DESIGN RAINFALL AND FLOOD ESTIMATION IN SOUTH AFRICA

By

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EXECUTIVE SUMMARY

Introduction

The estimation of design flood events are necessary for the planning and design of engineering projects (Rahman *et al.*, 1998). Hence, flood frequency analysis remains a subject of great importance owing to its economical and environmental impact (Pilgrim and Cordery, 1993; Bobee and Rasmussen, 1995). However, reliable estimates of flood frequency in terms of peak flows and volumes remain a current challenge in hydrology (Cameron *et al.*, 1999). Cordery and Pilgrim (2000) express the opinion that the demands for improved estimates of floods have not been met with any increased understanding of the fundamental hydrological processes.

Standard techniques for flood estimation have been developed for many countries. These generally include statistical analysis of observed peak discharges, where these are available, and event modelling using rainfall-runoff techniques. Observed streamflow data are often not available at the site of interest and frequently rainfall event-based methods have to be used. This requires a probabilistically based estimate of rainfall, generally referred to as design rainfall, to be made at the site of interest. The frequently used term design rainfall is thus the rainfall depth and duration, or intensity, associated with a given probability of exceedance, which in turn is inversely related to the commonly used term, return period.

Design rainfall depths for various durations are thus required for the many engineering and conservation design decisions made annually in South Africa and which result in many millions of Rands of construction. For example, engineers and hydrologists involved in the design of hydraulic structures (e.g. culverts, bridges, dam spillways and reticulation for drainage systems) need to assess the frequency and magnitude of extreme rainfall events in order to generate design flood hydrographs. Hence, Depth-Duration-Frequency (DDF) relationships, which utilise recorded events in order to predict future exceedance probabilities and thus quantify risk and maximise design efficiencies, are a key concept in the design of hydraulic structures (Schulze, 1984).

The duration of design rainfall which is required for design flood estimation may range from as short as 5 minutes for small urban catchments which have a rapid hydrological response, to a few days for large regional flood studies. One of the requirements for undertaking frequency analyses is long periods of records. Given that the data at a site of interest will seldom be sufficient, or available for frequency analysis, it is necessary to use data from similar and nearby locations (Stedinger *et al.*, 1993). This approach is known as regional frequency analysis and utilises data from several sites to estimate the frequency distribution of observed data at each site (Hosking and Wallis, 1987; Hosking and Wallis, 1997). Thus, the concept of regional analysis is to supplement the limited length of record by the incorporation of spatial randomness, using data from different sites in a region (Schaefer, 1990; Nandakumar, 1995). A regional approach has been shown in many studies (e.g. Potter, 1987; Cunnane, 1989; Hosking and Wallis, 1997) to result in more reliable and robust design values.

Regional approaches are not new in frequency analyses of hydrological data and many different techniques are available. The development of a regional index-flood type approach to frequency analysis, based on L-moments (Hosking and Wallis, 1993; 1997) and termed the Regional L-Moment Algorithm (RLMA), has many reported benefits and has been successfully used by Smithers and Schulze (2000a; 2000b) to estimate short (≤ 24 h) and long (1 to 7 day) duration design rainfall depths in South Africa.

The objectives of this project, as stated in the contract, consisted of major objectives related to design rainfall and design flood estimation and are detailed below.

Design Rainfall Estimation in South Africa:

- linking techniques developed during project K5/681 (Short design rainfall estimates for South Africa) to results from project K5/811 (Long duration design rainfall estimates for South Africa), thus increasing spatial resolution of short duration design rainfall estimates in South Africa,
- further verification of techniques, developed during project K5/681, for the estimation of design rainfall for durations 1 h and development, if necessary, of techniques using reliable data for these very short durations,
- development of new regionalised areal reduction factors for South Africa,
- development of new regionalised design and actual hyetographs for South Africa,
- development of revised rainfall erosivity map for SA,
- investigation into the effect of climate change on design storm estimates, and the
- production of comprehensive design rainfall user manual/computer package for short and long duration design storm estimation in South Africa.

