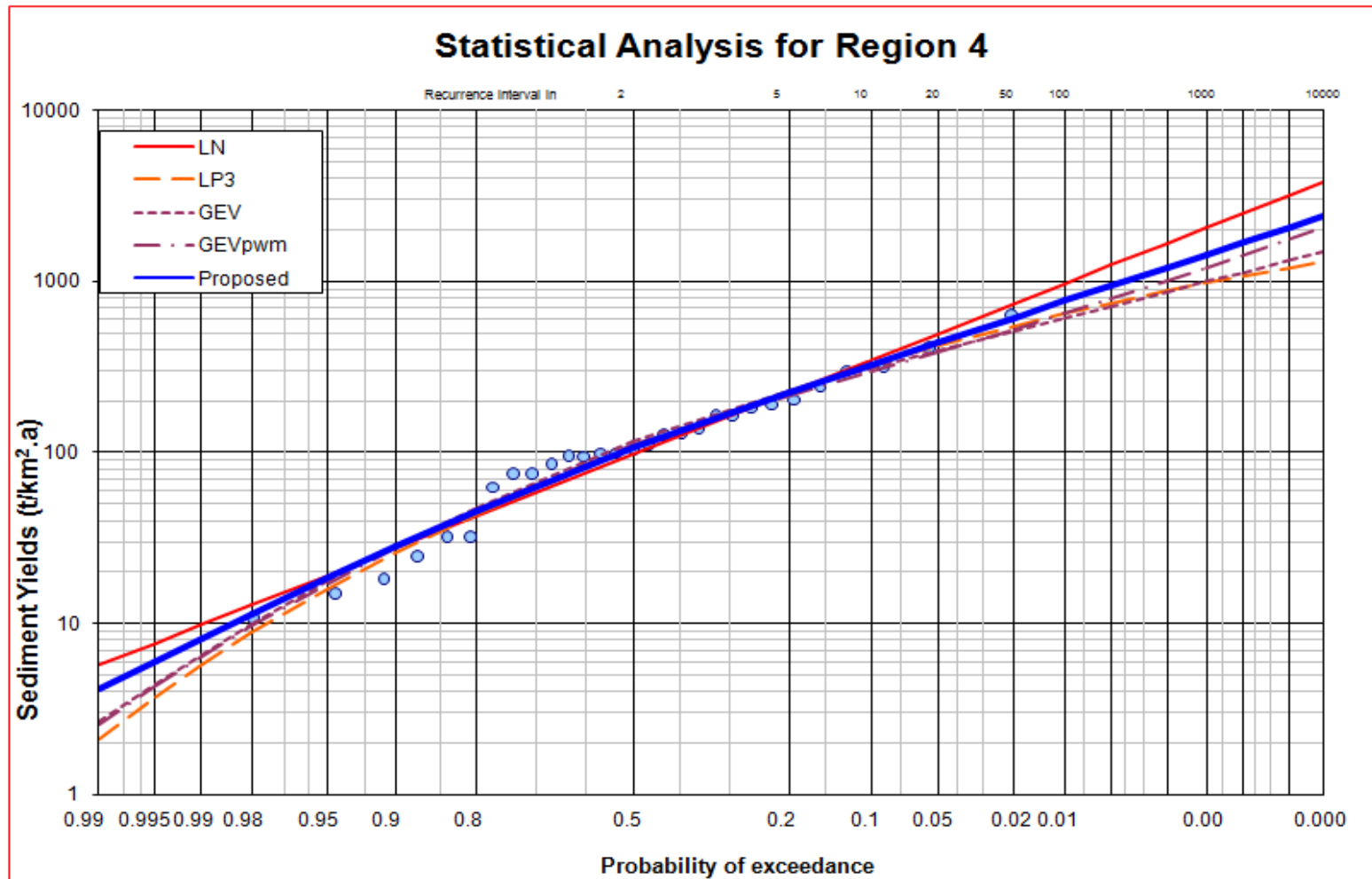
Statistical Analysis for Region 1



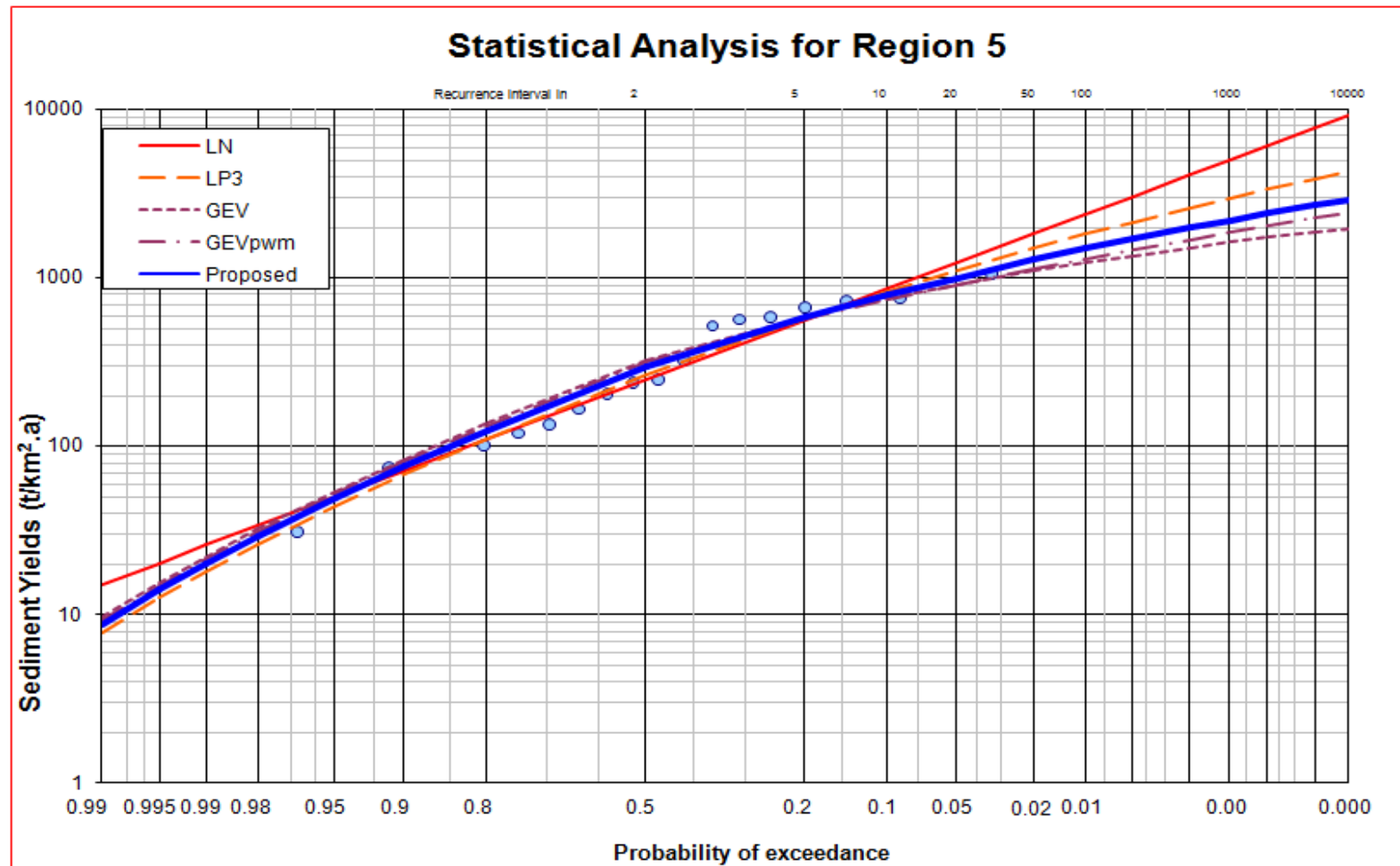
Statistical Analysis for Region 2



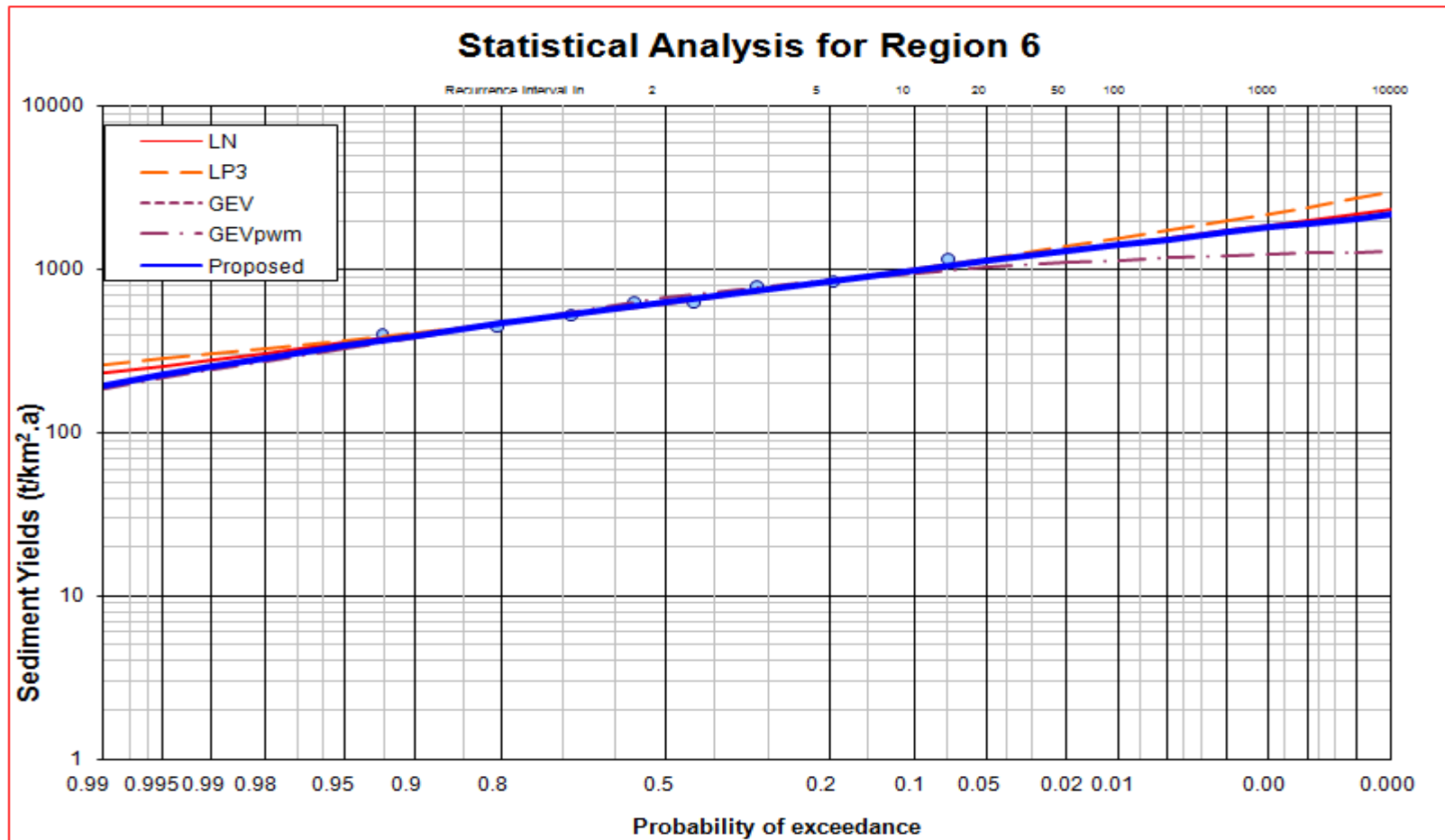
Statistical Analysis for Region 3



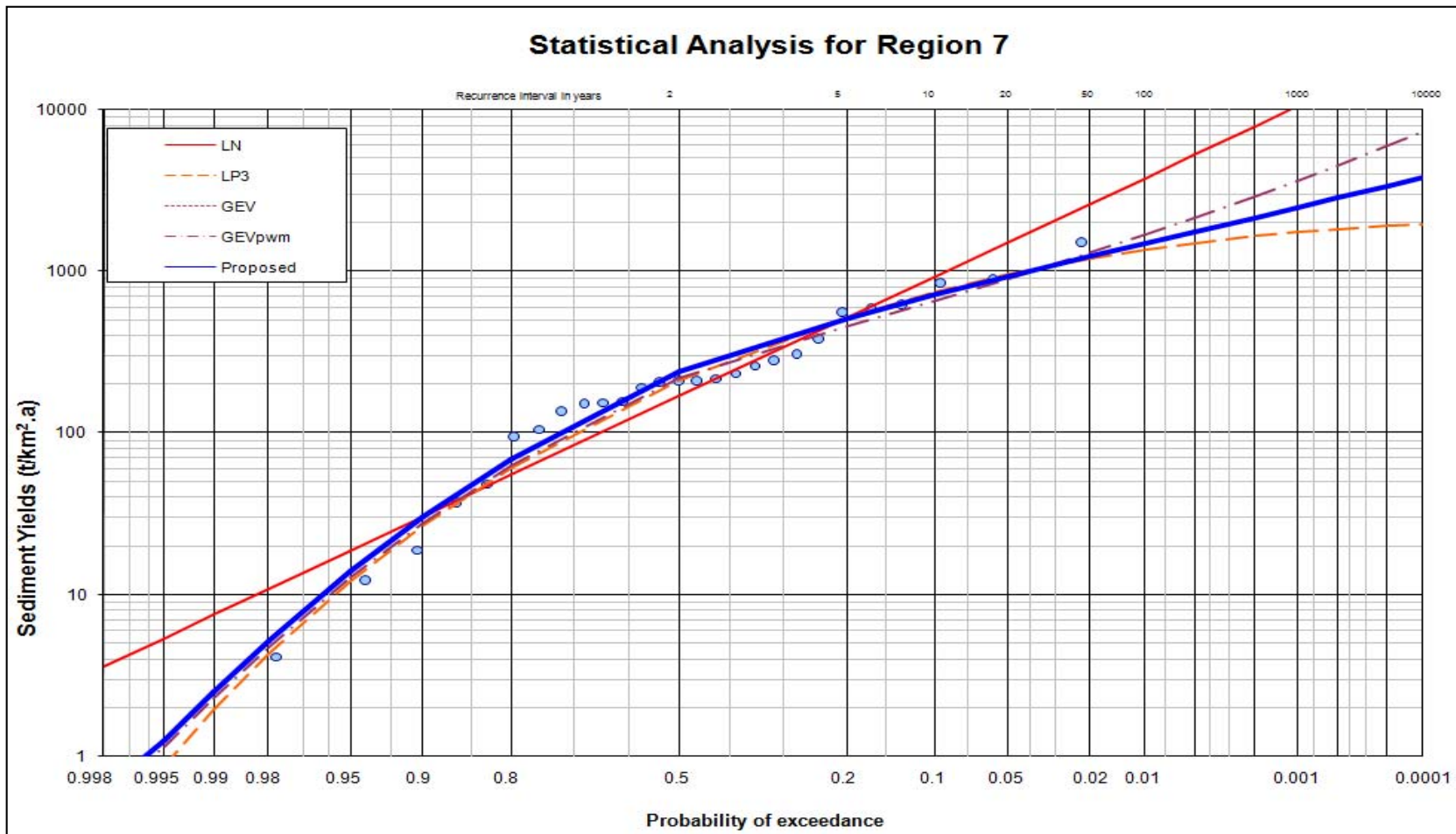
Statistical Analysis for Region 4



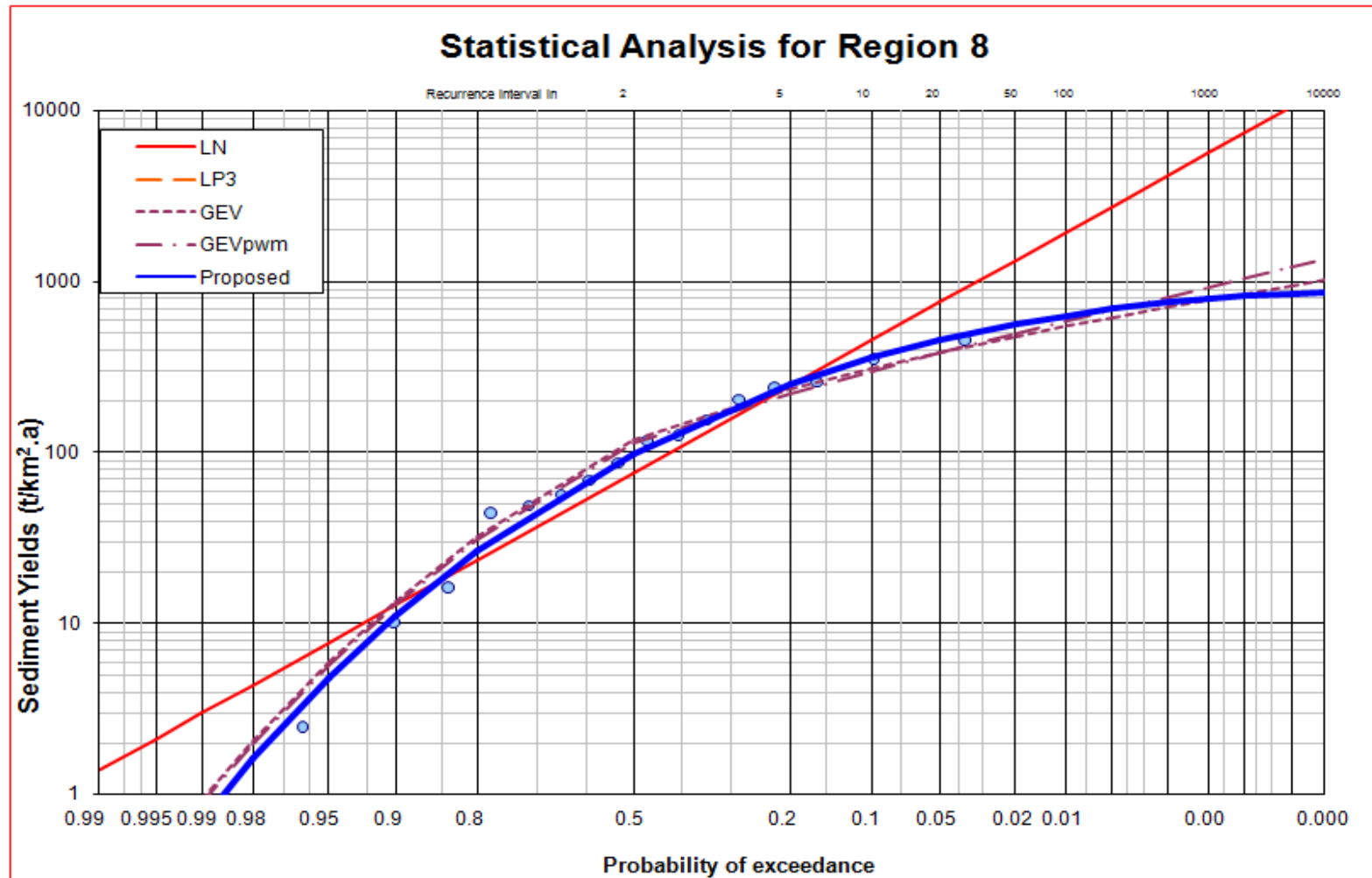
Statistical Analysis for Region 5



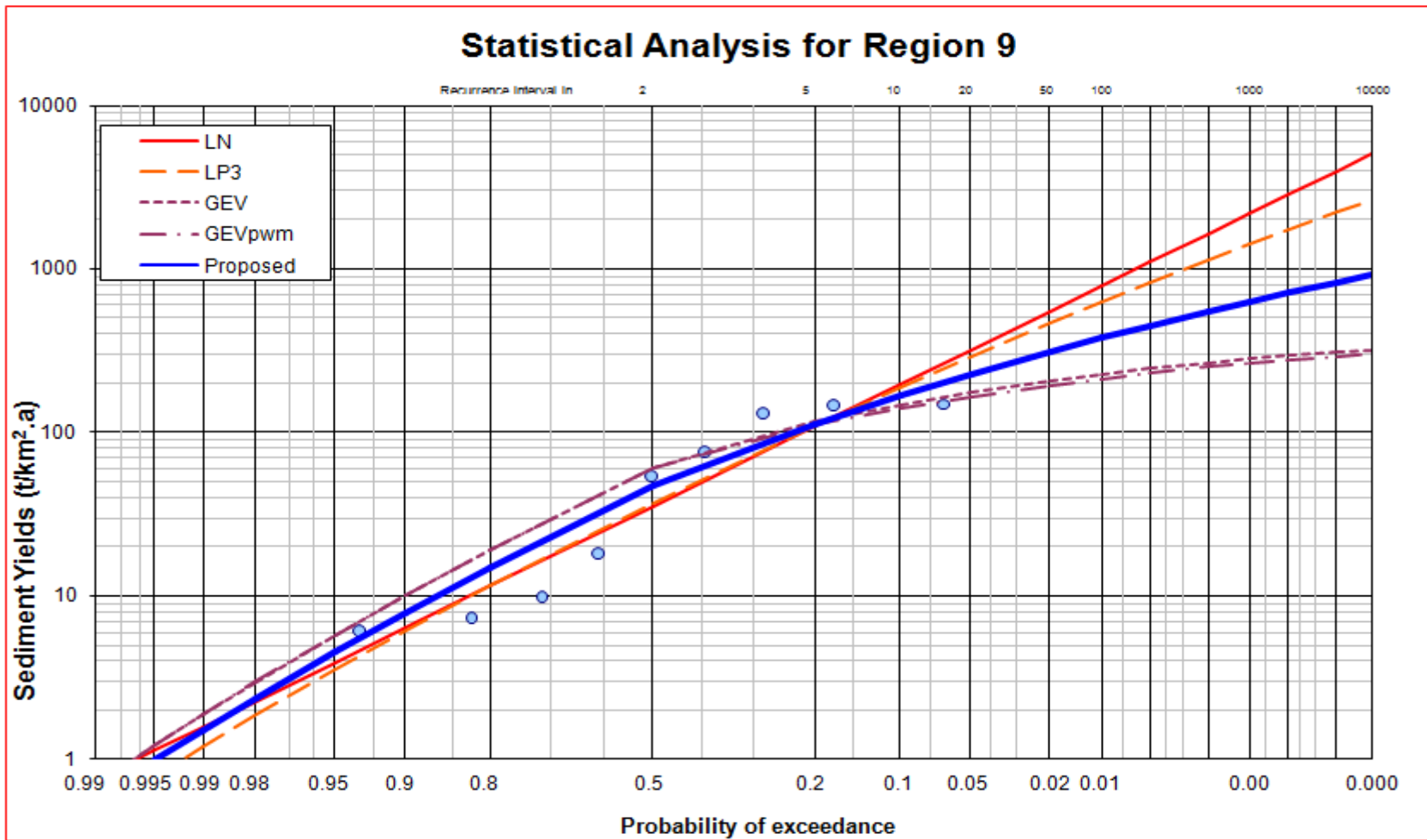
Statistical Analysis for Region 6



Statistical Analysis for Region 7

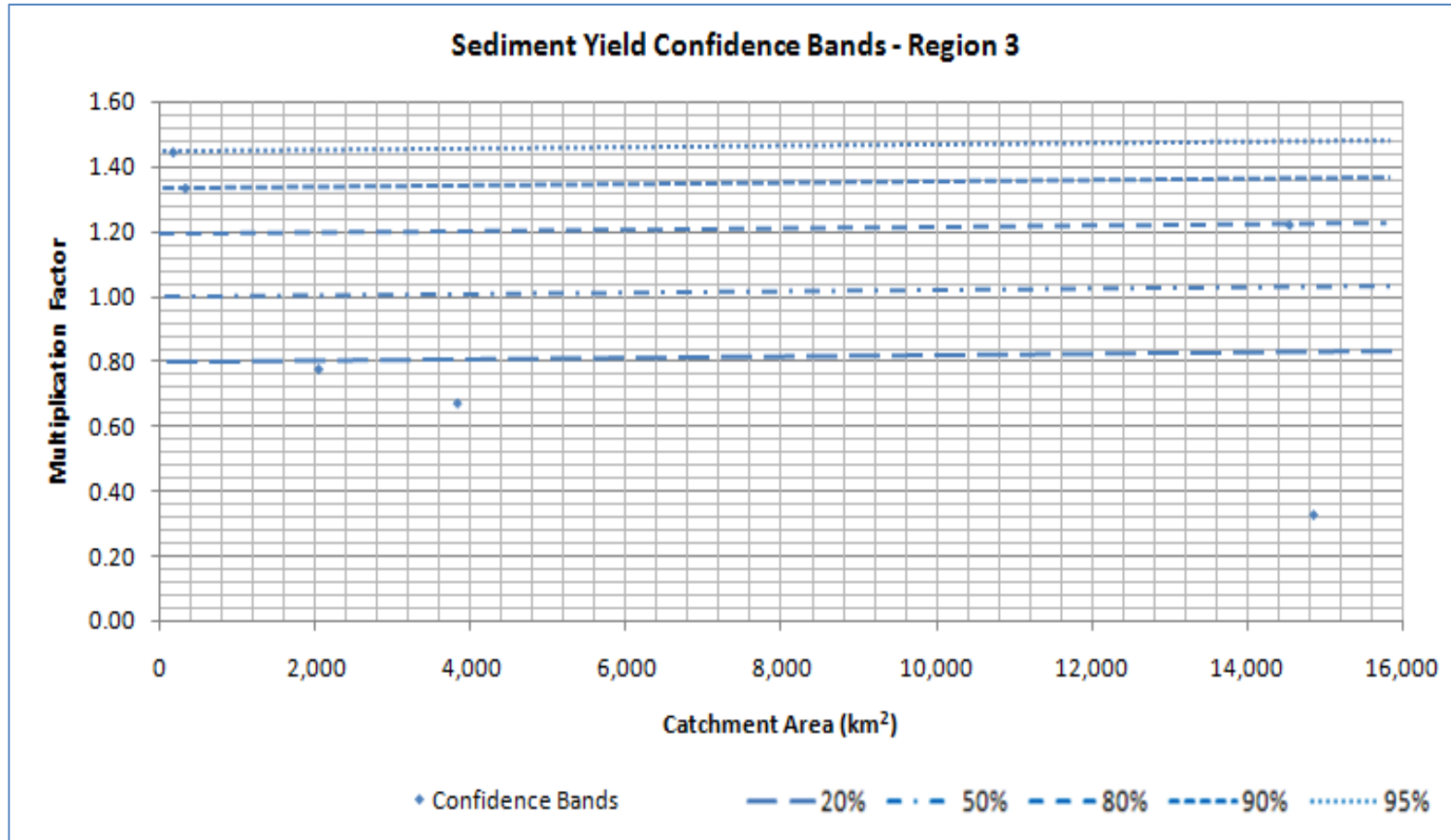


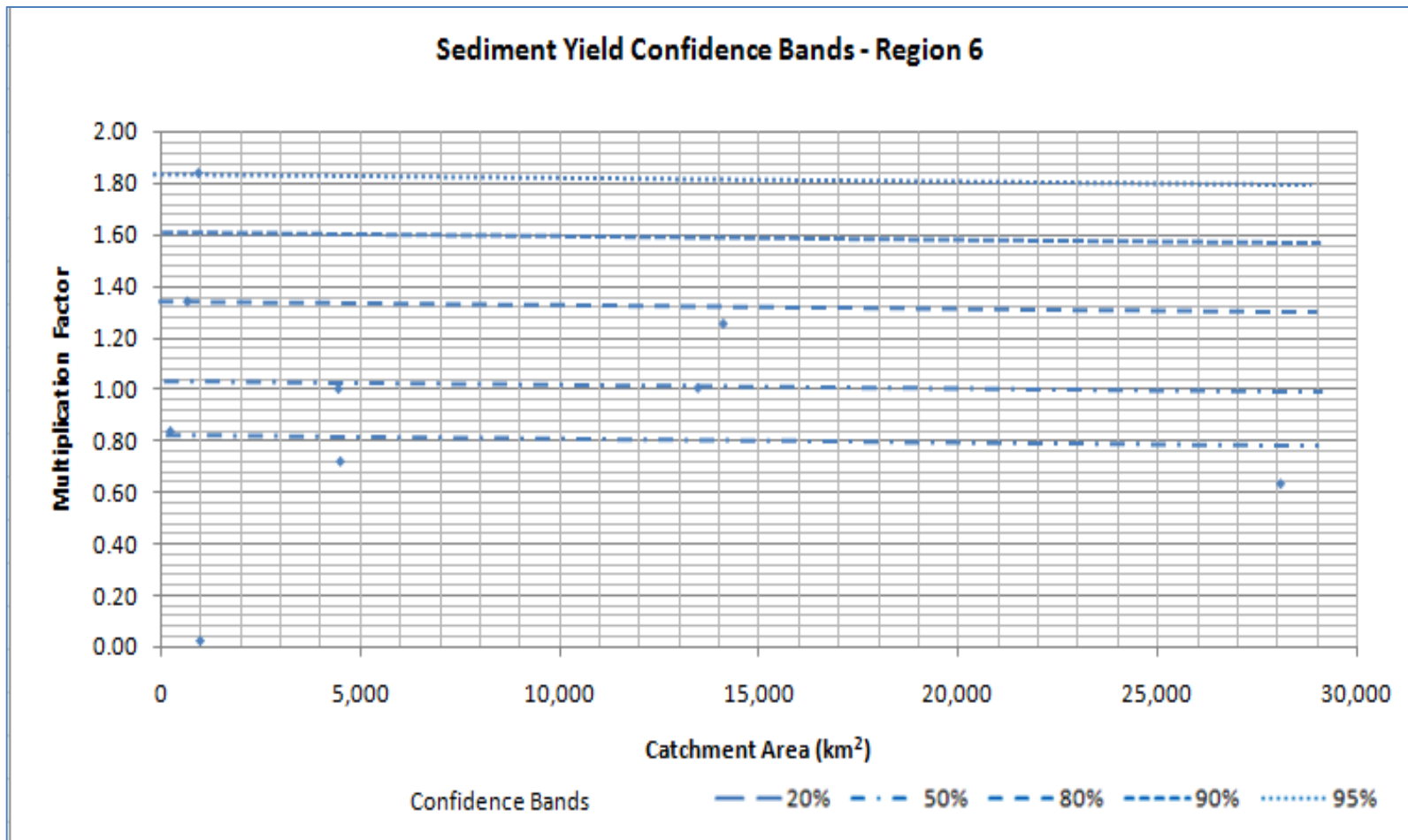
Statistical Analysis for Region 8

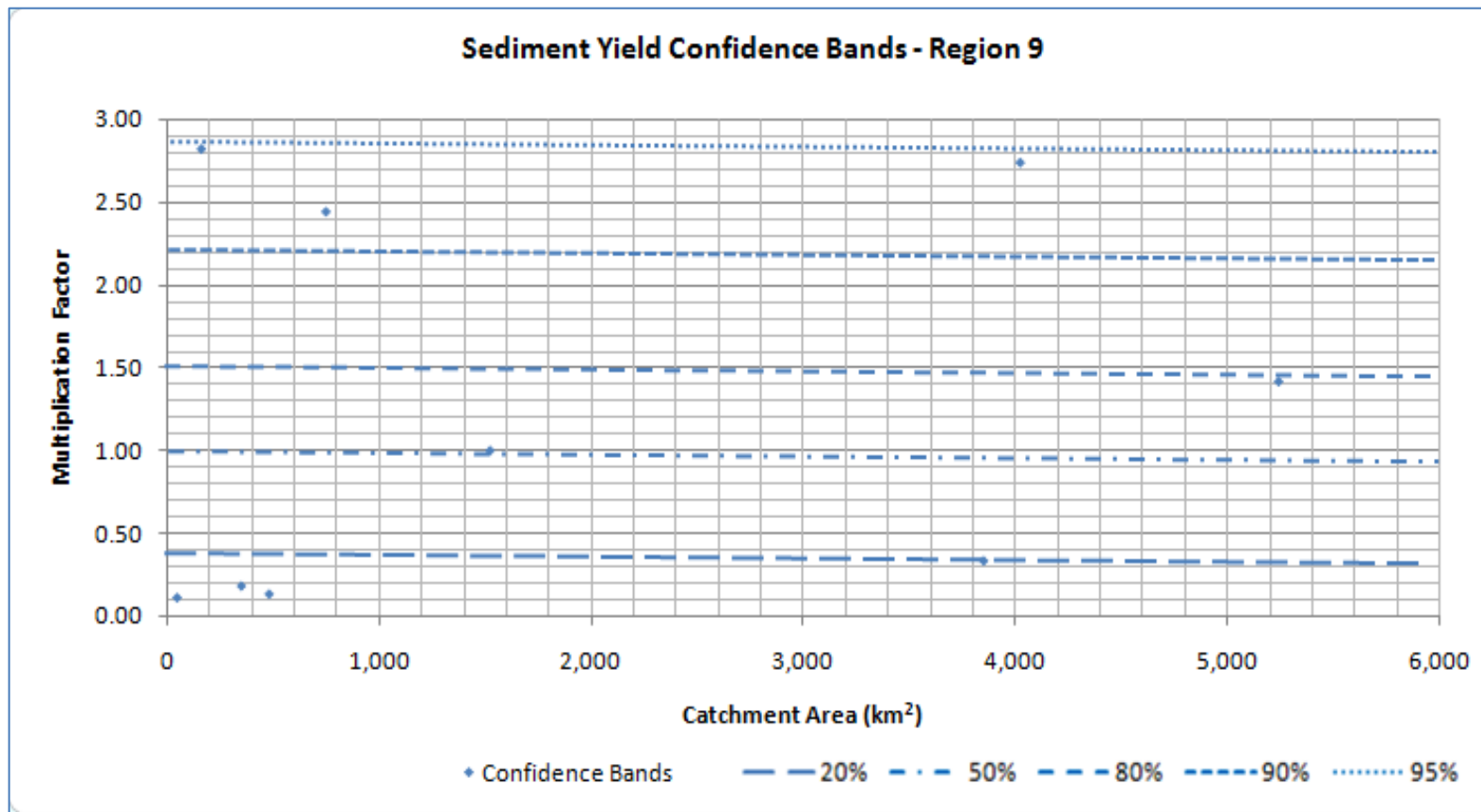