Design Flood Estimation in South Africa:

- critical review of existing techniques,
- investigation into and development of regionalised index-flood based design storm estimation methodology using L-moments at selected catchments,
- further evaluation and development of techniques for design flood estimation using a continuous simulation modelling approach at the selected catchments,
- investigation into the effect of climate change on design flood estimates at selected catchments,
- production of a report summarising the results from selected catchments of the feasibility of applying the index-flood and continuous simulation modelling approaches to design flood estimation in South Africa.

The major objective of this study was thus to further refine and link the results obtained independently in the studies by Smithers and Schulze (2000a; 2000b) and to be able to provide reliable and consistent estimates of design rainfall, for durations ranging from 5 minutes to 7 days, at any location in South Africa. Associated with this objective is the requirement to produce a user manual/computer package for the estimation of short and long duration design rainfalls in South Africa. A user manual and a Java-based computer program were developed to implement the procedures developed in this study and enables a user to estimate design rainfalls at any location in South Africa for return periods of 2 to 100 years and for durations ranging from 5 minutes to 7 days.

The approach developed to link and further refine the methodologies outlined by Smithers and Schulze (2000a; 2000b) for design rainfall estimation in South Africa utilises the daily rainfall database, which is considered to be more reliable, and has many more stations with longer record lengths when compared to the digitised short duration rainfall database. For example, approximately 1 800 rainfall stations in South Africa have more than 40 years of daily records while fewer than 200 automatically recording rainfall stations have more than 10 years of record.

The differences in the growth curves which relate design rainfall, scaled by an index value, to duration, developed using the digitised and daily rainfall databases by Smithers and Schulze (2000a; 2000b) respectively, is investigated and the use of scale invariance of the growth curves with duration is proposed. The methodology developed to estimate the index value at any location is South Africa scales the index values for all durations from the daily value, which is estimated as a function of site characteristics using regionalised relationships. Comparisons between design rainfalls estimated using the procedures developed in this study and previous studies indicate that generally methodology developed results in estimates of design rainfall which are frequently more reasonable and consistent than other estimates.

A secondary objective of this project was to review practices and research trends in techniques for design flood estimation, both in South Africa and internationally. In addition, the use of both a regionalised index flood and a continuous simulation modelling approaches for design flood estimation was to be evaluated for application in South Africa.

Recent reviews of approaches to design flood estimation indicate that, relative to other countries, little new research into techniques for design flood estimation has been conducted in South Africa since the early 1970s and that the methodologies used in practice in South Africa require updating and refinement.

A overview methodologies currently used to estimate design floods both in South Africa and internationally is utilised to develop perceived deficiencies in the techniques currently used to estimate design floods in South Africa. In addition, research needs to improve the estimation of design floods in South Africa are identified. The use of continuous simulation modelling for design flood estimation, which is finding increasing support internationally, is illustrated by means of case studies in the Mgeni and Sabie River catchments. The use of regional approaches to improve the reliability of design estimates is illustrated by a case study of the application of an index flood based approach to design flood estimation in KwaZulu-Natal. A summary of the main results emanating from this study follows.

Design Rainfall Estimation

Regional index storm based approaches which utilise L-moments for design rainfall estimation were developed by Smithers and Schulze (2000a) for durations $\leq$ 24 h using digitised rainfall data from 172 stations which had at least 10 years of record, and for 1 to 7 day durations by Smithers and Schulze (2000b) using daily rainfall from 1 789 stations which had at least 40 years of record. A comparison of the growth curves for the 24 h duration indicated inconsistencies in the results from the two studies. Possible explanations for the inconsistencies were attributed to the non-concurrent periods of data used in the two studies and the differences in the annual maximum series, which were extracted using a sliding window from the continuously recorded data and using a fixed period window from the daily rainfall data.

The results obtained in Chapter 3 indicate that there are no systematic differences between higher order L-moment ratios for annual maximum series extracted using fixed and sliding windows. It was also established that the 24 h growth curve, derived from digitised data using a sliding 24 h window, and the 1 day growth curve derived from daily rainfall data, should be the same. Hence, the differences in the short and long duration growth curves are attributed largely to the non-concurrent periods and different length of records used in the analyses and, to a lesser extent, to the errors in the digitised rainfall data.