Statistical Analysis for Region 9

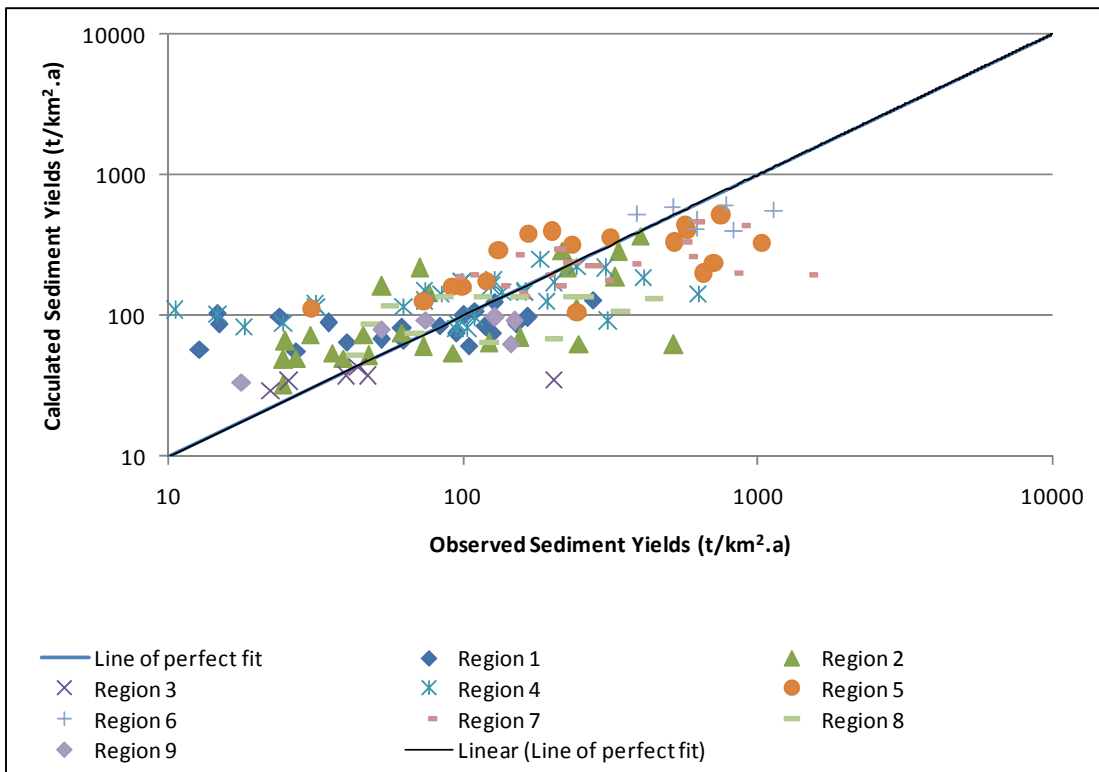
**APPENDIX F REGIONAL SEDIMENT YIELD CONFIDENCE
BANDS – PROBABILISTIC METHOD**



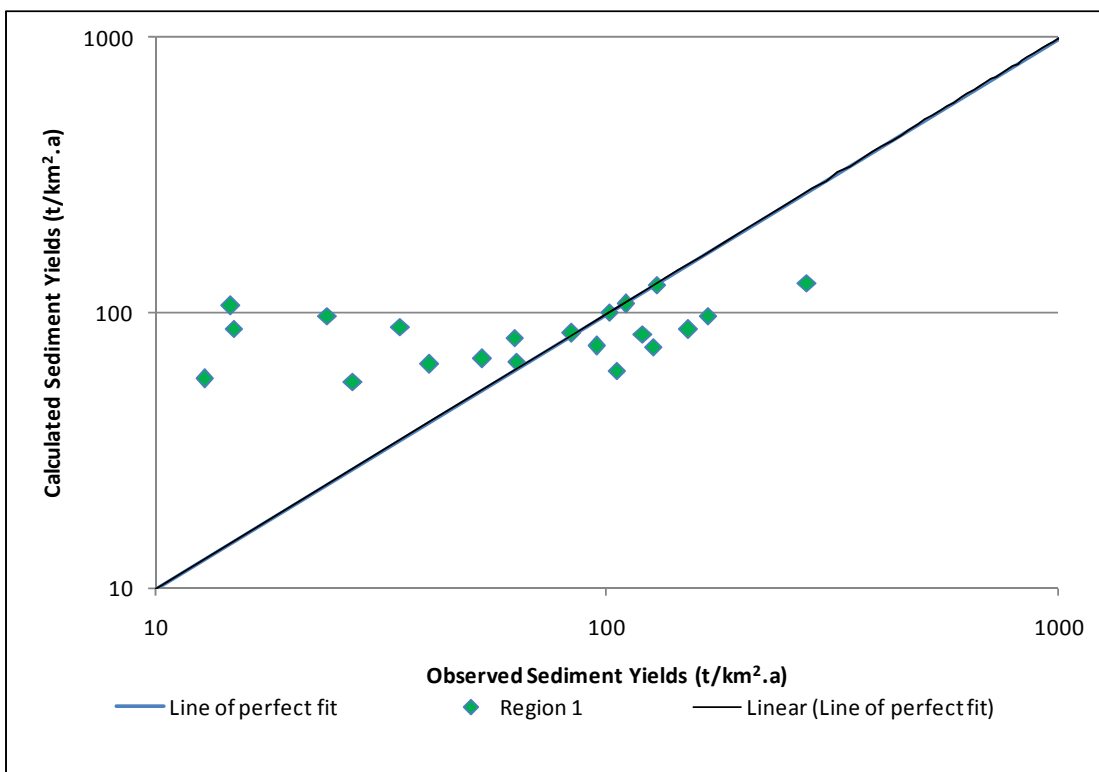




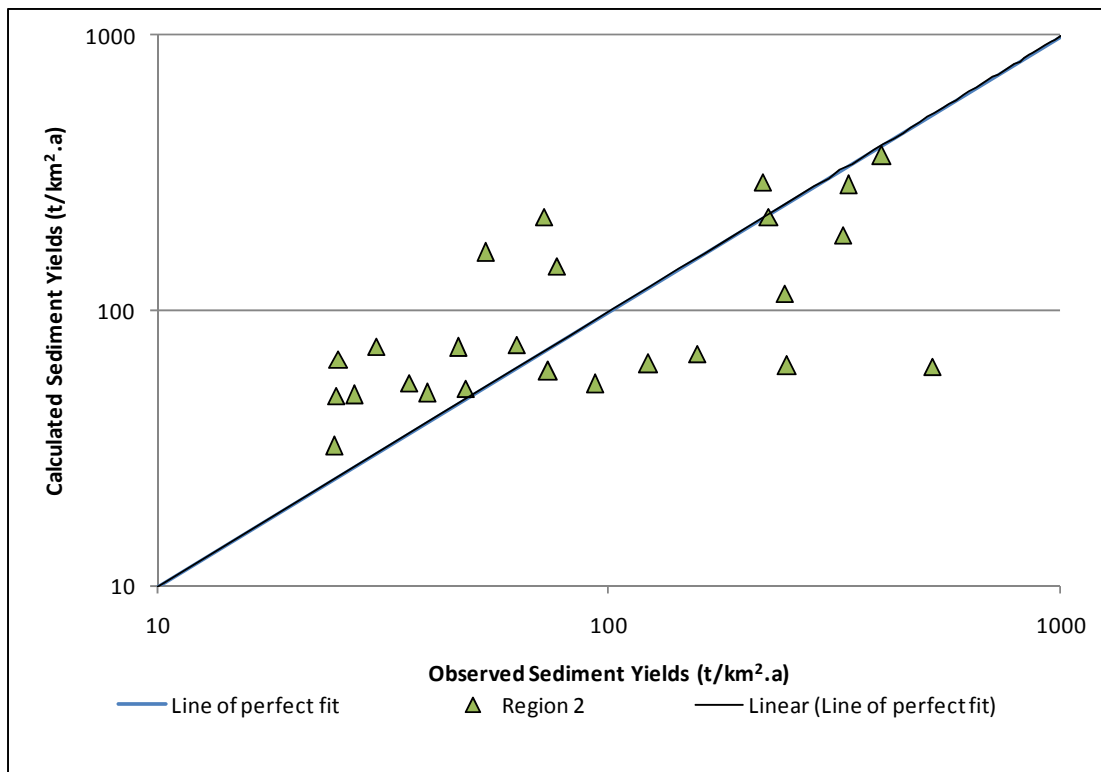
APPENDIX G SIMULATED AND OBSERVED DATA USING THE PROBABILISTIC METHOD



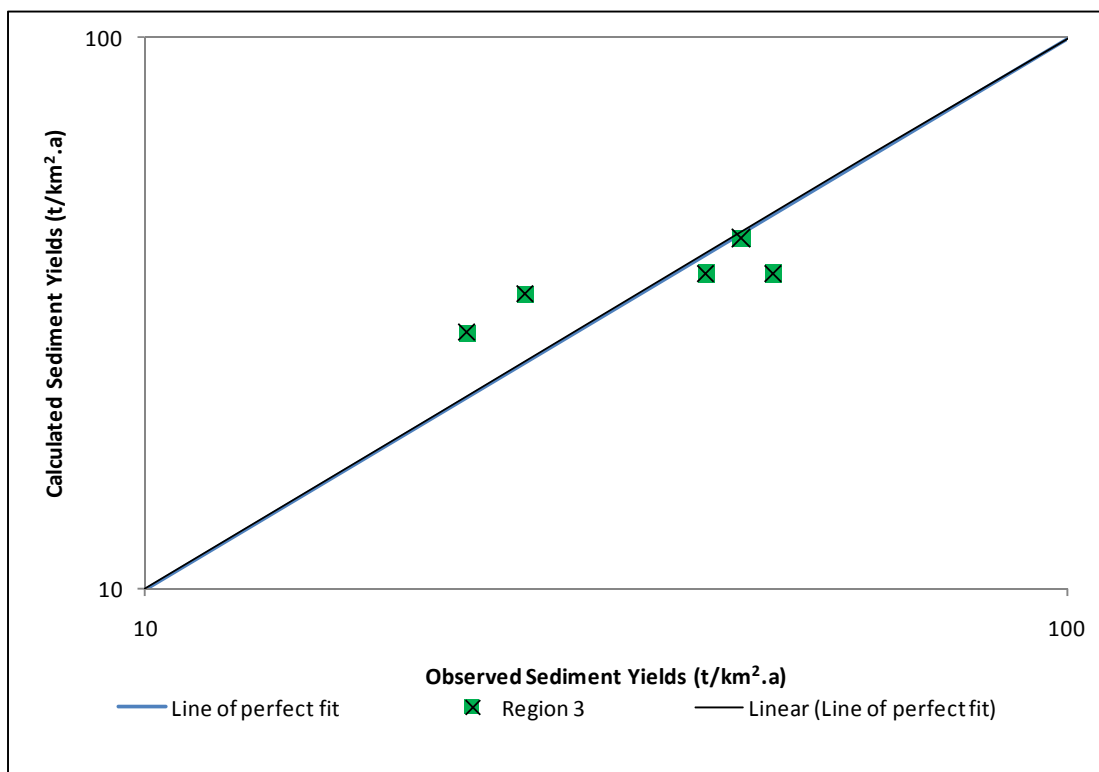
Simulated and observed data for all regions using the probabilistic method



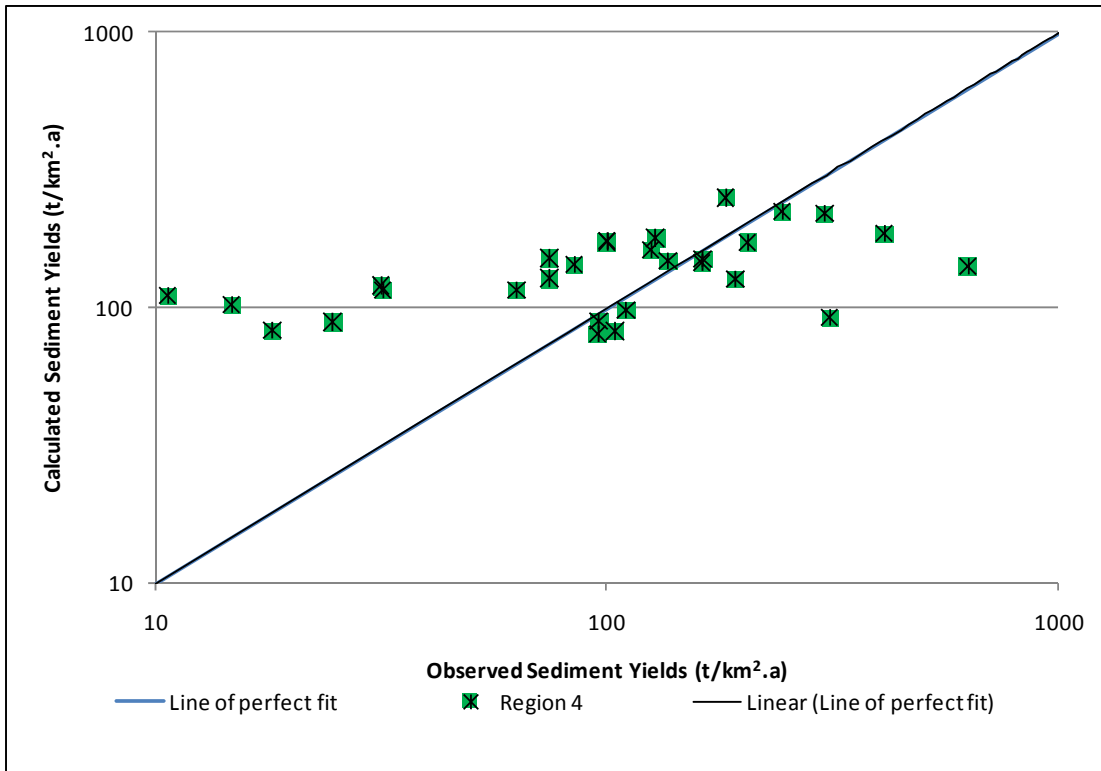
Simulated and observed data for Region 1 using the probabilistic method



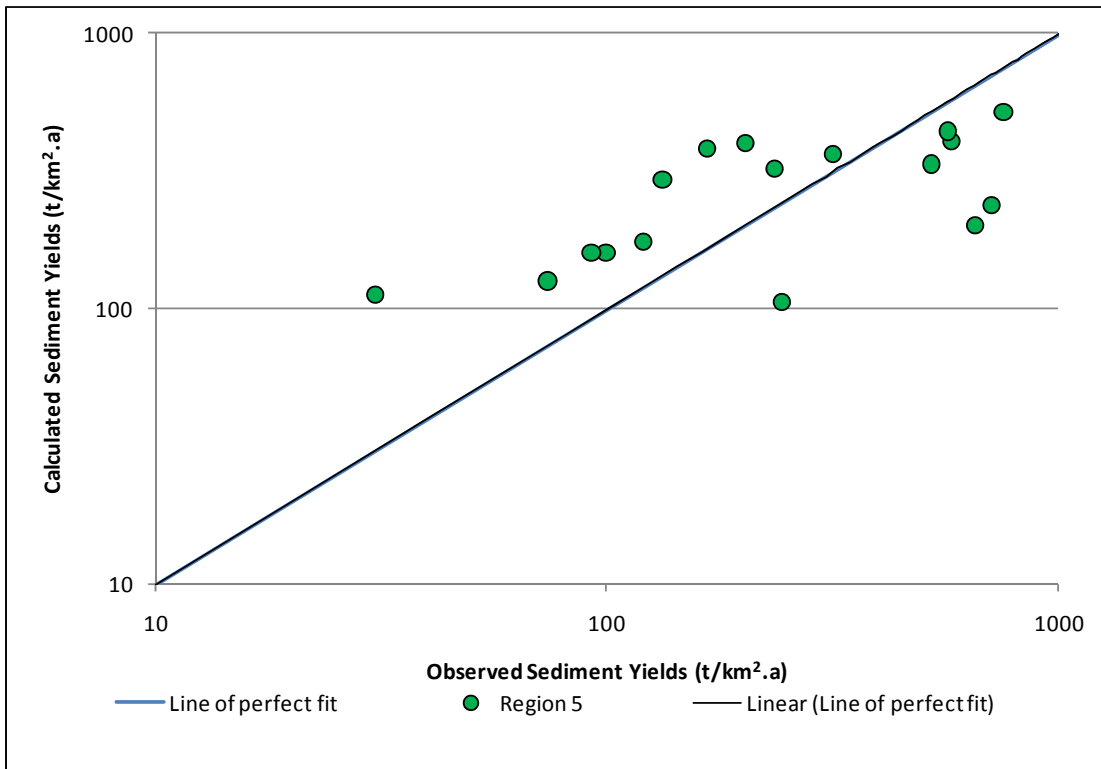
Simulated and observed data for Region 2 using the probabilistic method



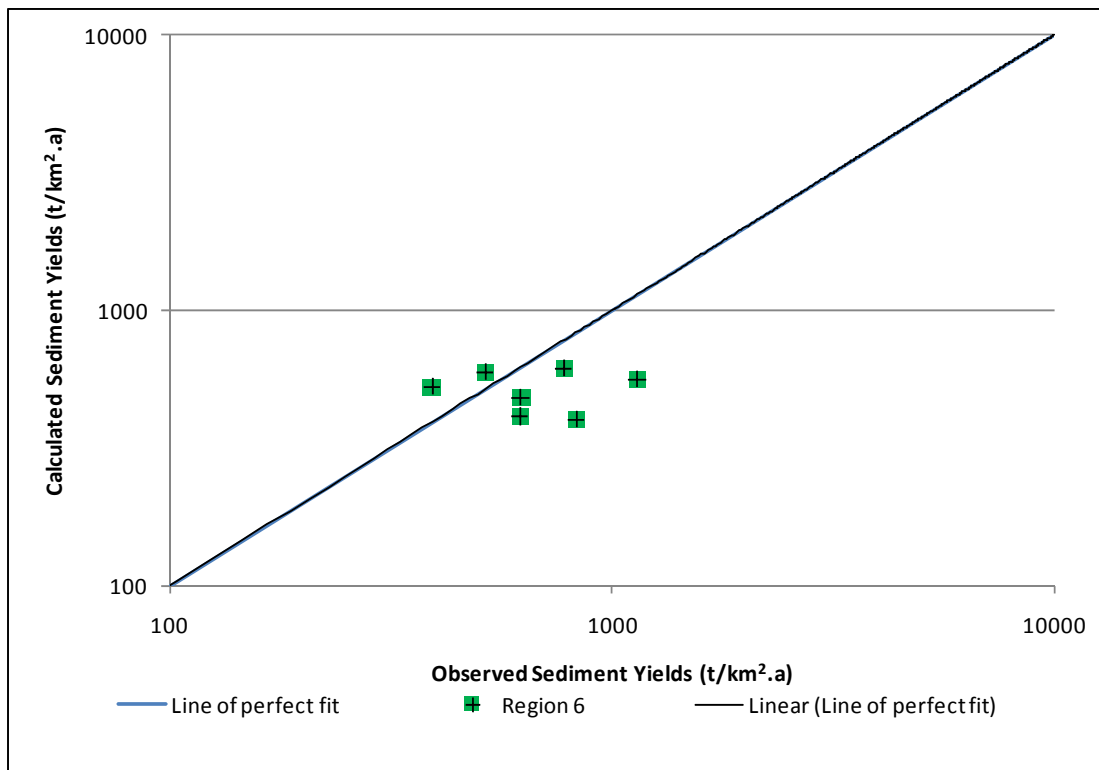
Simulated and observed data for Region 3 using the probabilistic method



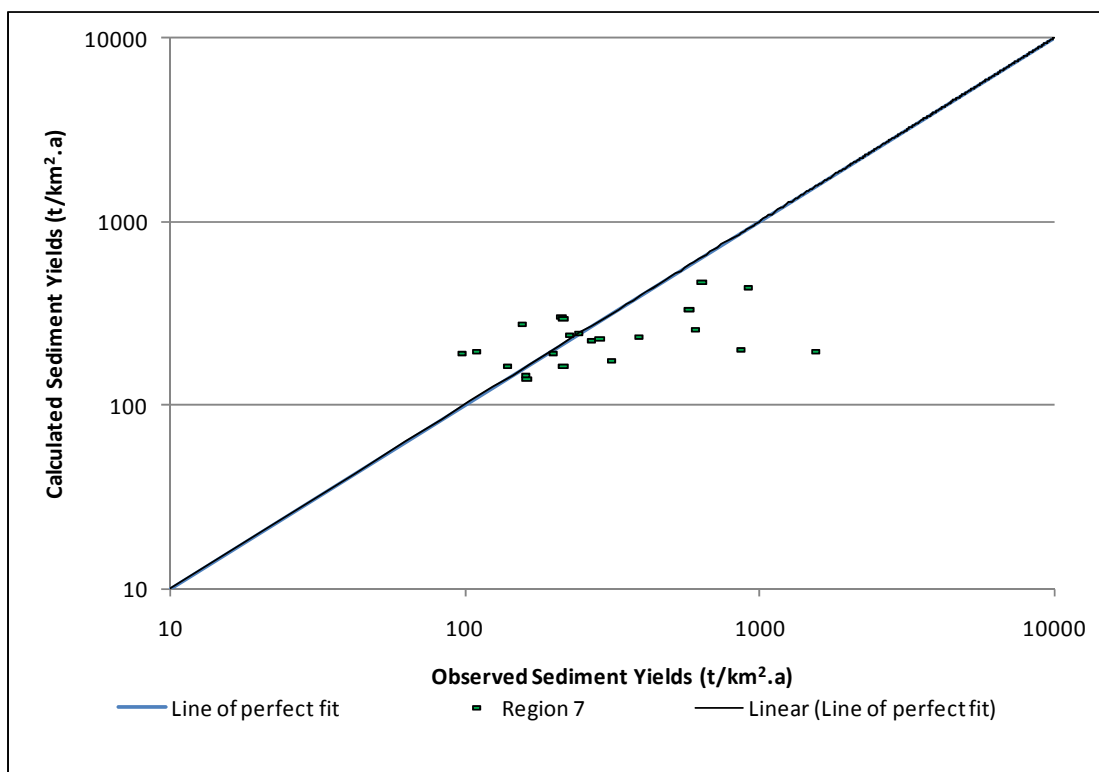
Simulated and observed data for Region 4 using the probabilistic method



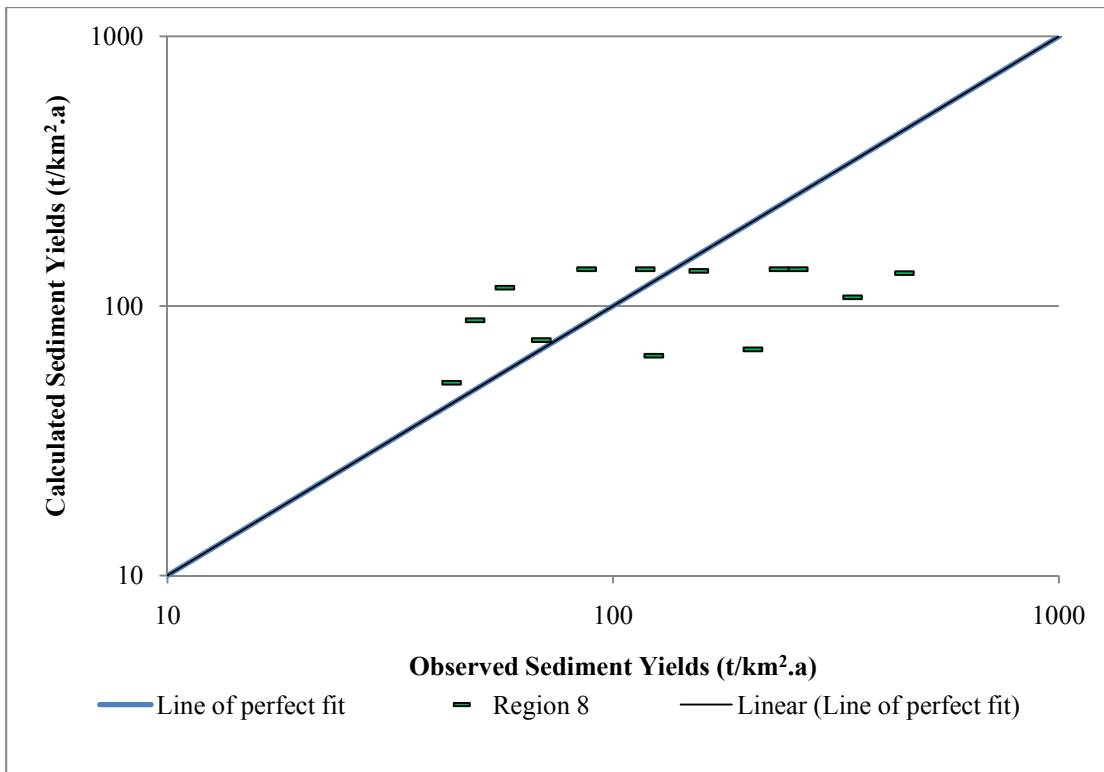
Simulated and observed data for Region 5 using the probabilistic method



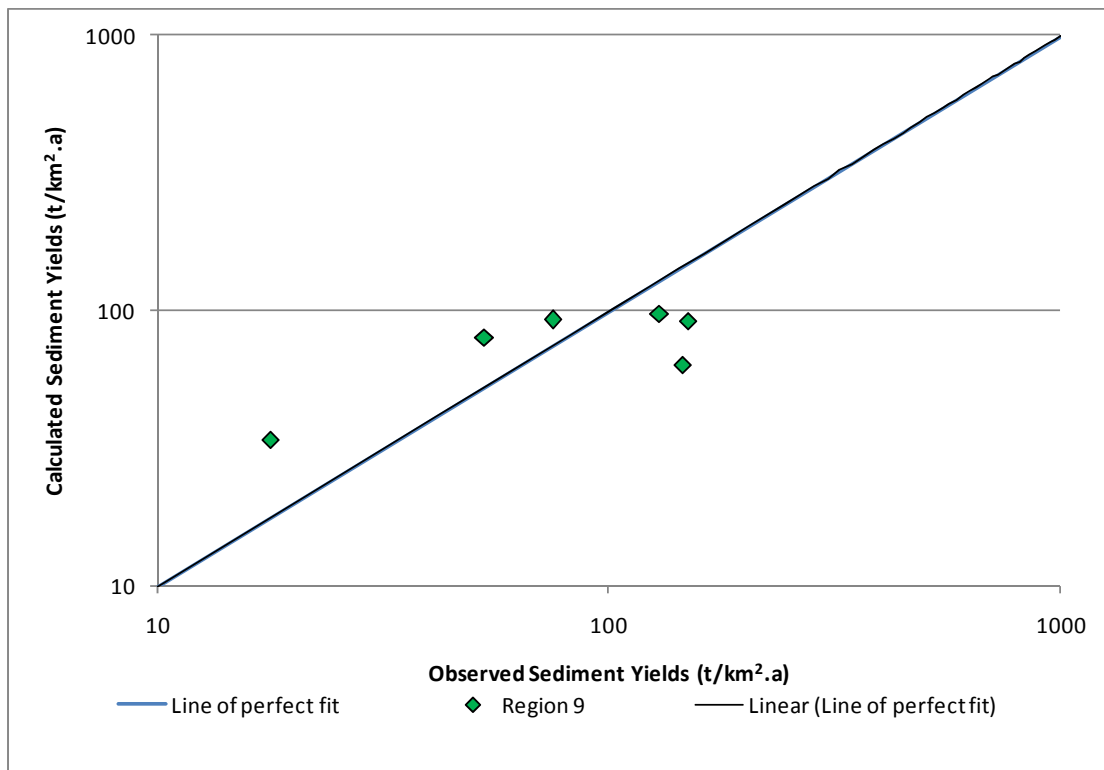
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Simulated and observed data for Region 7 using the probabilistic method

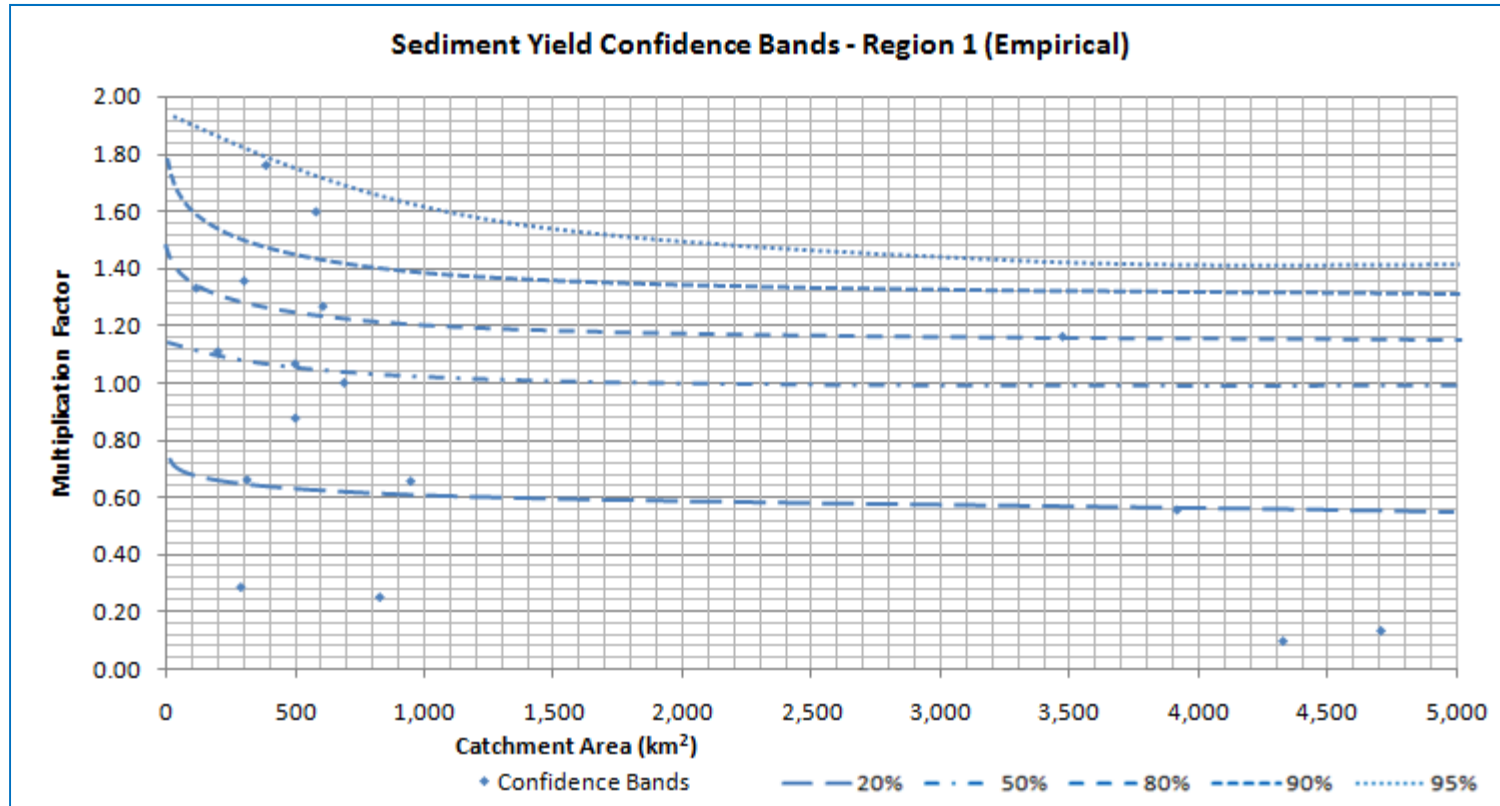


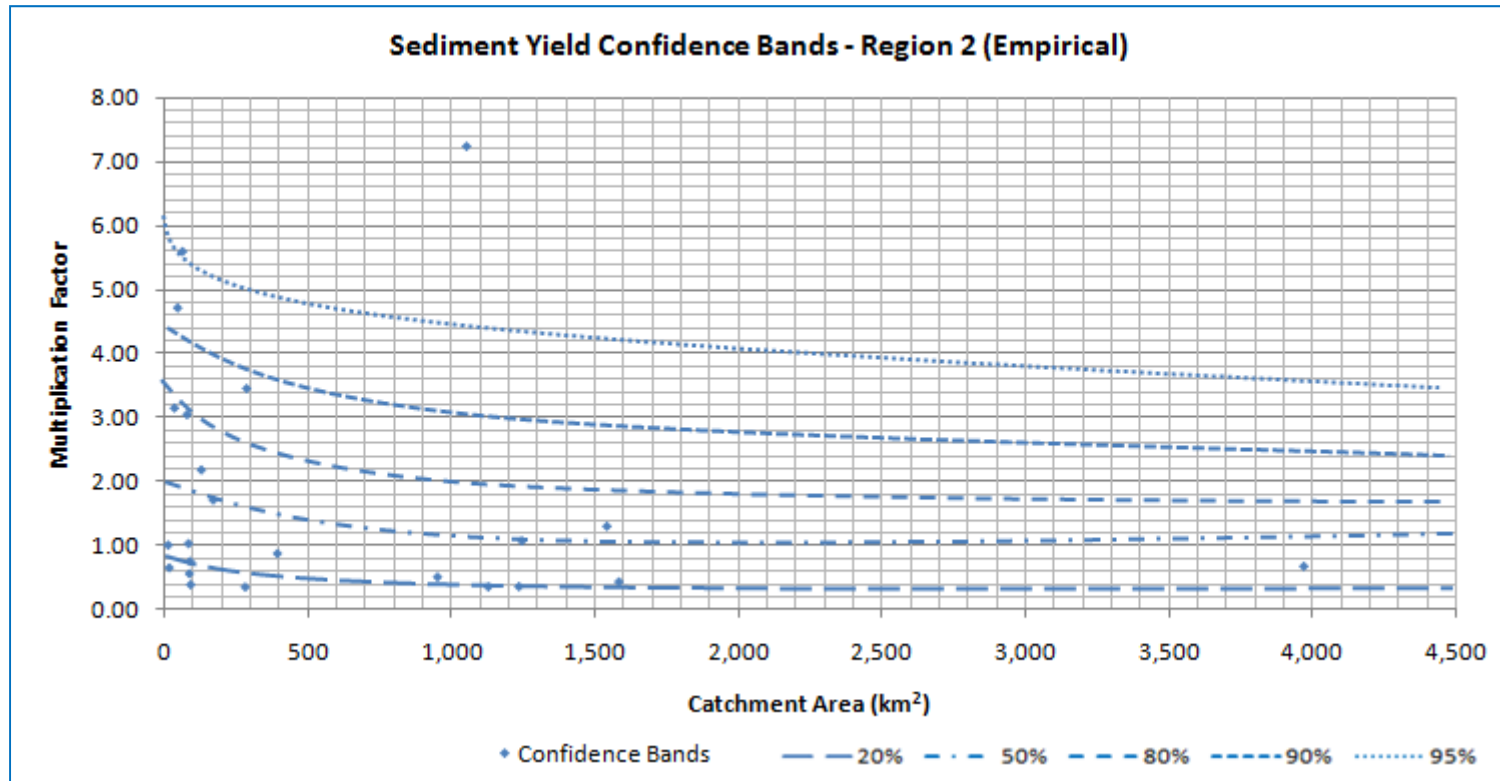
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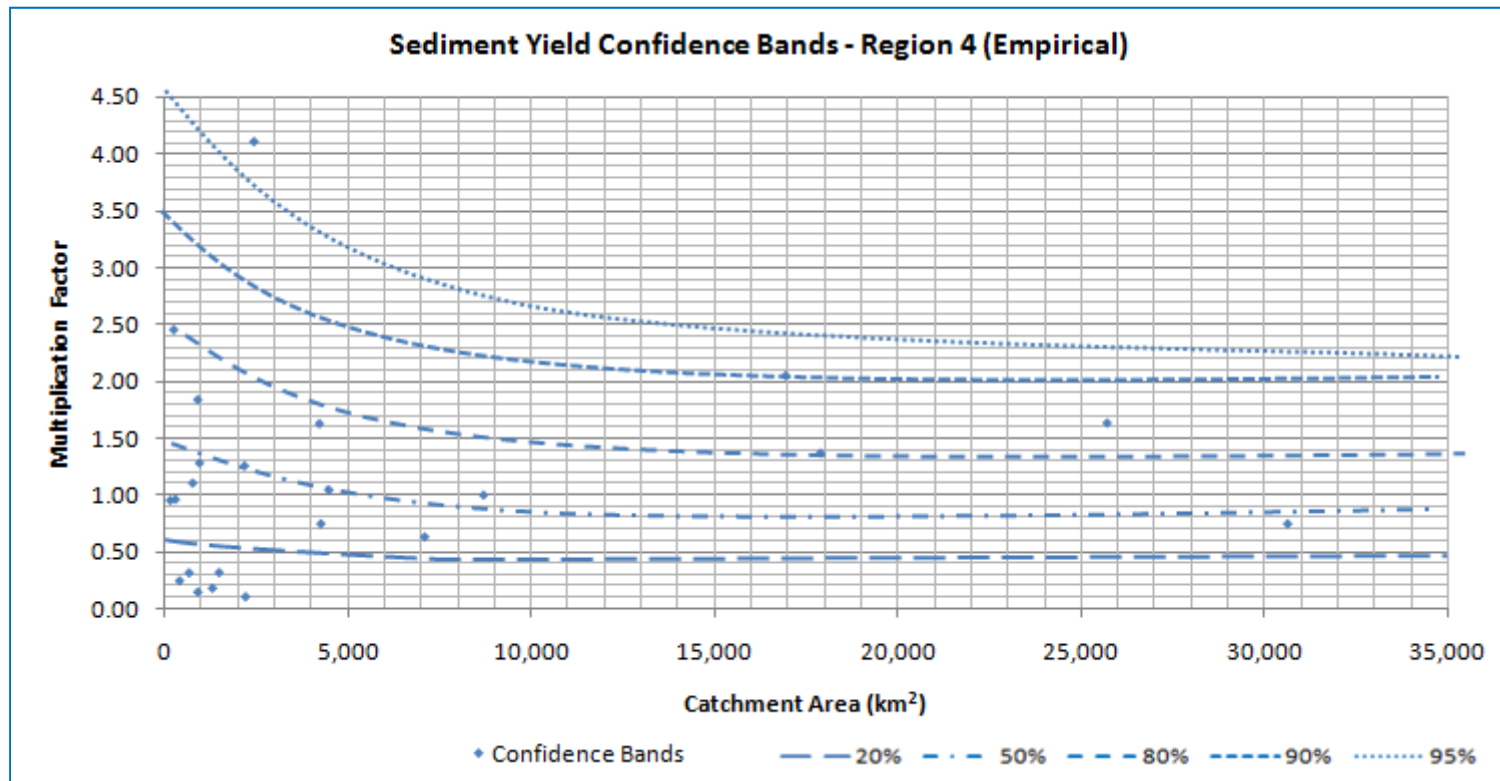


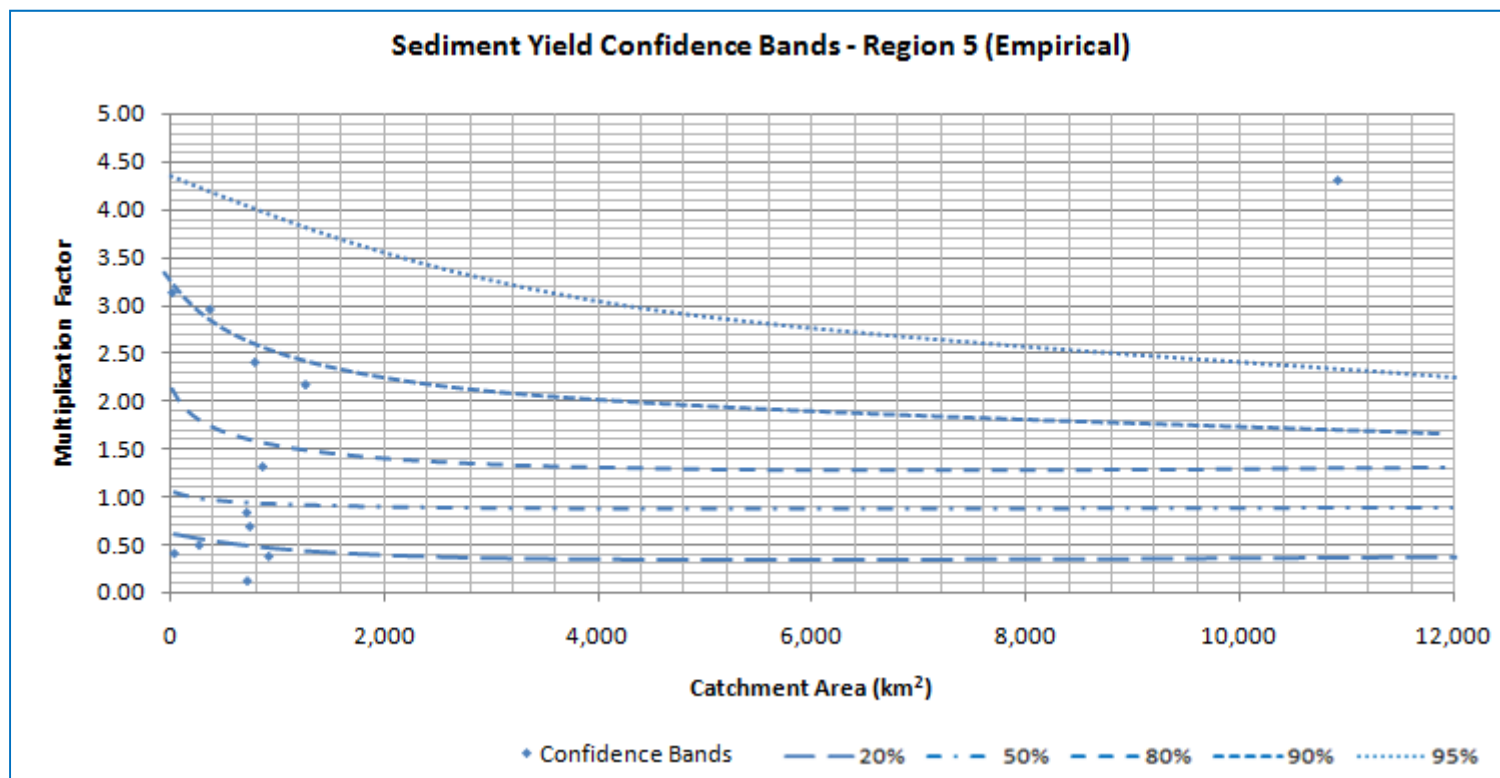
Simulated and observed data for Region 9 using the probabilistic method

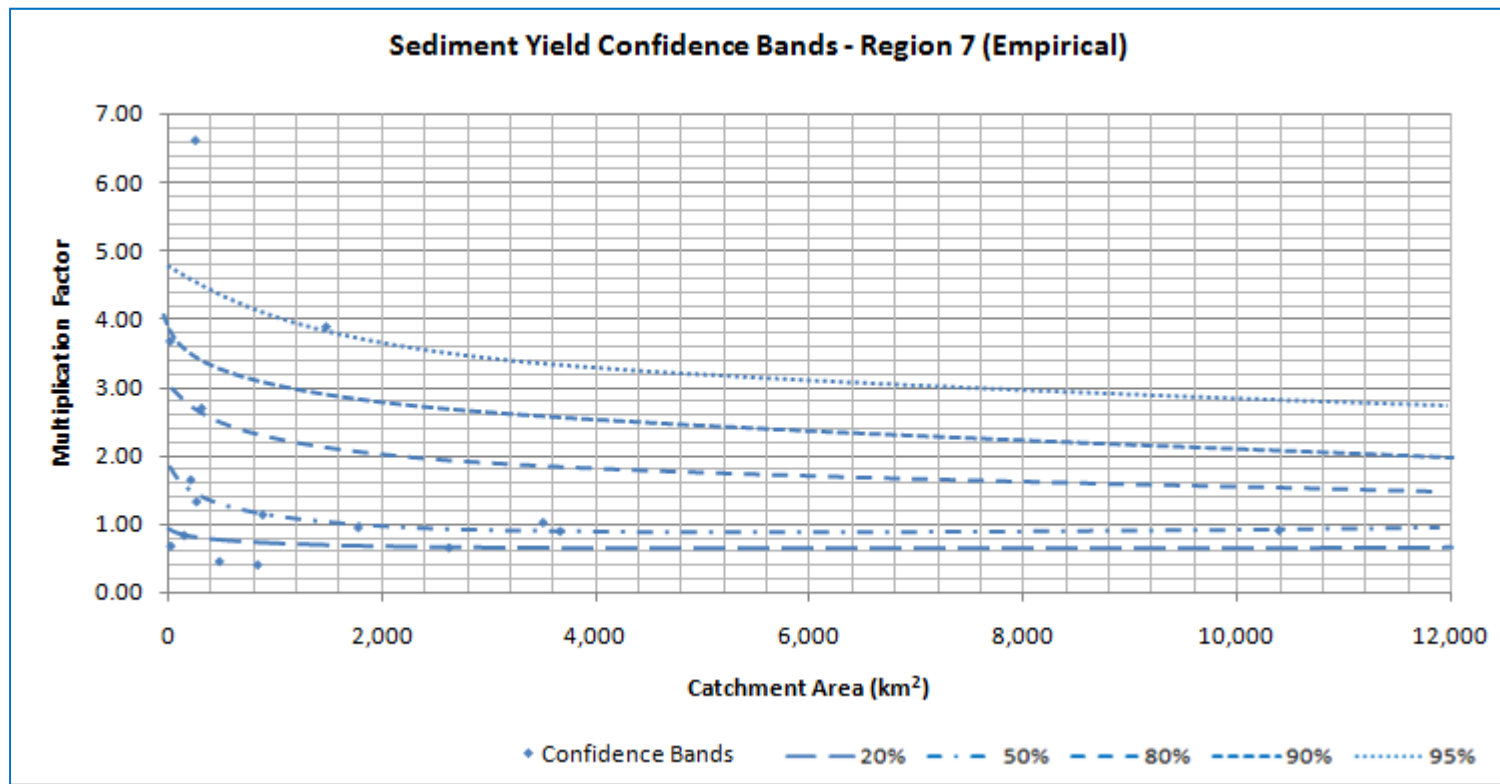
APPENDIX H REGIONAL SEDIMENT YIELD CONFIDENCE BANDS – EMPIRICAL METHOD

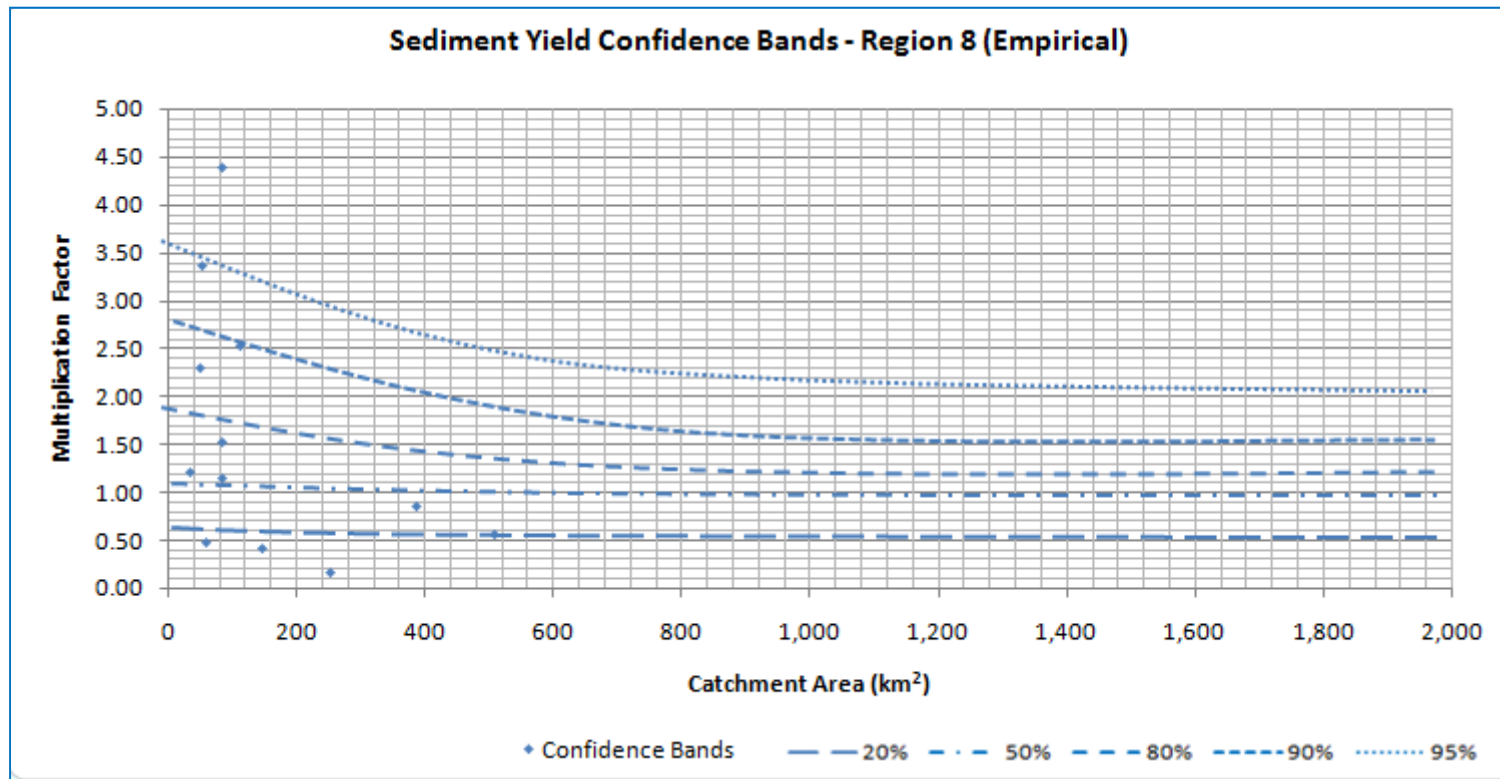




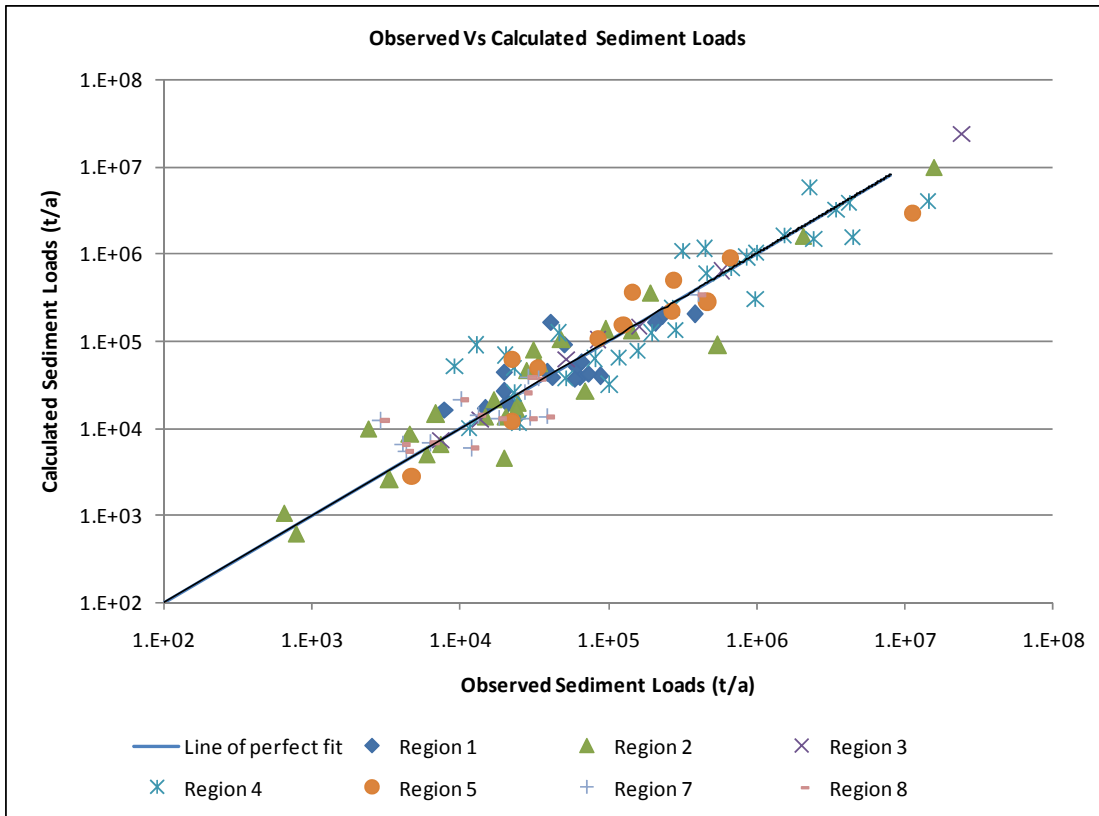




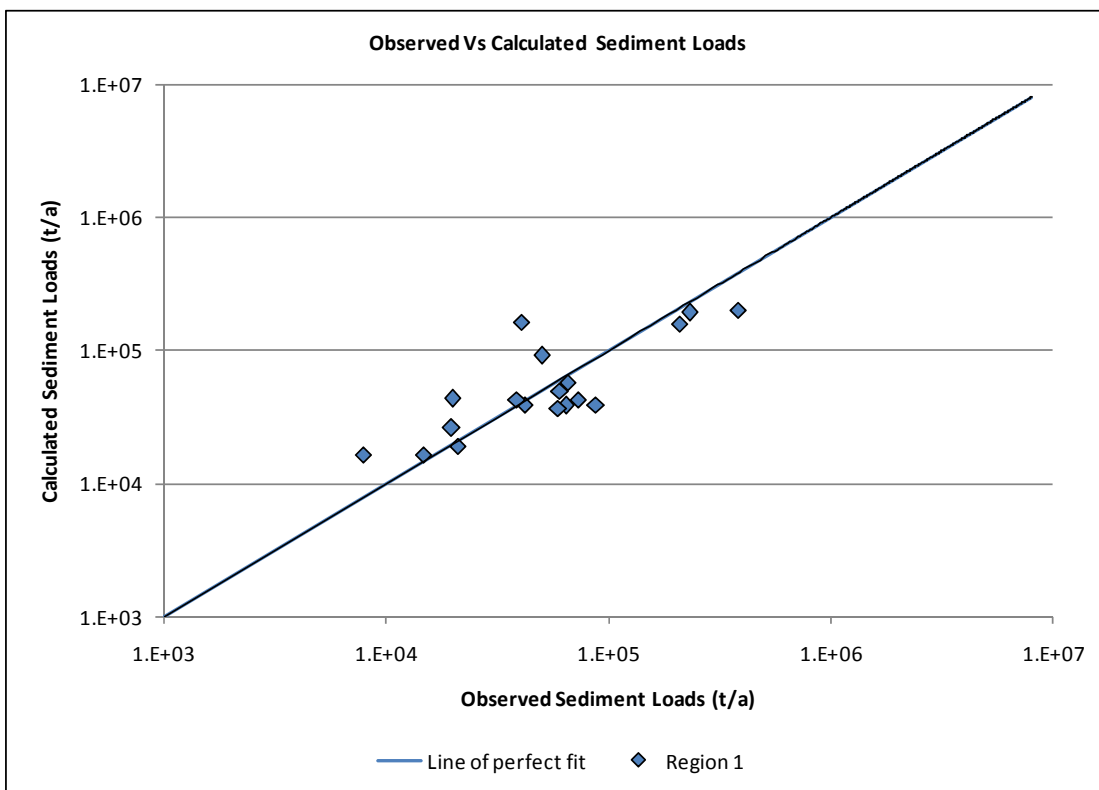




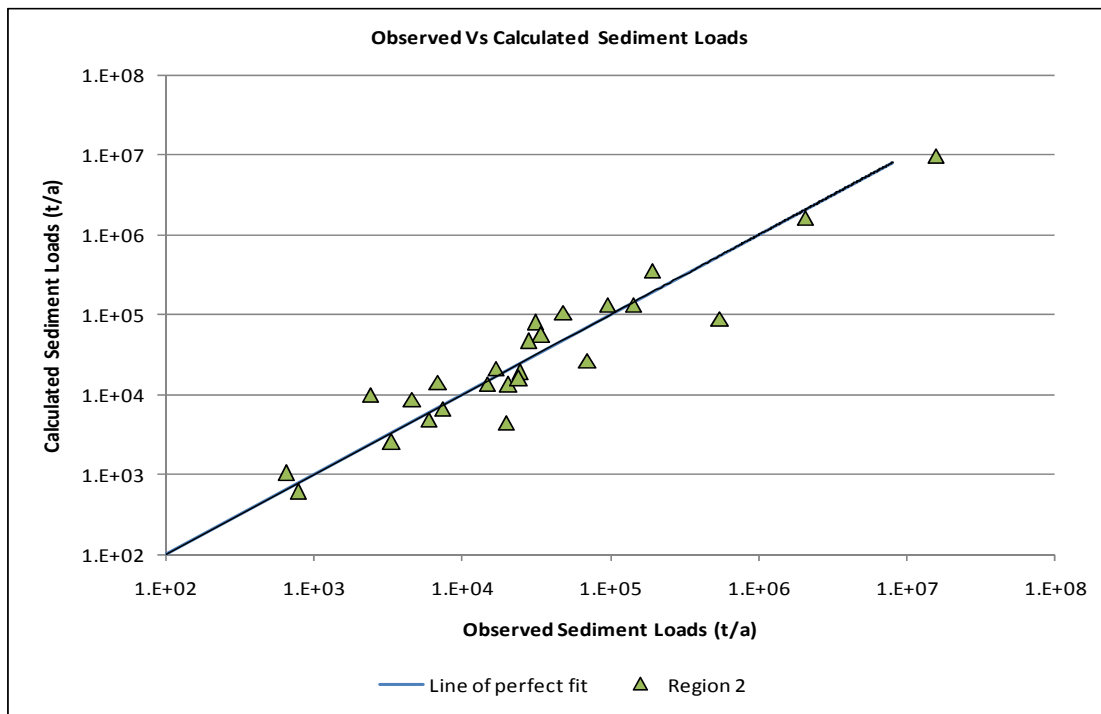
**APPENDIX I SIMULATED AND OBSERVED DATA USING
THE EMPIRICAL METHOD**



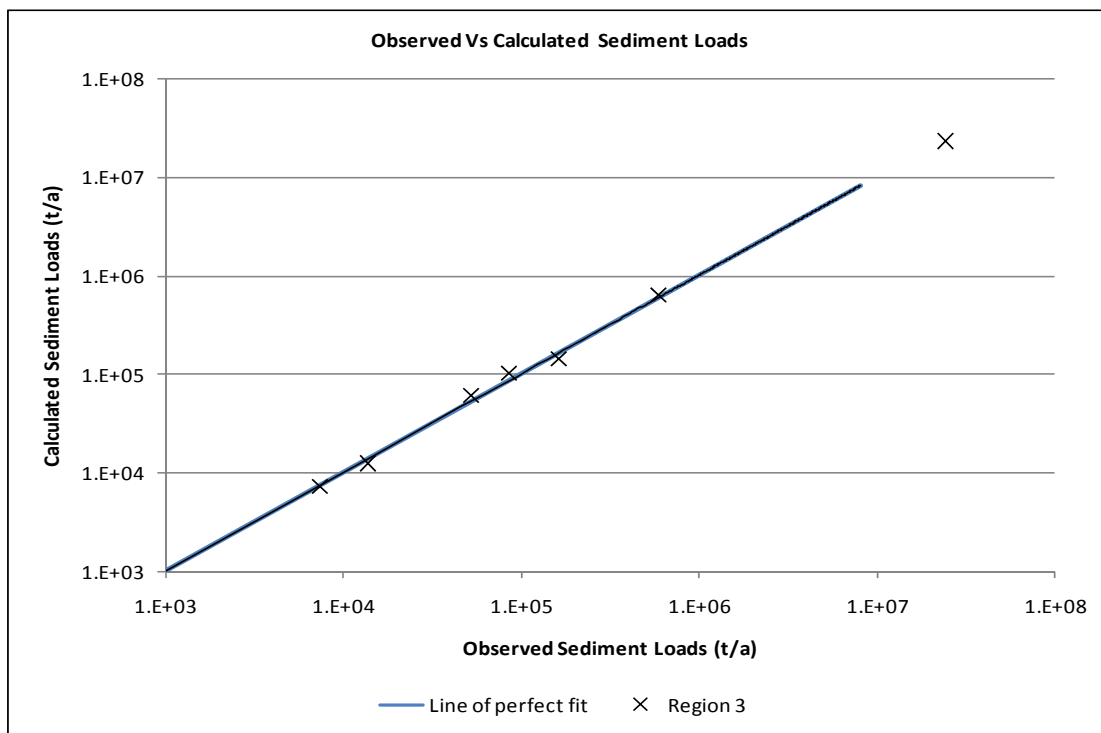
Simulated and observed data for all regions using the empirical method



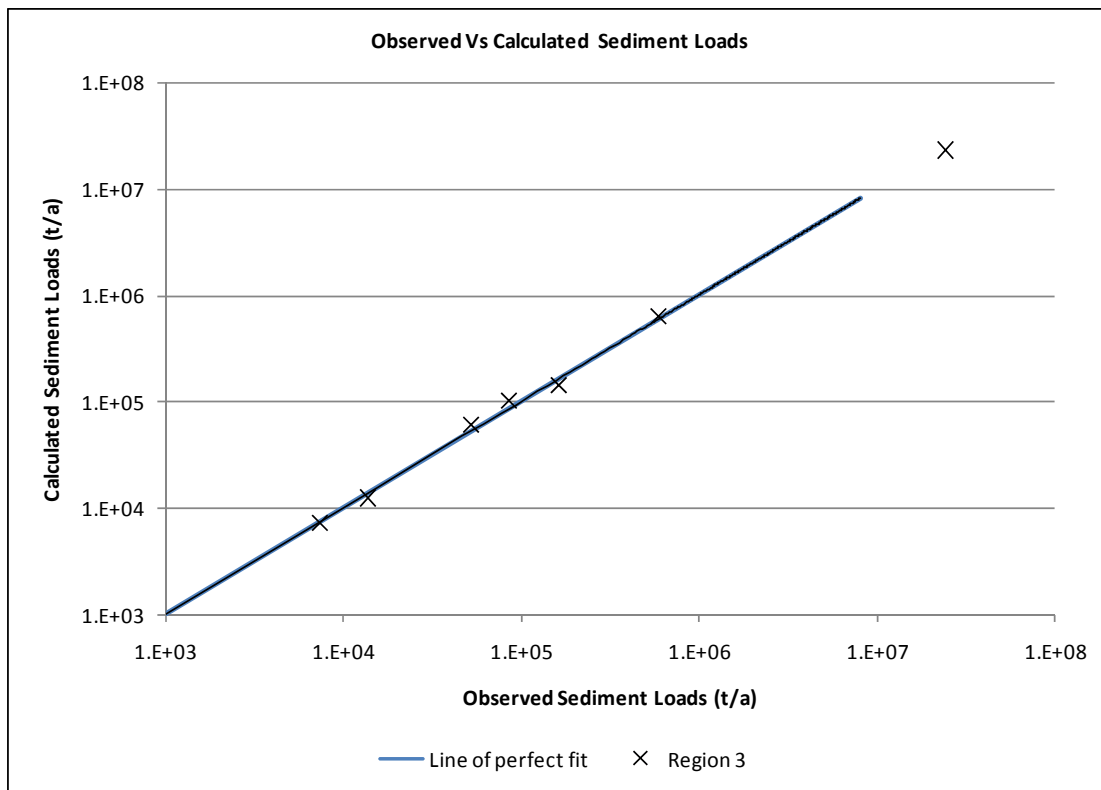
Simulated and observed data for Region 1 using the empirical method



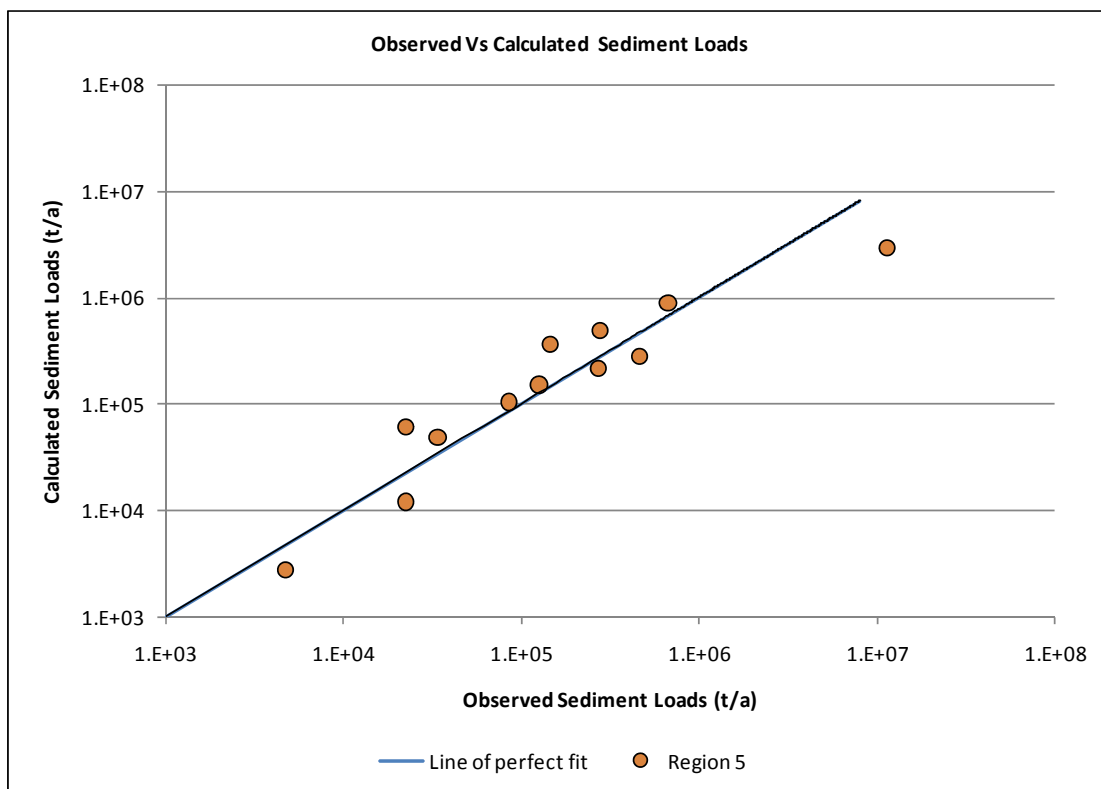
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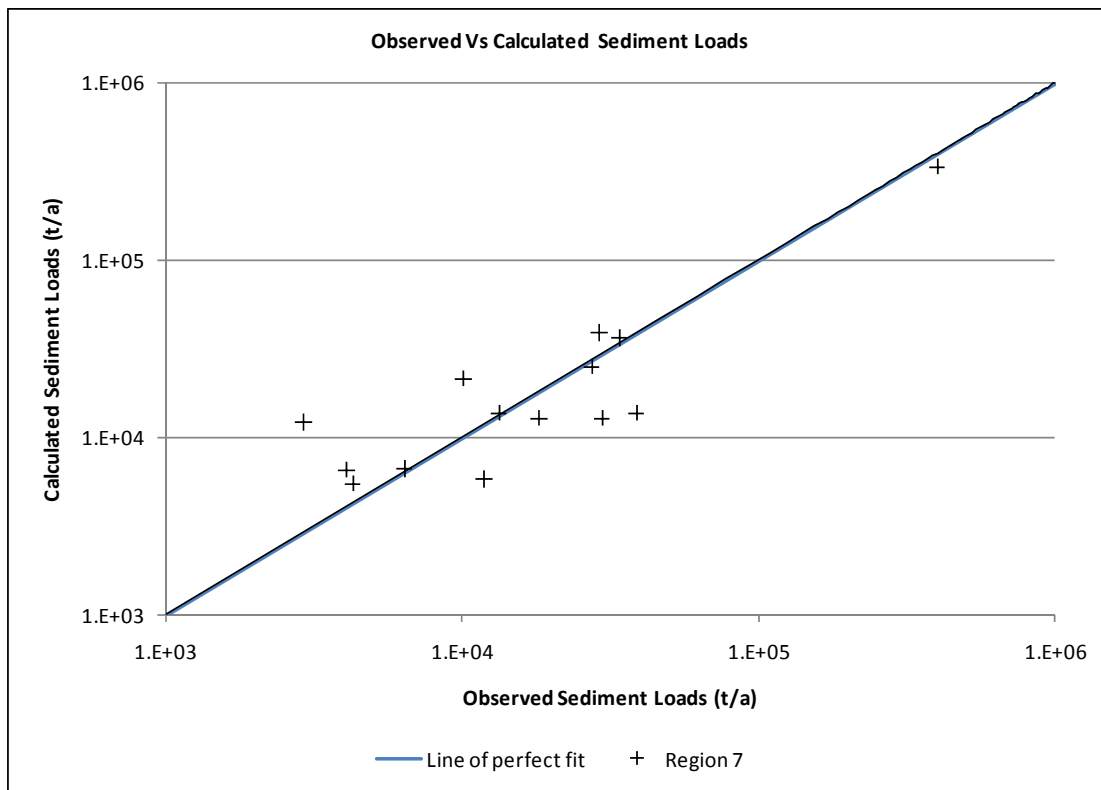
Simulated and observed data for Region 3 using the empirical method



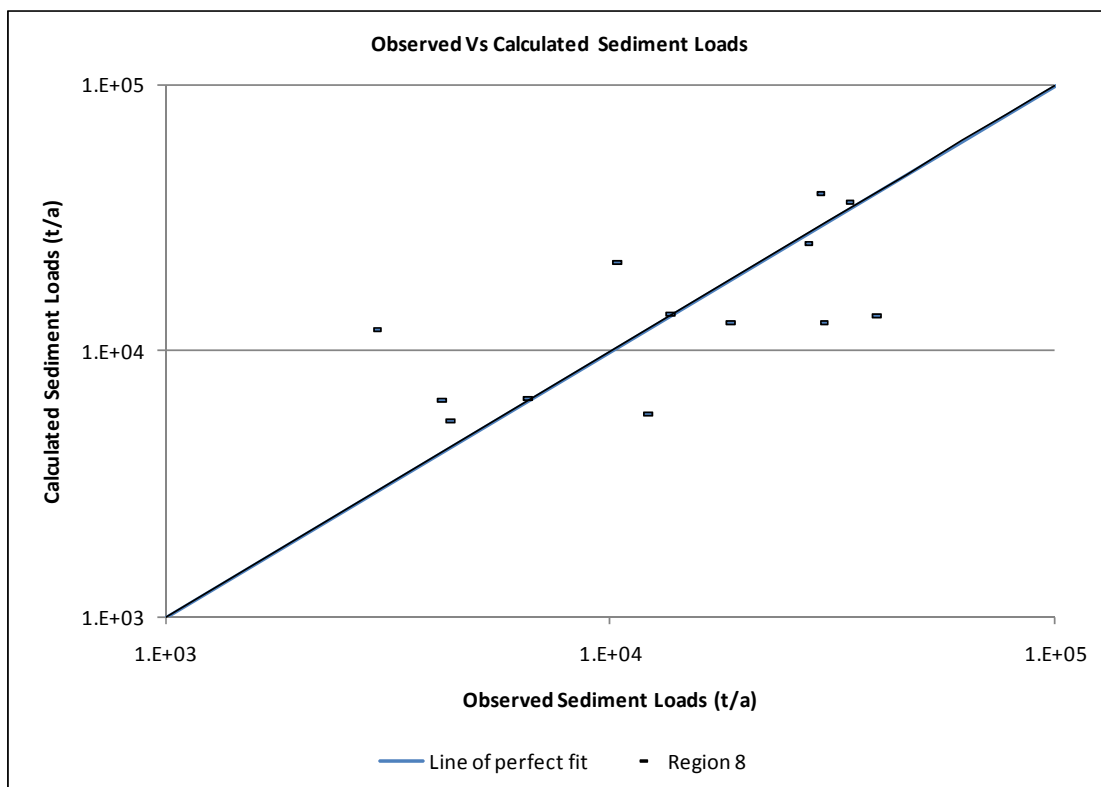
Simulated and observed data for Region 4 using the empirical method



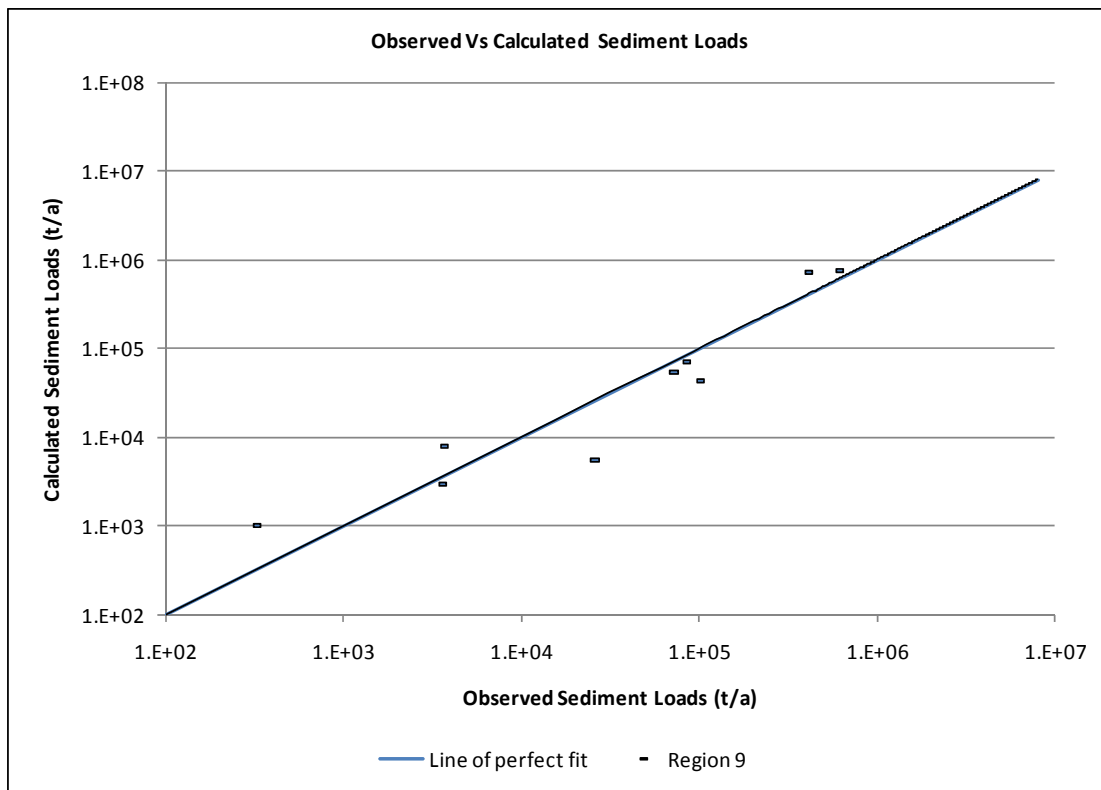
Simulated and observed data for Region 5 using the empirical method



Simulated and observed data for Region 7 using the empirical method



Simulated and observed data for Region 8 using the empirical method



Simulated and observed data for Region 9 using the empirical method

**APPENDIX J (a) SOIL EROSION PREDICTION IN SOUTH AFRICA:
EXISTING KNOWLEDGE AND LIMITATIONS**

BY

Le Roux, JJ

1. Soil Erosion prediction in South Africa: existing knowledge and limitations

1.1 General

1.1.1 The need for soil erosion indicators

Previous research indicates that more than 70% of South Africa (SA) is affected by varying intensities of soil erosion. The National Department of Agriculture has identified that there is a research need to improve techniques of estimating the soil erosion risk at a national level so that:

- Policy can be targeted to those areas where the greatest need exists.
- Soil erosion hazard maps on a national scale can be created (EEA, 2003) and used to make objective comparisons that are important for targeting of research and soil conservation efforts (Smith et al., 2000).
- Assessment of state of the environment studies can be assisted, in particular natural resources such as soil.
- Scenarios can be modelled to see what the effects of different land use will have on erosion.

The soil erosion hazard depends on the combined and interactive effects of climate, soil profile, relief, land use and vegetation, and cultivation system, also known as the soil erosion factors, namely rainfall erosivity, soil erodibility, slope steepness and slope length, crop management, and support practice factor (Wischmeier and Smith, 1978). A methodology to assess soil erosion would therefore need to take these factors into account.

1.1.2 Previous studies

The Global Assessment of Human Induced Soil Degradation (GLASOD) was one of the first major regional-scale degradation studies conducted by recognized experts in several countries across the globe (Oldeman et al., 1991), including South Africa (Laker, 2004). Experts divided soil erosion areas into relatively uniform units based on the most important erosion processes. From this a relative ranking of soil erosion risk per area was obtained and a soil erosion risk map was produced at a continental scale.

The Department of Agriculture (DoA) and the Water Research Commission (WRC) funded a number of regional-based research projects. At the request of the WRC, a sediment yield map for southern Africa was developed in 1991 (Rooseboom et al., 1992; Verster, 1992). Relevant geographical information which influences sediment yield values of small to very large catchments (14 to 60 000 km²) was gathered, including soil erodibility, rainfall, slope and land use. The sediment yield map was created using a combination of soil and slope factors extracted from published and unpublished land type data prepared by the Agricultural Research Council (ARC) – Institute for Soil, Climate and Water (ISCW) (Land Type Survey Staff, 1972-2006). However, more detailed maps derived from satellite imagery were necessary for measuring and monitoring soil degradation on a national scale.

In 1993, the ARC-ISCW was contracted by the DoA to investigate the use of remote sensing and GIS in soil degradation management. As a result, the Erosion Susceptibility Map was produced at a scale of 1:2.5 million. This map was created by integrating a green vegetation cover map produced from NOAA satellite data (Pretorius, 1995) with the sediment yield map of southern Africa (Verster, 1992). Research continued in 1998 with a second attempt to integrate the main erosion contributing factors at a national level. As a result, the Predicted Water Erosion Map (PWEM) was produced at a scale of 1:2.5 million using the Universal Soil Loss Equation (USLE) within a GIS framework (Pretorius, 1998). The methodology, however, is based on a considerable simplification of the USLE for which there is a massive database for US conditions, but little systematic data for SA. The sediment yield map of Verster (1992) and green vegetation cover map mentioned above were used to account for the soil-slope and vegetation factors, respectively.

Improvements to the Erosion Susceptibility Map include the inclusion of rainfall erosivity data obtained from the iso-erodent map of Smithen and Schulze (1982). However, PWEM gives percentage differences in erosion between regions without giving absolute values and is only suitable to prioritize problem areas at a broad scale due to the coarse resolution (1.1 km) of NOAA images. Subsequently, the ARC-ISCW was contracted to conduct studies at a provincial scale.

The ARC-ISCW completed the mapping and monitoring of natural resources of the Mpumalanga Province in 2000 (Wessels et al., 2001a). A similar project was completed for the Gauteng province in 2001 (Wessels et al., 2001b), as well as for the OR Tambo and Umkhanyakude Integrated Sustainable Rural Development Strategy (ISRDS) Nodes located in northern Eastern Cape and KwaZulu-Natal in 2004 (Ströhmenger et al., 2004).

The Revised USLE (RUSLE) was applied in a spatial context by using various remote sensing and GIS applications. Soil erosion was assessed by using three different approaches including: an erosion susceptibility map based on climate, soil and topography; a soil erodibility index that divides the province into highly erodible and non-erodible land; and erosion hazard under current land uses as predicted by soil erosion modelling. Climate and vegetation parameters were determined similarly to the above-mentioned techniques used for PWEM. Topography factors were facilitated with the application of digital elevation models with a resolution of 75 m. Soil maps (1:50 000 and 1:250 000) (Soil Survey Staff, 1973-1987) were used to obtain soil erodibility ratings for the individual soil series of the Binomial Soil Classification System of SA and erodibility values were linked to corresponding soil series in the Land Type Inventories (Land Type Survey Staff, 1972-2006) in order to be spatially displayed on a scale of 1:50 000.

In addition to the studies conducted by the ARC-ISCW and the DoA: Directorate Land and Resources Management (DLRM), the South African National Biodiversity Institute (SANBI) compiled a land degradation review of SA (Garland et al., 2000). This review was compiled using information obtained from 34 workshops throughout SA during 1997 and 1998. Results are presented as a series of maps illustrating the type and severity of soil degradation between land use types, including croplands, veld, forestry, conservation areas and settlements. Furthermore, the total soil degradation index for each magisterial district of SA was calculated by incorporating the severity, rate and percentage area of degradation of each land use type.

Clearly, methods to analyze and interpret broad spatial scales are becoming increasingly important for land degradation studies. Although the (R)USLE derived models are more appropriate in regional data needs, they are now recognized as lacking a physical basis which can be linked with current concepts and research in soil erosion (EEA, 2003). The growing need for geo-spatial techniques to support decision making provides the context for developing regional process models, which is another suitable alternative for future regional erosion risk assessment.

In some of these previous studies (e.g. Wessels et al., 2001a; Wessels et al., 2001b; Ströhmenger et al., 2004) regional soil loss models were applied in order to determine the erosion susceptibility of the physical environment and the erosion hazard by means of GIS and remote sensing techniques. During field verification by personnel of the DoA, it was found that some units displayed by the erosion susceptibility and hazard maps gave the

wrong impression of current soil loss damage and consequently a too severe or moderate classification of erosion susceptibility and hazard.

The research need to improve the spatial modelling of erosion in SA by revising the model components and techniques for estimating the climate erosivity, soil erodibility and topographical factors coverage, was therefore identified. To fulfil this research need, a study was awarded by the DoA, to the ARC-ISCW to improve the understanding of the factors governing erosion in SA by using a regional soil loss modelling approach. The aim of the study was to investigate soil loss model components and techniques of estimating climate erosivity, soil erodibility and topographical factors values for appropriateness under South African conditions in order to improve the spatial modelling of erosion in SA.

1.1.3 The ARC-ISCW's report "Improving Spatial Soil Erosion Indicators in South Africa" (Le Roux et al., 2006)

The report describes a spatial modelling framework which is used to predict water erosion (sheet and rill) at a national scale for SA. The approach used is based on the Revised Universal Soil Loss Equation (RUSLE) and spatial data layers for each of the contributing soil erosion factors, including rainfall erosivity, soil erodibility, topography and vegetation cover.

RUSLE groups the many influences on the erosion process into five categories including climate, soil profile, relief, vegetation and land use, and land management practices. These categories are known as the erosion factors, R, K, LS, C and P, respectively. The product of these factor values gives the expected soil loss (A) in t/ha/yr, depending on the dimensions used in the climate and soil factor. The equation is (Renard et al., 1994):

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (4.1-1)$$

where R is the rainfall erosivity in MJ·mm/(ha·hr·year), K is the soil erodibility in t/ha/(MJ/ha·mm/hr), L is the hillslope length, S is the hillslope gradient, C is the vegetation cover factor, and P is the supporting practice. A flowchart of the methodology used is given in Figure 1-1.

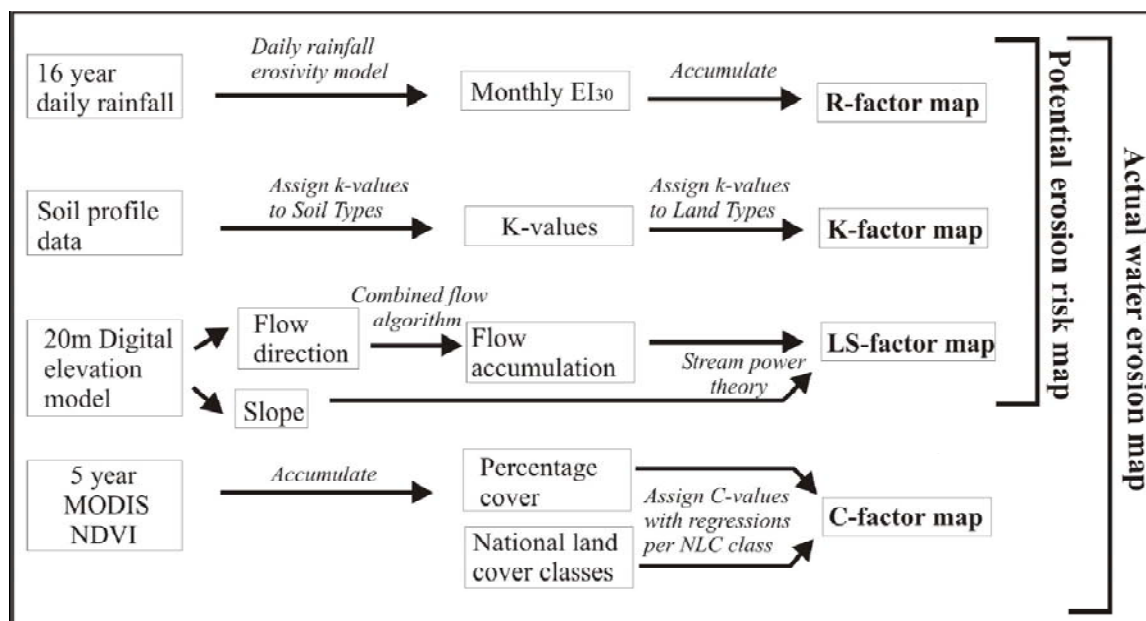


Figure 1-1: Flow chart of methodology used for the ARC-ISCW Soil Erosion Indicator project

Although RUSLE has been used in erosion studies before, the methodology was improved.

- **Erosivity (R)**

In the Universal Soil Loss Equation, climatic influence on soil erosion is represented by a rainfall and runoff factor, known as the R-factor. The R-factor is the mean annual sum of individual storm EI_{30} values (E is the total storm kinetic energy and I_{30} is the maximum 30-min rainfall intensity). However, reliable and long-term information on rainfall intensity is rarely available at a regional level and it is usually necessary to estimate rainfall erosivity from daily rainfall (Lu and Yu, 2002). In the current study, daily rainfall data was used as input to the daily rainfall erosivity model developed by Yu and Rosewell (1996a and 1996b) in Australia, to develop monthly EI_{30} surfaces for the entire SA. In addition, an interpolation method that compensates for topographical influences was developed instead of using a pure inverse distance weight technique which was used in previous studies. The resulting map is shown in Figure 1-2.

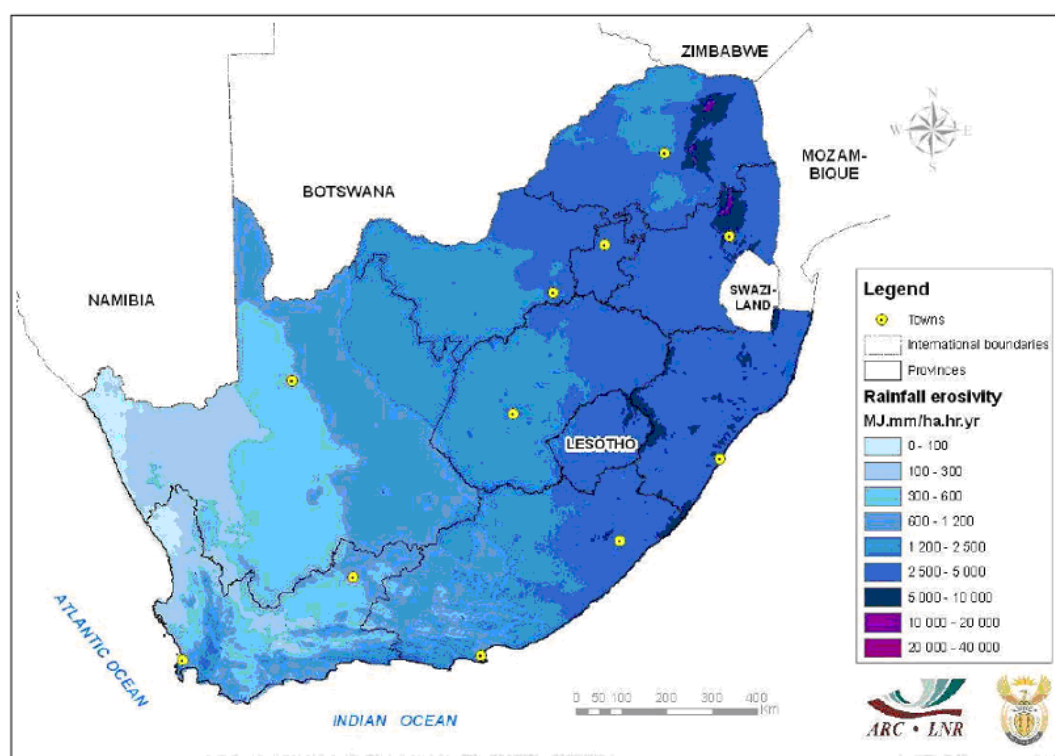


Figure 1-2: Rainfall erosivity map of South Africa

- **Soil erodibility (K)**

Soil erodibility accounts for the influence or response of soil properties on soil loss during rainfall events and is designated by the soil erodibility factor, K for (R)USLE. Wischmeier and Smith (1978) define K as the rate of soil loss per erosivity index unit for a specified soil as measured on a standard plot (22.1 m in length of uniform 9% slope in continuous clean tilled fallow). It is a lumped factor that represents the total soil response to a large number of dynamic soil erosion processes.

The K-factor may be estimated from data on the soil's particle size distribution, organic matter content, surface structure and profile permeability using the soil erodibility nomograph (Wischmeier and Smith, 1978). However, none of these soil data are available countrywide in digital form. Therefore, this study used an alternative approach similar to a study conducted in Australia (Carlile et al., 2001), using soil attribute polygon data for the estimation of K-values at a national scale. In the absence of soil analytical and experimental data, two alternative sources of soil information were used:

(1) Soil maps (1:50 000 and 1:250 000) (Soil Survey Staff, 1973-1987) were used to obtain soil erodibility ratings for the individual soil series of the Binomial Soil Classification System of SA; (2) and erodibility values were linked to corresponding soil series in the Land Type

Inventories (Land Type Survey Staff, 1972-2006) in order to be spatially displayed on a scale of 1:50 000 (see Figure 1-3).

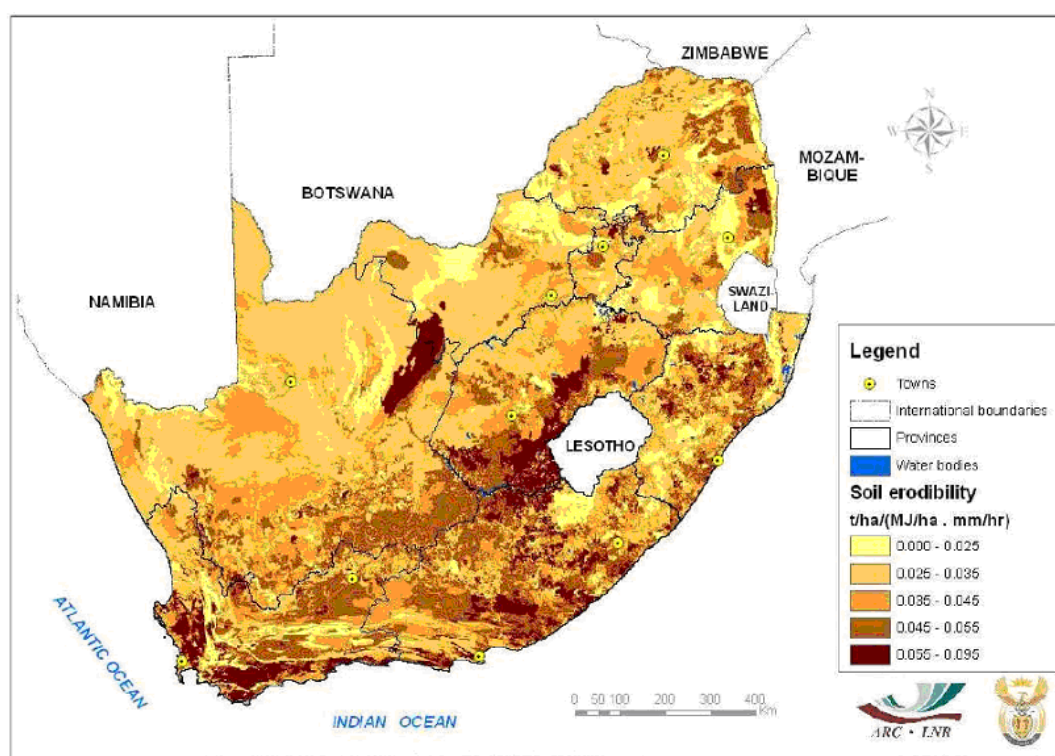


Figure 1-3: Soil erodibility map of South Africa

- **Topographical factors (LS)**

The effect of topography often operates at an essentially local level, erosion being initiated at specific locations on the slope, or in association with minor topographic variations (EEA, 1995). Several authors demonstrate that soil erosion is very sensitive to the topographical factor LS of the RUSLE (e.g. Risse et al., 1993; Mitasova et al., 1996; Wilson and Gallant, 2000; Biesemans et al., 2000; Gertner et al., 2002). For this reason, more detailed digital elevation data (20 m instead of 70 m or higher) (GISCOE, 2001) were used and the flow tracing refined using a combined flow algorithm (Schäuble, 2003), rather than single flow algorithms used in previous studies (see Figure 1-4).

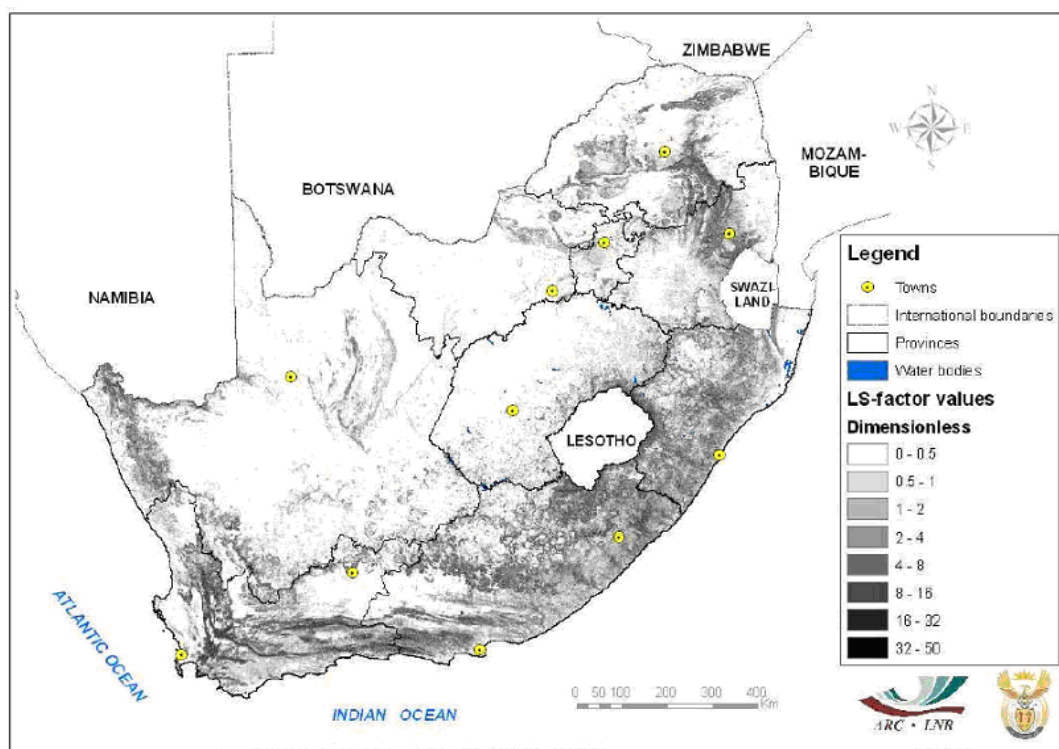


Figure 1-4: Topography factor (LS) map of South Africa

- **Potential soil loss map of South Africa**

The R, K and LS indicators were combined to create a potential soil erosion risk map of SA (see Figure 1-5). Potential soil erosion risk can be defined as the inherent susceptibility of the soil to rainfall erosion, irrespective of vegetation cover or land use (EEA, 1995). It is important in policy terms because it indicates those areas which are inherently susceptible to erosion, but which are presently protected by vegetation.

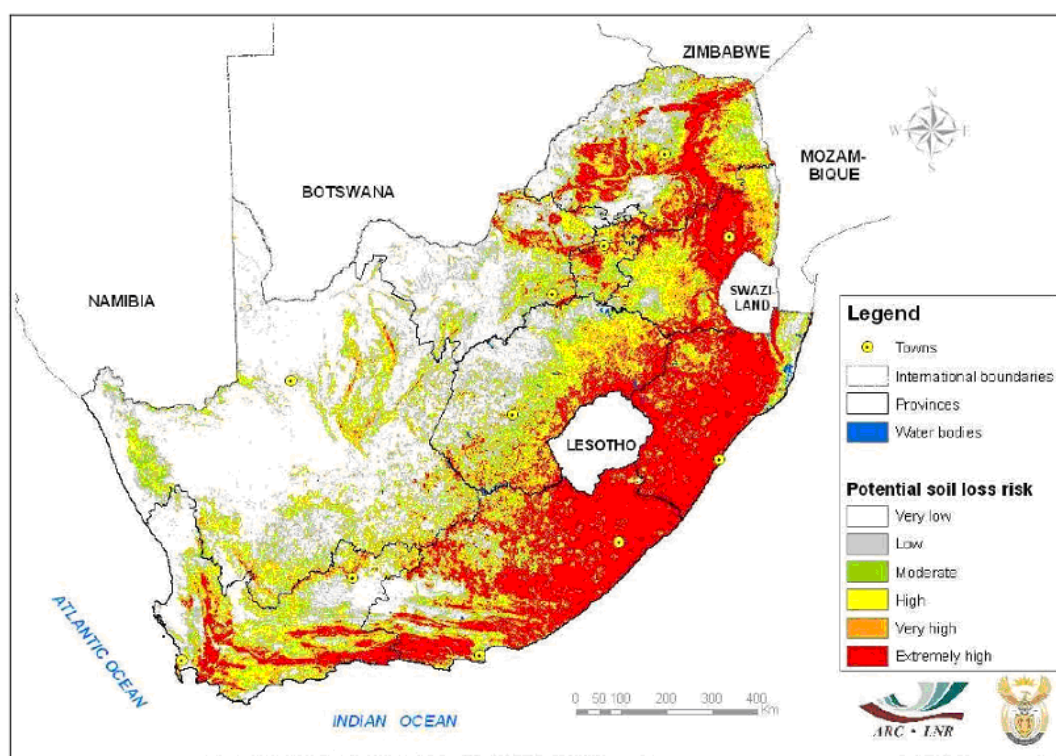


Figure 1-5: Potential erosion risk map of South Africa

- ***Cover and crop management factor (C)***

The (R)USLE C-factor is defined as the ratio of soil loss from land maintained under specified conditions to the corresponding loss from continuous tilled bare fallow (Wischmeier and Smith, 1978). Of all hazard factors, the cover management code is the most important soil erosion factor (Crosby et al., 1983; Renard et al., 1994; Garland, 1995; Evans, 2000). Not only does it represent conditions that can be managed to reduce erosion, but it also represents changes in land use. Therefore, a realistic estimate of the C-factor is essential if soil loss results are to be of any practical value.

Several authors state that the C-factor is the most critical part in soil loss modelling (e.g. Crosby et al., 1983; Garland, 1995; Lu et al., 2003). In order to obtain initial information for use in the RUSLE, most of the vegetation parameters, such as canopy cover and fall height, have to be measured for every crop system in the study area. However, since it is not possible to take field measurements at a national scale throughout the year, it was necessary to ascertain how crops change with time by means of remote sensing techniques and other sources of literature (e.g. Acocks, 1988; Low and Rebelo, 1998).

Remote sensing products, such as the Normalised Difference Vegetation Index (NDVI) provide temporal information and are an important source of information for vegetation cover (EEA, 2003). Actual soil erosion risk, which relates to the current risk of erosion under present vegetation and land use conditions, was accounted for by means of satellite imagery NDVI from MODIS images between 2000 and 2004 instead of NOAA. Vegetation cover index (C) values were assigned to mapping units on the National Land Cover (2000) map of SA through regression equations between vegetation cover and MODIS-derived spectral index (see Figure 1-6).

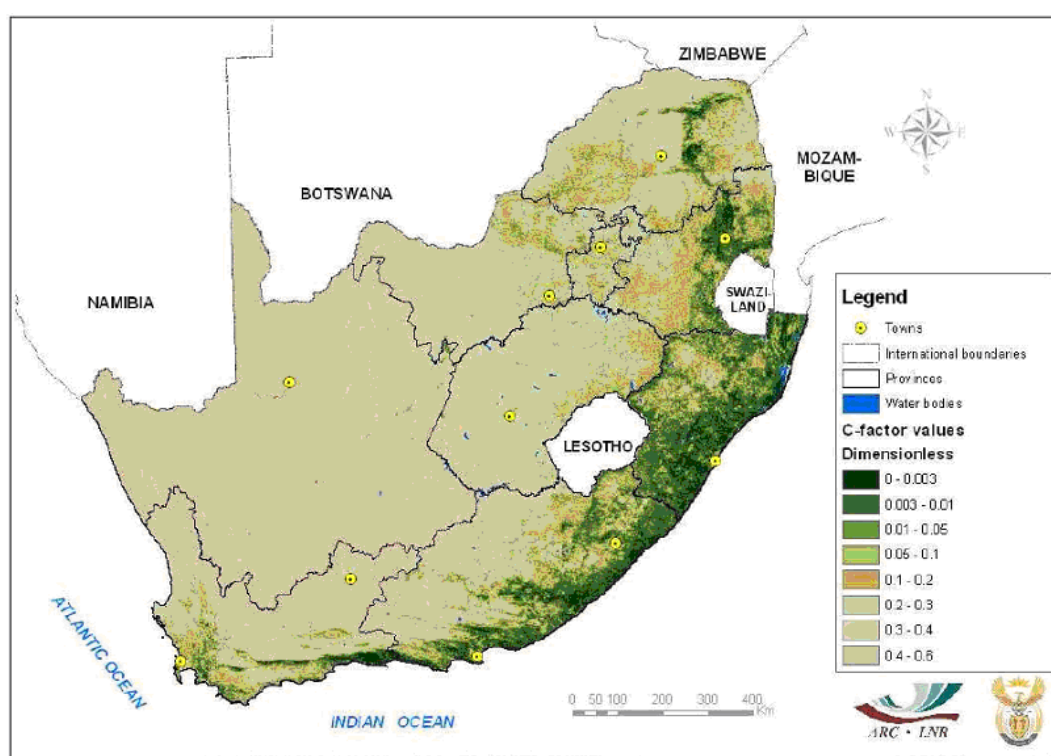


Figure 1-6: Cover factor map of South Africa

Further calibration or refinement of the actual water erosion prediction map can be achieved by improving C-factor maps, as well as erodibility factor values for South Africa. Limitations to the approach to obtain C-factor values are tied to the spatial variability of vegetation and soil parameters. However, of all hazard factors the cover management code (C) is the most important soil erosion factor (Crosby et al., 1983; Renard et al., 1994; Garland, 1995; Evans, 2000). Not only does it represent conditions that can be managed to reduce erosion, but it also represents changes in land use. Compared to the other soil erosion factors, the C-

factor weighting in the RUSLE model is most profound. Therefore, a realistic estimate of the C-factor is essential.

For example, C-factor values for Fynbos in the Western Cape are probably too high leading to over-estimated soil erosion values. This problem occurs during vegetation senescence when vegetation indices usually decrease even when the cover remains the same. However, senescent vegetation offers the same protection to the soil as green vegetation and it is important to also detect relatively dry vegetation.

- ***Actual water erosion prediction map***

An actual water erosion prediction map was derived by combining C-values with the physical indicators of erosion susceptibility mentioned above.

According to the EEA (1995), the actual soil erosion risk index relates to the current risk of erosion under present vegetation and land use conditions. It is derived by modifying the estimated potential soil erosion risk index according to the vegetation cover discussed above. Thus, actual soil loss is determined by multiplying together the four factors, R, K, LS and C.

It was noted in the ARC-ISCW's report (Le Roux et al., 2006) that various limitations to this modified version of RUSLE model used do exist and it is important to take cognisance of these. The limitations highlighted include the fact that the model does not:

- yield exact or definite outcomes
- accurately estimate erosion for a specific storm event, season or a single year
- estimate soil erosion on a catchment scale, but is designed for soil loss prediction on single slopes
- account for erosion by concentrated flow, stream channels
- account for gully erosion, and mass movement
- estimate on-site deposition
- accurately estimate sediment yield from fields using delivery ratios
- provide information on sedimentation characteristics required for estimating potential deposition and transport of chemicals by sediment.

The report concluded that improvements of the input datasets in the RUSLE model provide a valuable indicator of soil erosion, showing the potential to target erosion control to problem areas. However, it was acknowledged that with further research, it would be possible to further refine the results in order to (1) produce more accurate erodibility maps at a national scale; (2) estimate monthly erosivity in combination with monthly NDVI data in order to capture seasonal variations in soil erosion; (3) predict gully erosion extent at national scale using spatial modelling techniques; and (4) calibrate and validate the prediction model, especially when applied to large geographical areas.

1.1.4 Validation of RUSLE model and associated maps

The results obtained needed to be validated with independent data (Svorin, 2003). The choice of validation method depends on the purpose of the soil erosion modelling. Soil erosion encompasses a vast array of processes, which makes its assessment difficult to encapsulate in a few simple measures (Stocking and Murnaghan, 2001). Erosion occurs over a large variety of timescales such as a single storm to many decades. Furthermore, soil loss occurs over many spatial scales including the site of impact from a single raindrop to large fields and catchments. Therefore, measurements undertaken at one set of scales cannot be compared with measurements at another. Other than visual comparison of maps, there are very few pattern comparison techniques (Jetten et al., 2003). In this study, validation of results refers to the spatial patterns of the different classes of erosion, similar to Svorin (2003) and Flügel et al. (2003).

Three approaches were followed. Results were compared to (1) data collected during field observations, (2) the national Land Type Survey (Land Type Survey Staff, 1972-2006) and (3) verification of the National Land Cover (2000) map of SA (n = 10 290).

For the field observations, a total of 74 road intersections were selected (Figure 1-7). Sites were visited in December 2005 and in April 2006 to acquire observations and measurements of the type and severity of soil erosion. Results were verified on relatively simple field indicators described in Stocking and Murnaghan (2001). Different soil erosion types at each site were classified according to the classification system of the Southern African Regional Commission for the Conservation and Utilization of the Soil (SARCCUS, 1981), including additional information such as the local topography, parent material, land use and biome classes. Sampling methods aimed at validating severely eroded areas within SA, such as KwaZulu-Natal and the Eastern Cape. These highly eroded areas were targeted for

verification for the reason that the accurate prediction of the spatial pattern is even more important than the accurate prediction of the amount of soil loss, since it is much more cost-effective to over-dimension an erosion control measure than to put it in the wrong spot (Jetten et al., 2003). Therefore, the modelling results were validated qualitatively by comparing modelled erosion patterns with erosion patterns observed in mostly KwaZulu-Natal and parts of the Eastern Cape.

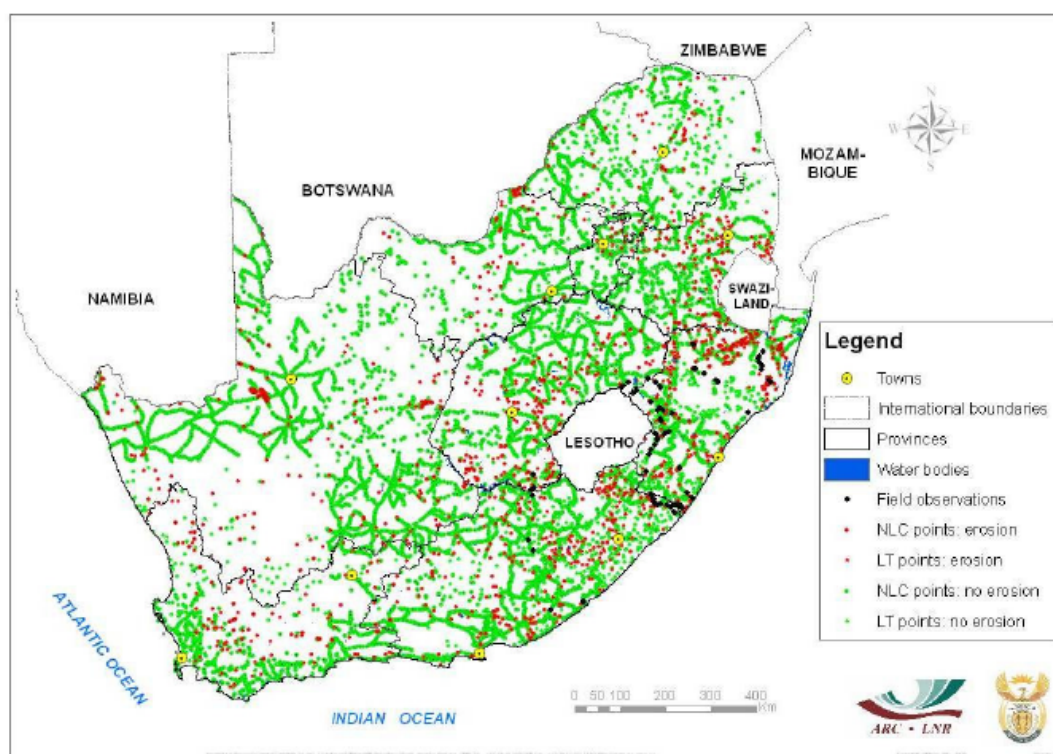


Figure 1-7: Location map of sample sites of field observations, as well as National Land Cover (NLC) database and Land Type (LT) surveys

In addition to the field measurements mentioned above, existing databases were used for verification purposes. Actual water erosion was verified with sampling point data collected for the National Land Cover (NLC 2000) map of SA. The NLC study used 6764 points, sampled in 2000 for the NLC project, in a stratified random fashion based on vegetation and land use across SA. These sample points and their coordinates also included the types of erosion observed during field visits. In addition, results of this study were also verified with sampling point data obtained during the Land Type Survey of the ARC-ISCW from 1972-1993 (Land Type Survey Staff, 1972-2006) (see Figure 1-7).

For validation purposes, it was decided to group the actual soil erosion map into two classes of severity (above and below 10 t/ha/yr, the suggested soil loss tolerance value), but not into different erosion types since the soil erosion maps do not distinguish between erosion types. Furthermore, most highly degraded areas are recorded as having combinations of interrill, rill and gully erosion. In this context, the error matrix shown in Table 1-1 indicates that the overall accuracy of the actual water erosion prediction map is 77%. For points where no erosion was observed, a distinctly higher number of points (7168) have very low to low erosion compared to points (1947) where erosion was observed. The omission and commission accuracies of this category are 74% and 94%, respectively. For points where erosion was observed, 408 points have very low to low erosion compared to 767 points where erosion was observed. The omission and commission accuracies of this category are 65% and 28%, respectively.

Table 1-1: Error matrix

	Erosion	No Erosion	Row Total
n (>10 t/ha/yr)¹	767	1947	2714
n (<10 t/ha/yr)²	408	7168	7576
Column Total	1175	9115	10290
Omission³	0.652	0.786	
Commission⁴	0.282	0.946	
Total accuracy	0.771		

1. Number of points on the actual water erosion prediction map that have less than 10 t/ha/yr soil loss.
2. Number of points on the actual water erosion prediction map that have more than 10 t/ha/yr soil loss.
3. Sample points that have not been correctly classified and have been omitted from category.
4. Sample points that have been incorrectly commissioned into another category.

As a third step in the validation process, results were compared with other sources of literature. Although many previous observations of soil erosion have been carried out in SA, field measurements of soil erosion are sparse. A limited number of long-term natural runoff plot experiments have been established. One exception is the Department of Agriculture's initiative to calibrate USLE factor values from standard runoff plots at various sites in KwaZulu-Natal, e.g. Cedara Agricultural Research Station since 1983 (Russell et al., 1995). However, these experiments do not provide a broad range of input data for regional soil loss

modelling in SA. The derived statistical relationships from individual erosion measurements are confined to their local conditions and provide a limited basis for extrapolating to wider areas (Lu et al., 2003). Therefore, care was exercised in using individual observations and measurements to extrapolate across the country. Mostly recent regional-scale studies were used for comparison.

1.1.5 Observed sediment yield data

The RUSLE model was not calibrated with observation point data or flow data. This procedure is usually done with catchment-scale models such as the Soil and Water Assessment Tool (SWAT); developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields on complex landscapes with varying soils, land use, and management conditions over long periods of time. Although the RUSLE model is not primarily used to estimate sediment yield using delivery ratios, it would be valuable to correlate the average soil erosion rates (from erosion map) per catchment with available sediment data (at catchment outlets/reservoirs) obtained from the current project. Such a comparison would also give an indication of the accuracy of the erosion map when used at catchment scale.

Since the publication of the WRC's 1992 sediment yield reports (Rooseboom, 1992), that were based on analysis of observed data, little work in this field has been published in South Africa, particularly with regards to the analysis of recorded sediment yield data and the production of sediment yield maps based on such data. The comprehensive WRC report that was compiled in 1992 was reviewed in detail to assess its weak points and the methodology followed during the earlier research project.

Some valuable sources of information in this regard are available to the project team. DWAF publishes the so-called "dam list" on a regular basis, which includes the last sediment survey for each dam as a percentage value. The most recent list was published in 2006 (DWAF, 2006). It is also possible to obtain accurate sediment yield volumes from the chronologically listed yield information in the dam list. The project team have obtained the latest dam list from DWAF.

DWAF also publishes reports for individual dams that contain additional, detailed information not included in the more general dam list. These reports are also valuable in view of analysing sediment yield. Most of these reports have been obtained by the project team.

The most recent sediment yield maps for South Africa were completed in 1992, implying that at least 15 years of additional data, such as suspended sediment measured in rivers and sediment volumes in reservoirs from bathymetric re-surveys, have now become available.

1.2 Review of existing sediment yield maps for South Africa

The existing sediment yield maps for South Africa were reviewed in detail by the project team. The aim of the review was to revisit the methodology, to obtain the information used, and to identify weaknesses and strengths of the previous maps.

The most notable advantages of the 1992-maps are:

- they are self-explanatory and easy to use
- a detailed description of the basic sediment transport theory is included in the documentation
- the whole South African region is covered by the map (not only South Africa), making the map practical to use when considering trans-boundary catchments
- the hard copy map format does not date as fast as the electronic formats
- the methodology incorporates measured sediment yield data and is not limited to a mathematical description of the soil erosion process.

1.3 Limitations of existing sediment yield maps

1.3.1 Record length

The record length for sediment yield data used for compilation of the existing 1992-sediment yield maps is ± 15 years old. The most recent dam list of 2006, with updated sediment yield data, provides researchers with valuable additional information on recorded sediment yields.

1.3.2 Map format

Although the existing maps were compiled in GIS-format, the final product maps were made available in hard copy format as part of the 1992-WRC report. However, the original GIS-format is 17-years old – more than a lifetime in IT-terms! If the old GIS files could be located some of the information could be useful during this analysis. However, the research team could not yet locate the original GIS information.

The hard copy map format is useful, mainly because it does not date as electronic information does, but this format could also be viewed as a limitation in its own right. The format of the new sediment yield maps should be updated during this project to be available in electronic format (GIS).

1.3.3 Maintaining the maps

The South African sediment yield maps have been updated at intervals of about 15 years (2007, 1992, 1974). This relatively long interval makes sense considering the frequency of sediment yield surveys – about 10 to 15 years. A limitation in this regard is that the maps could actually be maintained in a more "up to date state" than is possible with the 15-year update intervals. The establishment of a national database (refer to aim No. 5) is considered to be a critical step towards achieving this.

1.3.4 Accuracy and verification of maps

In the process of compiling the South African sediment yield maps in 1992 an attempt was made to link sub-areas with differing yield potential and land-uses to their observed sediment yields. This was done with the aid of multiple linear regression techniques. However, the attempt failed due to the lack of individual variables, inter-correlation between independent variables, large standard errors and physically insignificant results.

The ARC are currently in the process of compiling GIS-based maps for soil erosion in South Africa based on ± 1 km sized pixels as minimum mapping unit, as discussed in more detail earlier in this report. This resolution entails a much higher accuracy than the work in 1992, raising the hope for successful calibration to measured sediment yields. Further refinement of the work to date will be possible given additional research, including careful calibration and validation of prediction models and model components, especially when applied to large geographical areas.

It is apparent that there is a need to improve the verification and accuracy of the sediment yield maps of South Africa.

2. Methods for long-term spatial distribution of sediment yield maps

Since 1992 various spatial soil erosion studies have been conducted at the ARC (e.g. Wessels et al., 2001a; Wessels et al., 2001b; Strohmenger et al., 2004) and by others. The methodologies used in these studies will be investigated. As mentioned in more detail earlier in this report, a soil erosion prediction map for South Africa (Le Roux et al., 2006) was created by using the Revised Universal Soil Loss Equation (RUSLE) in a GIS environment. The model involves the computation of four separate indices, which are then combined to give an assessment of erosion risk, including soil erodibility, rainfall erosivity, topography, and vegetation cover. Data used to generate the RUSLE variables include: Land Type soil data prepared by the ISCW (Land Type Survey Staff, 1972-1993), 16 years of daily rainfall interpolated from station measurements, 20 m resolution DEMS, 5 year MODIS derived 10-day maximum composite NDVI data and National Land Cover data (National Land Cover 2000, 2006). Remote sensing images were used to develop land use cover factor (C) Classes. Other data layers used to create this map include soil erodibility (K), rainfall erosivity (R) and topography factors (LS) the digital elevation models (LS). The project team will investigate the possibility to use a similar methodology to create the sediment yield maps or to improve/replace the Rooseboom et al. (1992) erosion index map with the aforementioned erosion prediction map. Work done using a rainfall simulator on various soils (REF) will be used to verify K values. The ARC-ISCW is involved in current Water Research Commission project (K1516) which aims to identify important sediment transport processes that should be included in models when up scaling from field to catchment scale. The identified methods and processes will be considered in this project.

Recent work by Buhman et al. (2006) suggests that the mineral composition of soils with a high clay content and other factors may play a major role in the erodibility and therefore the production of sediment. It may be necessary to include this information in the methods to determine spatial distribution of sediments.

All development and map creation will be performed with ESRI ArcGIS software. The ArcGIS software has the capability of performing statistical analyses and for model building through logical combination of layers. These capabilities of the software will be used to improve existing methods where possible. In addition, the ArcGIS software will be used for scenario building and testing by making use of pre-generated layers, e.g. the effect of high and low rainfall conditions can be used to predict sediment yield under different conditions.

With the rise in computing power and GIS capabilities, several erosion models have been interfaced with GIS. Spatially distributed catchment models have been developed to simulate the runoff and soil erosion processes in complex models. These models have the potential advantage to identify source and sink areas of water, sediment and associated chemicals within a catchment, and to provide the user with a distributed image of the runoff and erosion.

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**APPENDIX J(b) RECALIBRATION AND NEIGHBORHOOD
STATISTICS OF EROSION DATA**

ARC-ISCW project GW 51/076

WRC project K5/1765

July 2009

PROGRESS REPORT
FOR THE
WATER RESEARCH COMMISSION

BY

Le Roux, JJ

AGRICULTURAL RESEARCH COUNCIL

INSTITUTE FOR SOIL, CLIMATE AND WATER

1. Introduction

Given the increasing threat of the sedimentation/siltation of reservoirs, a need was identified to improve previous sediment yield and associated maps of Rooseboom et al. (1992). One of the main proposed improvements involves the identification of new regional boundaries based on latest sediment and soil erosion data, including the latest water erosion prediction map of South Africa (SA) by Le Roux et al. (2008). The latter mentioned erosion map is based on a simplification of the Revised Universal Soil Loss Equation (RUSLE) of Renard et al. (1994). Initially, attention was focused on calibration of the RUSLE method against reservoir and river sediment yield data, in order to use it for more detailed prediction of sediment yields in regions with limited observed data.

Before calibration could be carried out, an attempt was made to correlate the calculated sediment yield values obtained from the Institute for Water and Environmental Engineering (IWEE) with the water erosion prediction map of Le Roux et al. (2008). As a first step, soil erosion – sediment yield correlation analysis was carried out by means of statistic functions in a GIS (ArcMap) and correlation graphs. However, previous analysis of the results indicated very poor correlation between the mean erosion and calculated sediment yield. The main reason is that the mean net soil loss (i.e. the sediment yield at the outlet) in a catchment differs from the mean total soil erosion (i.e. the total sediment produced in the catchment). Depending on the spatial configuration of topography and land use, a significant part of the eroded soil will deposit again before reaching a river channel or the outlet of the catchment (Van Rompaey et al., 2003). Therefore, erosion cannot be successfully correlated with sediment yield without linking them with a hydrological component (e.g. mean annual runoff and peak runoff). Ideally, the RUSLE erosion map must be hydrologically linked with the sediment data by means of the sediment delivery ratio (SDR). The SDR is the ratio of sediment yield at the outlet over the total volume of produced sediment in the drainage basin. For example, in Europe, Van Rompaey et al. (2003) applied a regional scale model (WaTEM/SEDEM) that requires river and trap efficiency data in order to assess a SDR for each reservoir.

Due to the lack of reliable hydrological data at a national scale, it was decided to focus on certain relationships between sediment production (water erosion map) and reservoir sediment deposits in a spatial manner. As a result, it was possible to explain regional trends

at a broad erosion response unit level. For example in some parts of the Western Cape, erosion seems to be greatly overestimated when compared to sediment yield. The main reason is that the relatively dry canopy cover for Fynbos is not represented in remotely sensed data (NDVI), leading to over-estimated soil-erosion values. This problem occurs during vegetation senescence when vegetation indices usually decrease even when the cover remains the same (French et al., 2000). However, senescent vegetation offers the same protection to the soil as green vegetation and it is important also to detect relatively dry vegetation. Another example includes the underestimation of erosion for catchments located in areas with good canopy cover (especially KwaZulu-Natal); having erosion rates that are less than the sediment yield (approximately one quarter of a magnitude). The erosion rate for these areas is probably underestimated due to (poor) ground cover not always being accounted for or represented in remotely sensed data. Dense tree canopy may conceal poor ground cover when monitored by satellite. Lastly, soil-erosion risk seems to be overestimated for areas containing very steep mountain ranges. Although several studies in SA and across the globe demonstrate that soil erosion is very sensitive to the topographical factor of RUSLE (Biesemans et al., 2000), additional work is still needed to test and validate the suitability of topography indices in SA and how they affect soil erosion in the country. It appears that the inherent erodibility of the soil and parent material is the overriding erosion risk factor in South Africa, and not the slope gradient, as determined in the USA (Laker, 2004).

For these reasons it was decided to develop and apply a methodology based on present knowledge and available data for the re-assessment of soil erosion risk at the national scale, especially for the problem areas mentioned above (instead of conducting further correlation analyses). The goal was to adjust the cover (C) factor map used in the latest erosion hazard map of Le Roux et al. (2008), as well as to modify the topography (LS) factor map. This progress report presents the soil erosion work/modifications completed since September 2008 for use in revision of the 1992 sediment yield map including:

- Modification of the C-factor- and LS-factor maps and subsequent improved water erosion prediction map of Le Roux et al. (2008);
- Classification/aggregation of the improved erosion map into 10 erosion hazard classes.

The following section explains the methodology followed to modify the erosion data.

2.0 Methodology

Detail on the procedures to create the original erosion map is provided by Morgenthal et al. (2006) and Le Roux et al. (2008). As mentioned above, the water erosion prediction map of Le Roux et al. (2008) was modified and improved by means of new C-factor- and LS-factor maps. The new C-factor map was created as follows. The same/current vegetation cover map was used (obtained from MODIS-NDVI-derived spectral index). However, new C-factor values were assigned to the vegetation cover map, using new stratification rules similar to a study performed in Italy by Van der Knijff et al. (1999). The latter mentioned study showed that estimating the C-factor from NDVI-images can result in unrealistically high C-values for especially woodland and grassland (Van der Knijff et al., 2000). Van der Knijff et al. (1999) therefore used the European Land Cover database (CORINE) to assign maximum C-values for these classes.

Likewise, the current study assigned C-factor values according to certain National Land Cover (2000) zones and biomes (Low and Rebelo, 1998), i.e. cultivated land and Fynbos. More specifically, the following rules were applied:

- All cultivated land with C-factor values lower than 0.15 were increased to 0.15;
- All Fynbos (not cultivated) with C-factor values higher than 0.003 is reduced to 0.003.

The resulting C-factor map, as well as the previous C-factor map is show in Figure 1. Visual comparison between the two maps indicate that C-factor values for Fynbos adequately reduced, whereas C-factor values in cultivated areas increased (e.g. areas in KwaZulu-Natal with good canopy cover but probably poor ground cover).

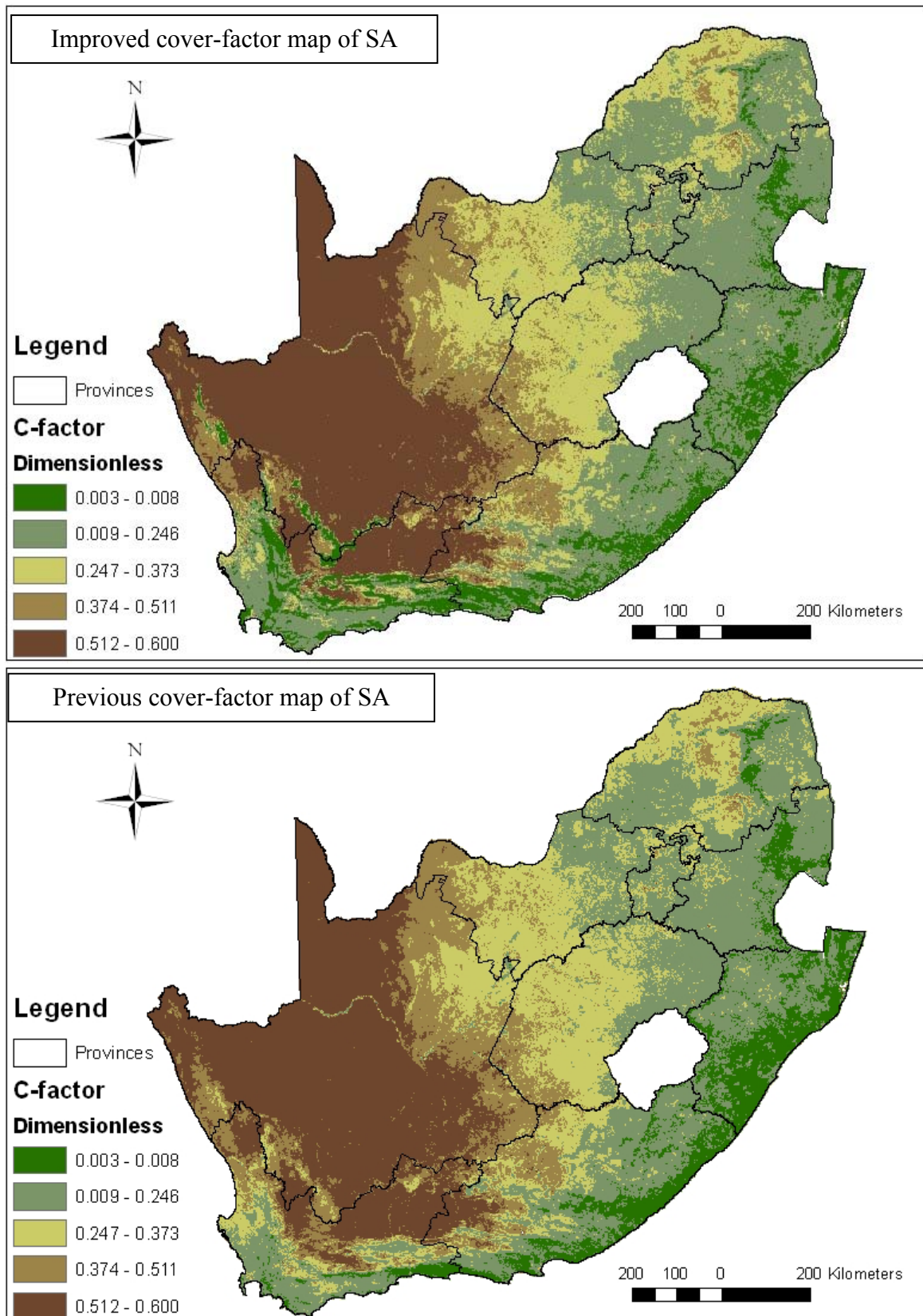


Figure 8: Improved and previous cover factor (C) maps of South Africa.

The following rules were applied to the LS-factor map:

- All slopes higher than 18 degrees were reduced to 18 degrees (since most of the algorithms used to calculate LS come from studies with gradients <18% (e.g. Wischmeier and Smith, 1978; McCool et al., 1987; Desmet and Govers, 1996);
- LS-factor maps were calculated by means of a terrain-based index of Desmet and Govers (1996) (that explicitly accounts for flow convergence and divergence) instead of the stream power theory of Moore and Burch (1986).

The resulting LS-factor map, as well as the previous LS-factor map is show in Figure 2. Despite their visual similarities, the new LS-factor values are up to two times lower than previous values in steep areas and up to five times higher than previous values in flat areas. Effectively, these changes tend to have a “smoothing” effect on the computed topographic factor. In this way the LS-factor’s exceedingly strong influence on erosion prediction is adequately reduced.

The other factor maps needed in the modelling exercise were unchanged, i.e. rainfall erosivity (R) and soil erodibility (K). Detail on the procedures to create the latter mentioned maps is provided by Le Roux et al. (2008).

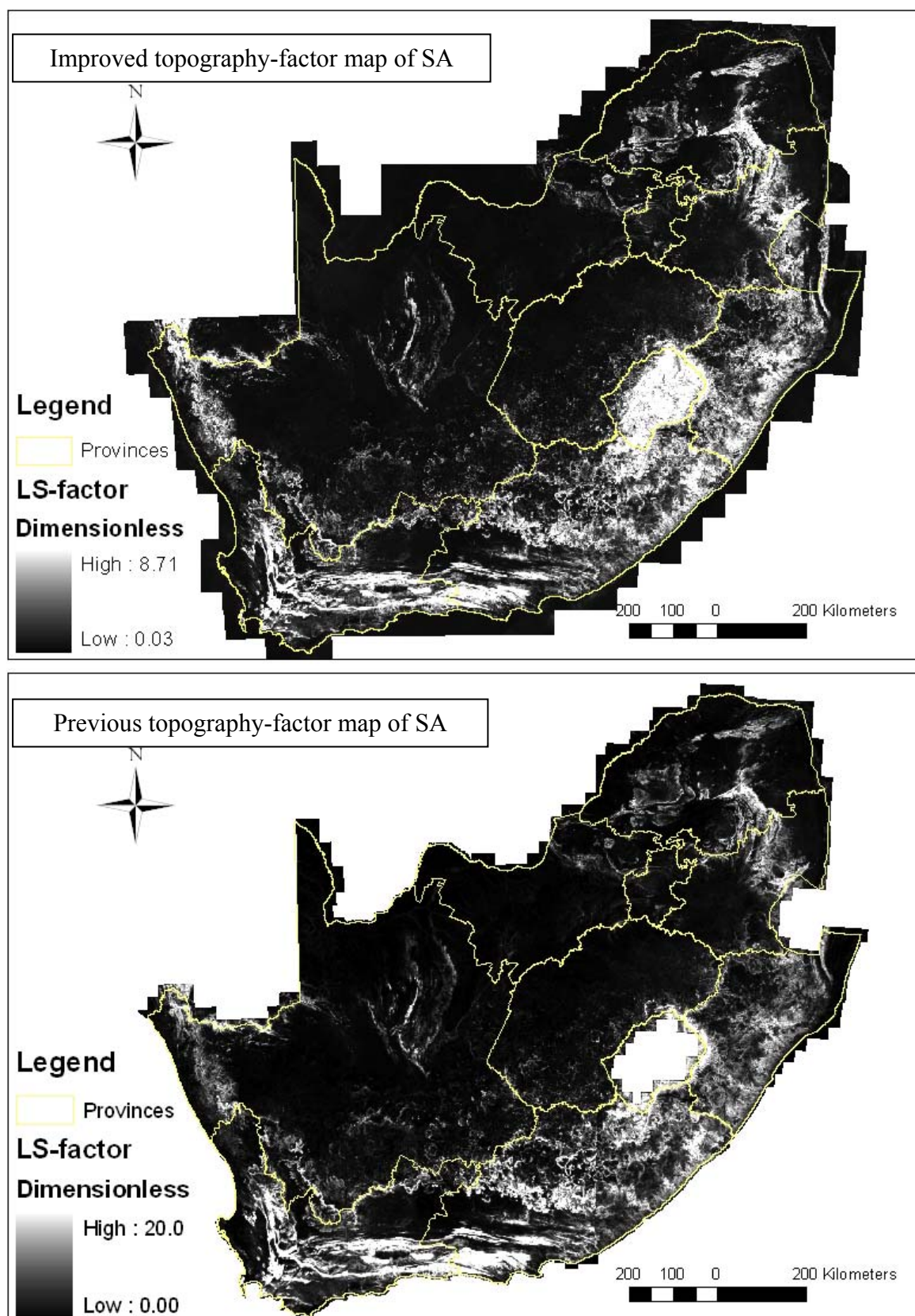


Figure 9: Improved and previous topography factor (LS) maps of South Africa.

The study also required spatial soil erosion data for Lesotho. However, due to the lack of appropriate data (especially for soil erodibility), the currently utilized erosion study of Le Roux et al. (2008) could not predict soil erosion for Lesotho. Therefore, erosion data for Lesotho was obtained from previous regional scale studies (that integrated the main erosion contributing factors in applicable formats and units for Lesotho in a GIS):

- The Predicted Water Erosion Map of SA by Pretorius (1998);
- Predicted Vulnerability to Soil Erosion for the Maloti Drakensberg Transfrontier Project by Maloti Drakensberg Ecology Consultants (2007).

It is noteworthy here that the spatial distribution of soil erosion in Lesotho remains questionable due to the lack of appropriate soil data at this scale; and above-mentioned soil erosion maps for Lesotho were not verified with independent data. Therefore, the current study performed spatial aggregation to smooth out local variation. Subsequently, a new water erosion prediction map was created by aggregating above-mentioned water erosion grids by means of neighborhood statistics in ARC/INFO (i.e. focal statistics set as the sum of a circle with a radius of 40 cells). Thus, it was possible to create 10 erosion zones for final appliance in the identification of new regional boundaries.

3. Results and discussion

The improved predicted water erosion map of SA (obtained by incorporating new C-factor- and LS-factor maps discussed above), as well as the previous erosion map is show in Figure 3. Visual comparison between the new and previous erosion maps illustrates noticeable changes. Erosion rates are reduced in areas containing Fynbos vegetation, especially in the Western Cape. In contrary, erosion rates satisfactorily increased in areas containing cultivated land, especially in KwaZulu-Natal. Furthermore, it seems that the new erosion map illustrates a more “dispersed” erosion pattern than before. For example, new erosion rates are slightly higher than before in areas that were previously classified as having very low erosion rates (e.g. North West and Northern Cape). At the same time, new erosion rates are slightly lower than before in areas that were previously classified as having very high erosion rates (e.g. Eastern Cape).

Figure 4 illustrates the average erosion rates per province (excluding Lesotho). Average erosion rates almost halved in the Western Cape (from 15 to 8 t/ha•yr), whereas erosion increased by approximately 20% in KwaZulu-Natal (from 13 to 16 t/ha•yr). Despite these changes the national average erosion rate of the improved erosion map didn't change. The average soil erosion rate for SA for both scenarios is 13 t/ha•yr. It is noteworthy that differences between sediment yield and soil loss can be very high. Research findings of Scott and Schulze (1991) suggest that soil loss within a catchment can be up to five times greater than sediment yield due to the reduction of the total eroded volume by deposition within the catchment. Consequently, a soil-erosion figure of 12.6 t/ha•yr could correspond with a sediment yield of 2.5 t/ha•yr.

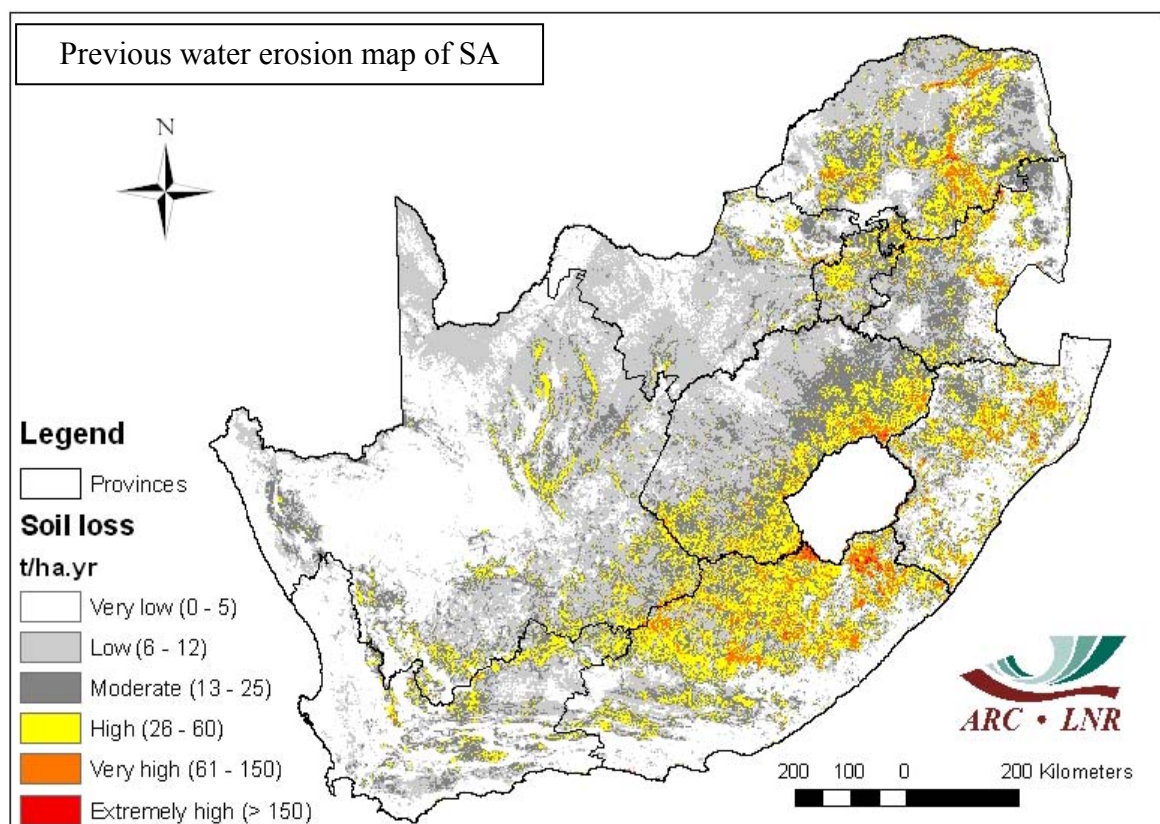
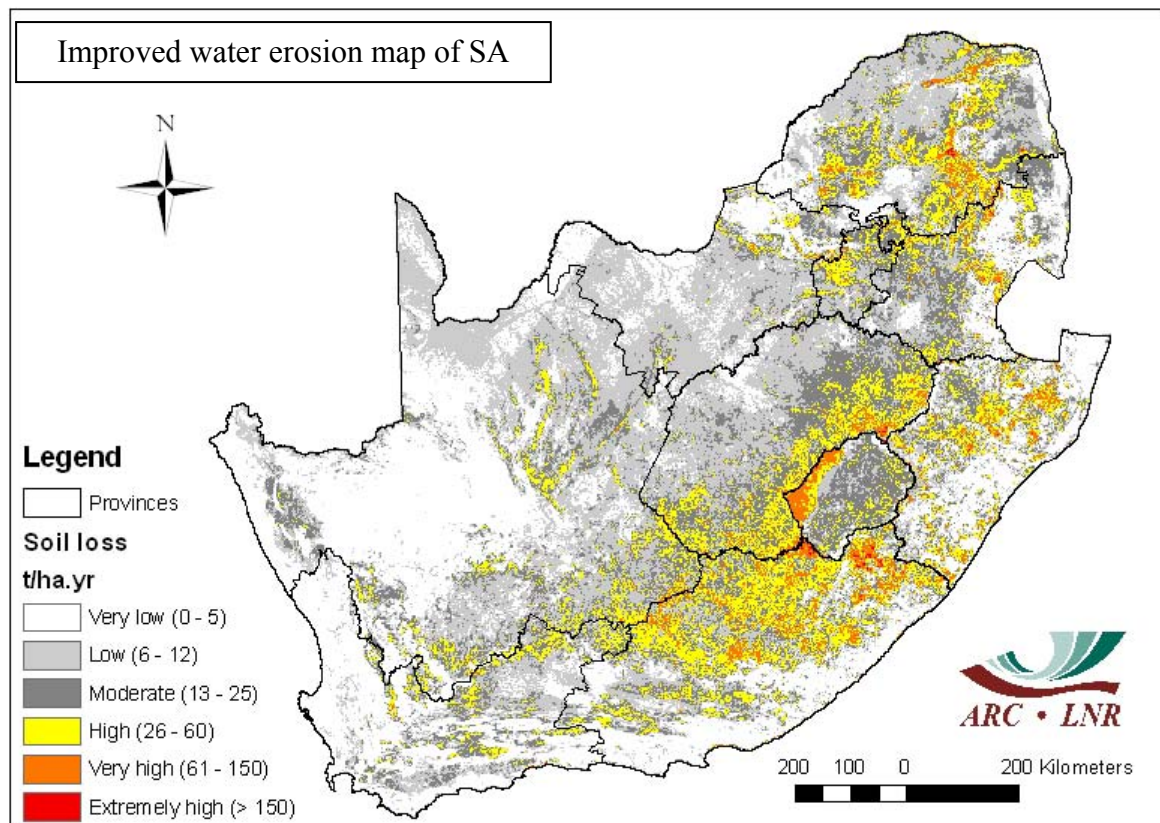


Figure 10: Improved and previous predicted water erosion maps of South Africa.

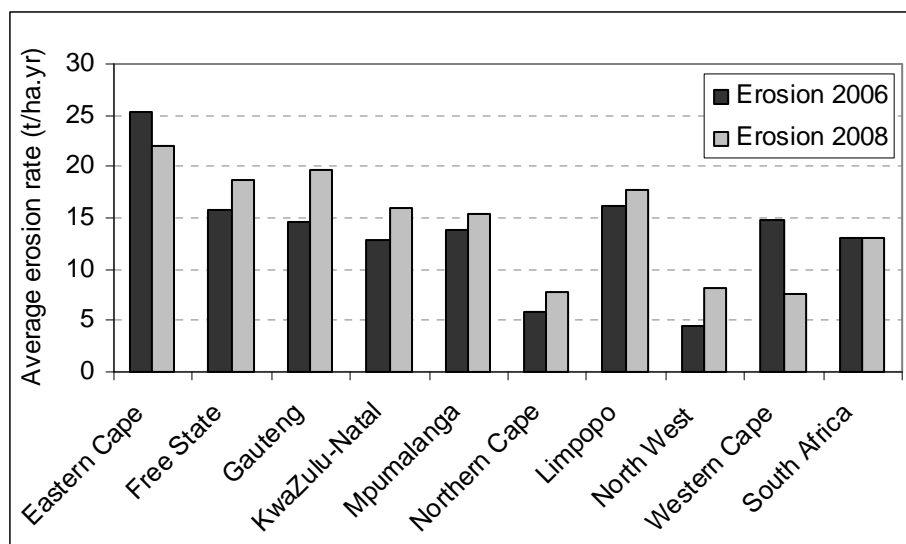


Figure 11: Average erosion rates per province.

Figure 5 illustrates the erosion hazard classes obtained by means of neighborhood statistics in ARC/INFO (i.e. focal statistics set as the sum of a circle with a radius of 40 cells). This map proposes 10 new erosion zones/regional boundaries. Most of the high to very high erosion hazard classes occur in the Eastern Cape, followed by KwaZulu-Natal and Limpopo provinces. Numerous high erosion hazard classes also occur in the eastern Free State and northern Mpumalanga.

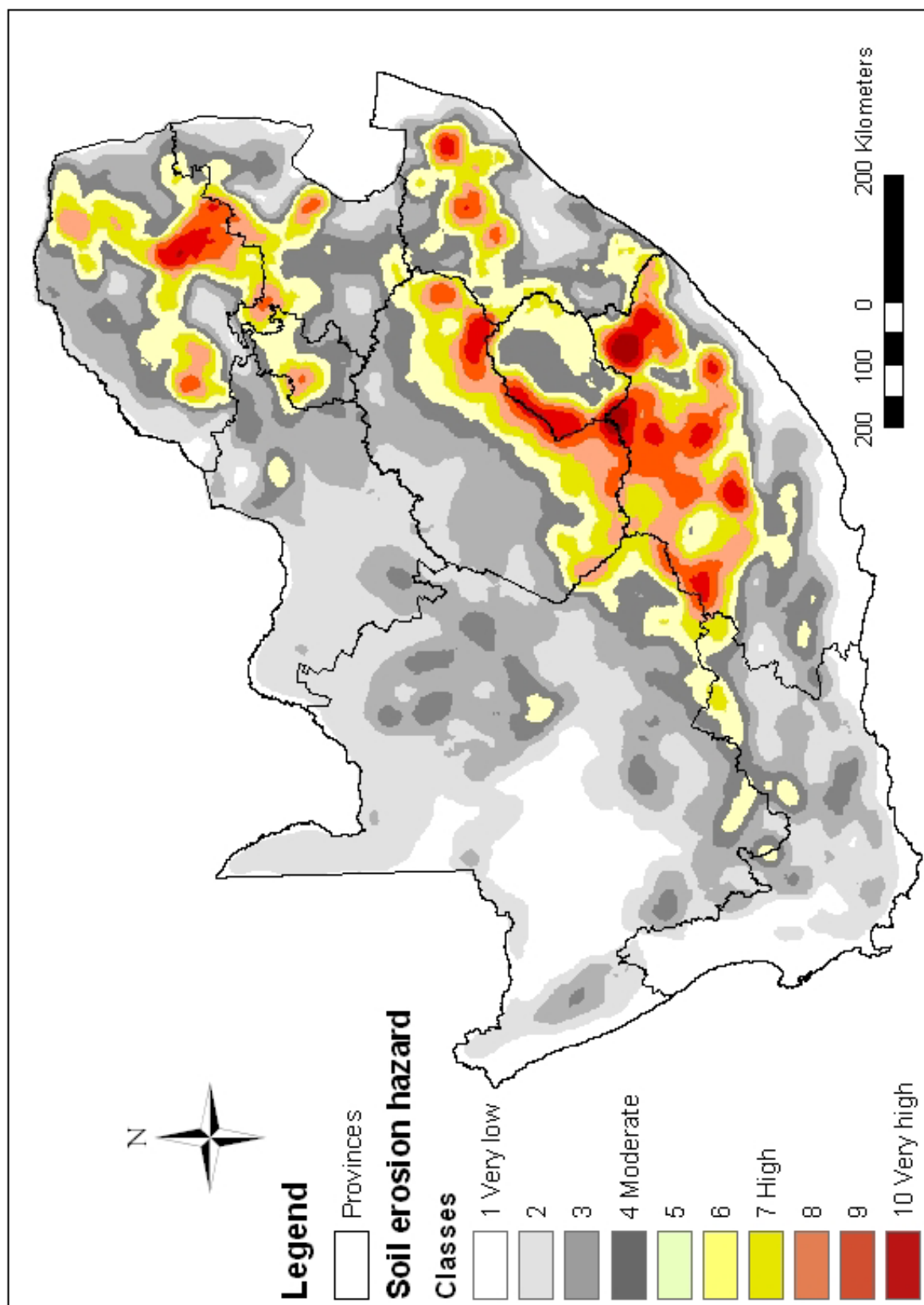


Figure 12: Erosion hazard classes obtained by means of neighborhood statistics.

4. Conclusion and recommendations

This progress report presents the soil erosion work/modifications completed since September 2008 for use in revision of the 1992 sediment yield map. Initially, attention was focused on calibration of the water erosion prediction map of SA by Le Roux et al. (2008) against reservoir and river sediment yield data, in order to use it for more detailed prediction of sediment yields in regions with limited observed data. However, previous analysis of the results indicated very poor correlation between the mean erosion and calculated sediment yield, including possible explanations. The main reason being that erosion cannot be successfully correlated with sediment yield without linking them with a hydrological component (e.g. mean annual runoff and peak runoff). Ideally, the RUSLE erosion map must be hydrologically linked with the sediment data by means of the sediment delivery ratio (SDR). Due to the lack of reliable hydrological data at a national scale, it was decided to focus on certain relationships between sediment production (water erosion map) and reservoir sediment deposits in a spatial manner. Therefore it was decided to develop and apply a methodology based on present knowledge and available data for the re-assessment of soil erosion risk at the national scale, especially for certain problem areas (instead of conducting further correlation analyses). As a result, erosion rates were adequately reduced in areas containing Fynbos vegetation, especially in the Western Cape. In contrary, erosion rates satisfactorily increased in areas containing cultivated land, especially in KwaZulu-Natal. Furthermore, improvements on the LS-factor effectively “smoothed out” the exceedingly strong influence of the LS-factor on erosion. Erosion data in grid format for Lesotho was obtained from previous studies similar to the study of Le Roux et al. (2008). Lastly, spatial aggregation was performed to smooth out local variation, making it possible to propose 10 erosion zones for final appliance in the identification of new regional boundaries. Most of the high to very high erosion hazard classes occur in the Eastern Cape, followed by KwaZulu-Natal and Limpopo.

Further spatial correlation between erosion data and sediment yield could yield valuable insights. However, erosion en sediment data should first be linked with a hydrological component, i.e. the SDR. Typical data requirements include rainfall energy, flow energy, catchment area and slope. The SDR can also be assessed by means of regional hydrological models, e.g. WaTEM/SEDEM but requires reasonable river and trap efficiency data. The South African model ACRU incorporates runoff and peak runoff rates. Other promising techniques include grid-based drainage networks and instream sediment routing that

incorporates connectivity and stores/deposition of sediment in large catchments (e.g. Colombo et al., 2000).

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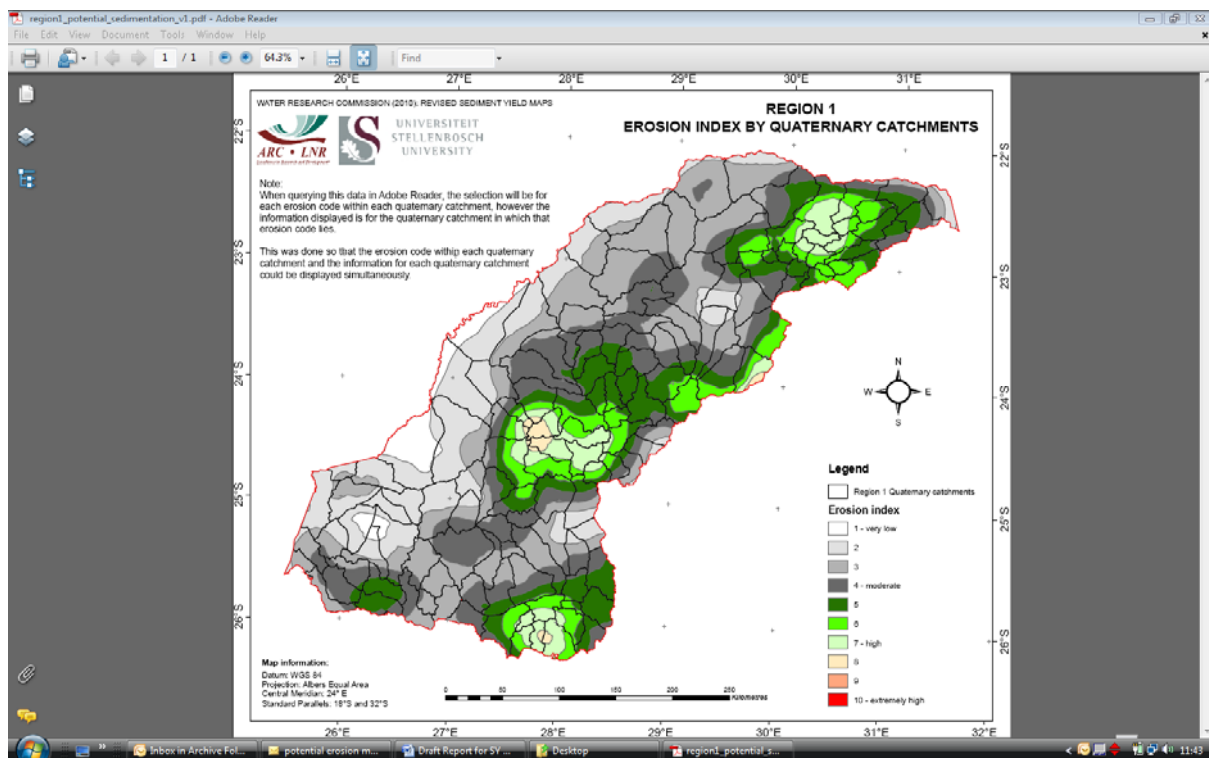
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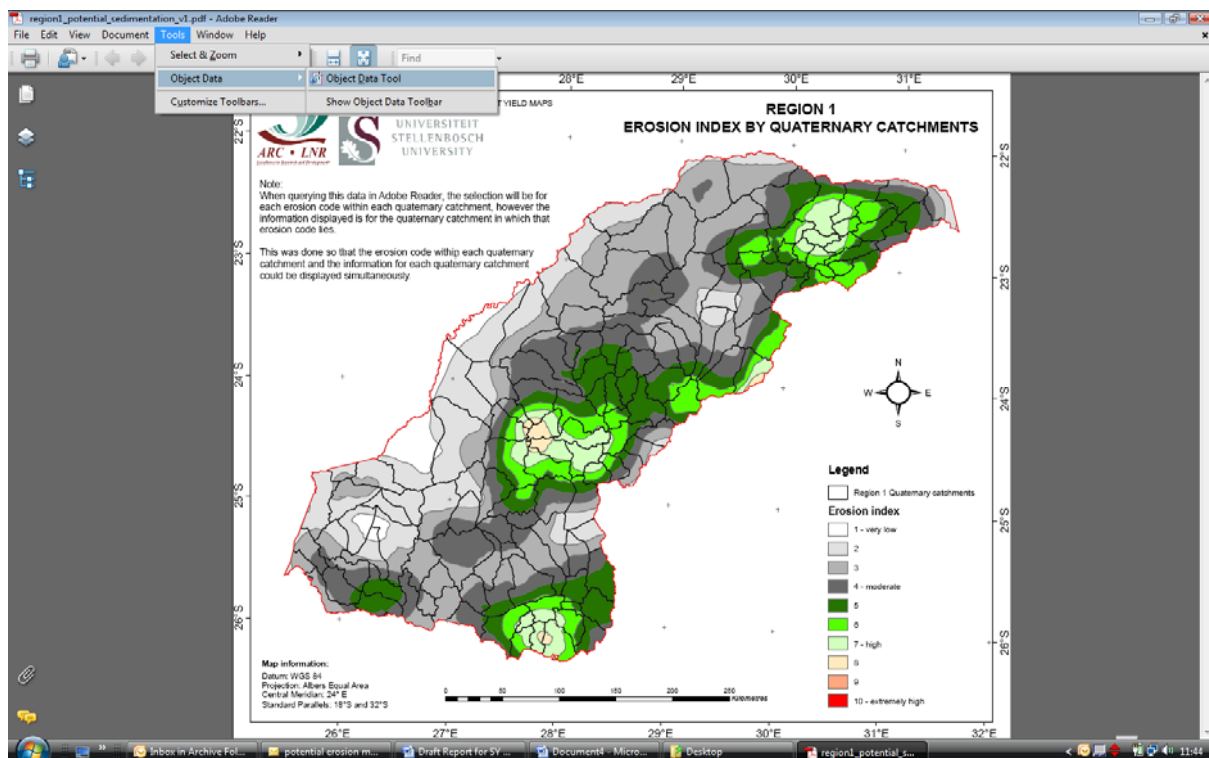
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**APPENDIX K HOW TO OBTAIN CATCHMENT SPECIFIC DATA FROM
PDF FILE – SHORT USER MANUAL**

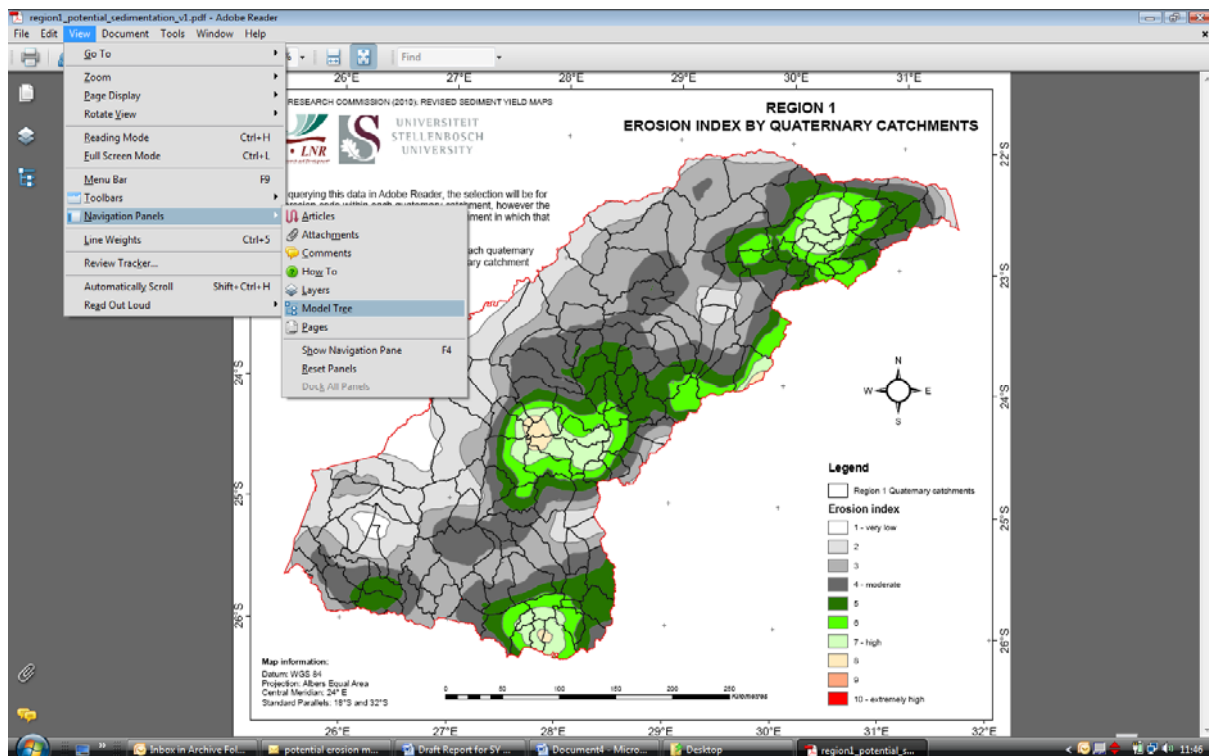
1. Open the PDF file



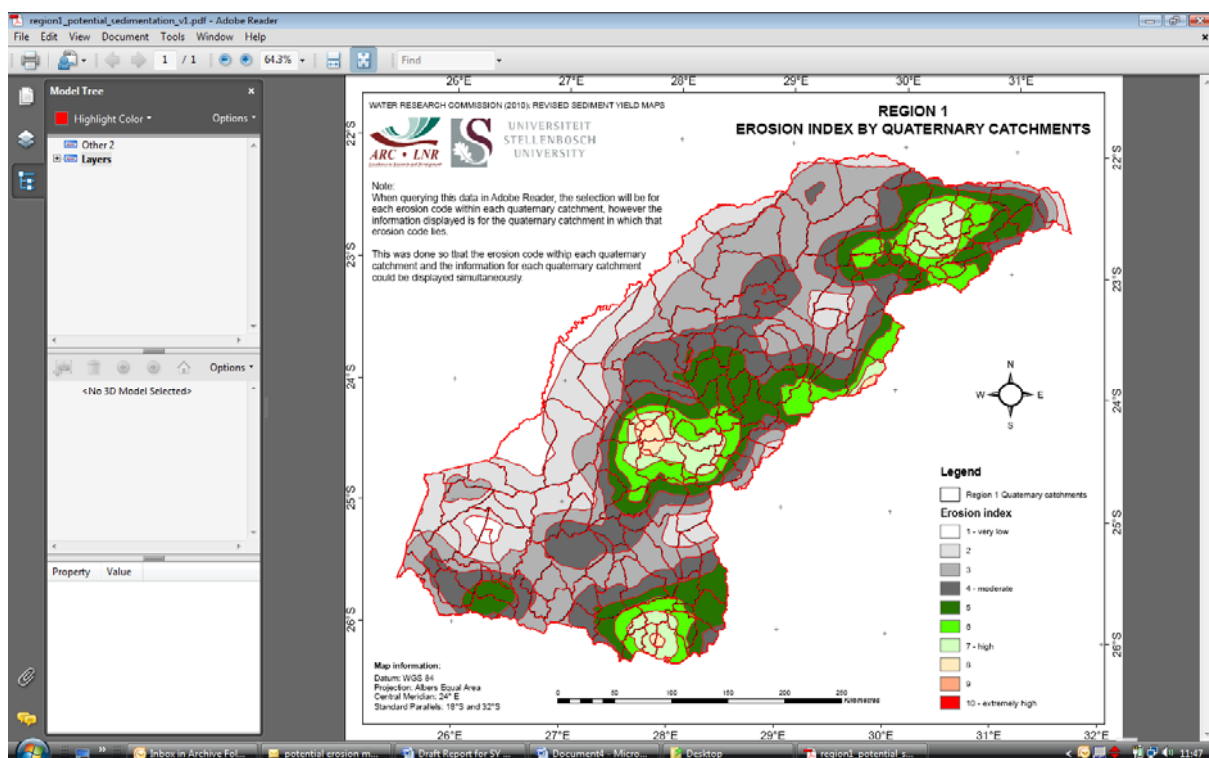
2. Open Tools, Object Data and click "Object data Tool"



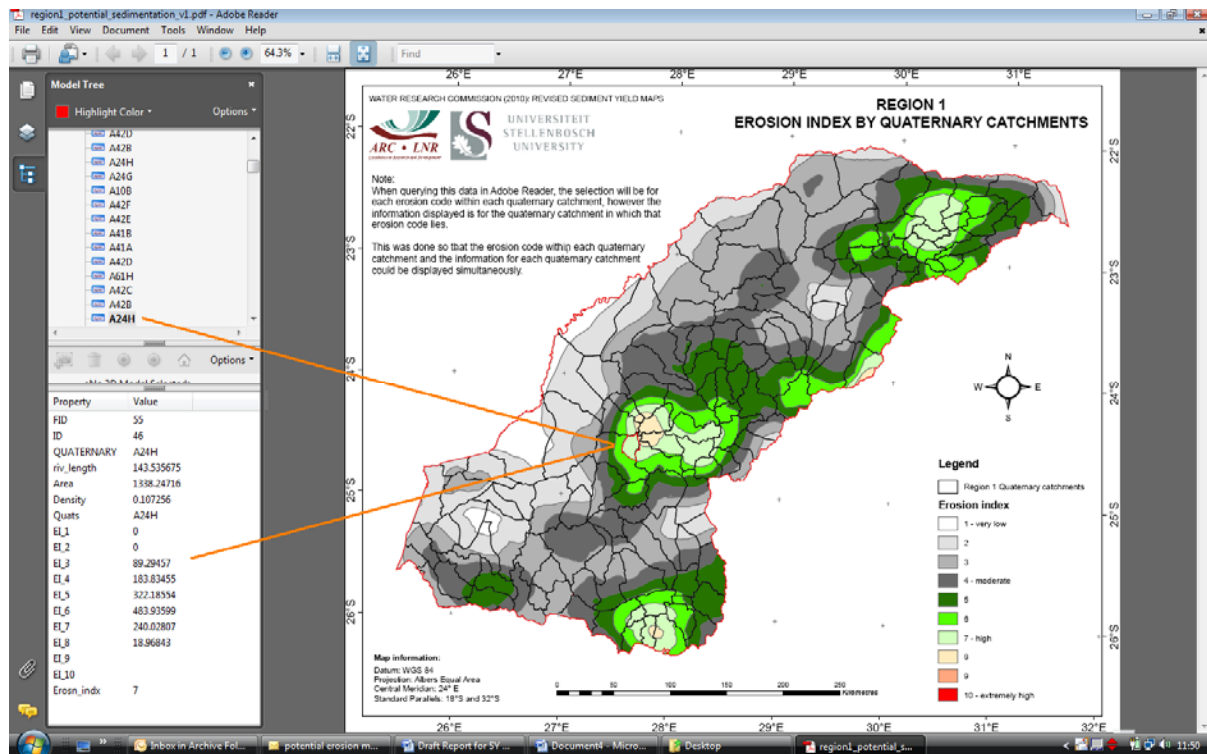
3. Open View, Navigation Panels and then click "Model Tree"



4. Click on the required quaternary catchment. Note that the whole catchment is highlighted.



5. Then double click on the specific quaternary catchment whose data is required. Figure below shows that when quaternary catchment A24 is double clicked, its properties are given on the bottom left hand corner of the PDF file.



- Get the relevant data, i.e. erosion statistics, area, river length and river network density for the quaternary catchment on the bottom left hand corner of the PDF file.