The scaling properties of the L-moment ratios and growth curves with duration were also investigated in Chapter 3. It was noted that the long duration (1 to 7 days) growth curves derived from the daily rainfall data were relatively scale invariant with duration, whereas the short growth curves derived from the digitised rainfall data did not display the same degree of scale invariance. Results in the literature indicate evidence of scale invariance of the L-moment ratios of extreme rainfall. Hence, is was postulated that the departure from scale invariance of the short duration growth curves could be attributed to a combination of sampling variability, errors in the digitised rainfall data and limitations in the resolution of measurement of the rainfall data.

The sampling variability of the annual maximum rainfall series was estimated using three approaches. The first utilised windows of data extracted from the entire period of record, the second utilised stochastic modelling of the rainfall process and the third approach implemented a bootstrapping technique. The results indicate that there is considerable variation with duration in observed higher order L-moments. This is associated with the sampling variability and length and period of record. The most reliable estimates of the L-moment ratios are computed from the more dependable daily rainfall data, which are more abundant and have longer record lengths than the digitised (< 24 h) rainfall data. It is thus postulated that the 1 day L-moment ratios, and hence growth curves, are the most reliable estimate of the L-moment ratios for all durations. Thus, design rainfalls for all durations may be estimated as the product of the 1 day growth curves and an estimate of the mean of the annual maximum series (index value) for the duration in question.

As detailed in Chapter 4, the methodology developed for estimating the mean of the annual maximum series for all durations at an ungauged location is dependent on the mean of 1 day annual maximum series. Using a cluster analysis of site characteristics, the 78 long duration clusters were grouped into 7 regions for the estimation of the mean of the 1 day annual maximum series. Multiple linear regression relationships with site characteristics (MAP, latitude, altitude) as independent variables enabled the mean of the 1 day annual maximum series to be estimated at any location in South Africa. Gridded residual errors at stations which had at least 40 years of data were used to correct the estimated values at these sites and ensure that the estimated value were the same as the observed values at these sites. This approach was shown to result in reliable and consistent estimates of the 1 day annual maximum series.

For durations longer than 1 day, the mean of the D day ($2 \leq D \leq 7$) duration values were noted to scale linearly as a function of the 1 day values. The parameters of the regression were found to scale (by a power law relationship) with duration, and three parameters were derived to describe the relationship between the two regression parameters (coefficient and intercept) and duration. Thus, 6 parameters in all were derived for each of the 7 regions which enable the estimation of the mean of the annual maximum series for durations ranging from 2 to 7 days at any location in South Africa.

For durations shorter than 1 day, the mean of the H minute ($H \leq 1440$) duration values were found to scale linearly as a function of the 24 h values. Thus, for each of the 15 short duration clusters and for 15 durations ranging from 5 to 1200 minutes, linear regression coefficients were derived.

The approach adopted to estimate the mean of the annual maximum series for any duration is a two step process. Firstly, the mean of the 1 day annual maximum series is estimated at the required location using regionalised regressions. Secondly, the mean of the annual maximum series for durations longer than 1 day are scaled directly from the 1 day value. For durations shorter than 1 day, the values are scaled from the 24 h value, which in turn is estimated directly from the 1 day value for the location. This approach for durations < 24 h was shown to be more efficient and reliable than the methodology developed by Smithers and Schulze (2000a).

The daily rainfall database, which is more reliable and has many more stations and longer records lengths than the digitised rainfall database, is utilised in the estimation of the mean of the annual maximum series for all durations. Thus, inconsistencies in the digitised rainfall database are, to some extent, compensated for by scaling from the daily values.

In the application of the regression relationships to estimate the mean of the annual maximum series for durations shorter and longer than 1 day, it was noted that inconsistencies between estimated values could arise if 1 day values which were outside of the range of values used to develop the relationships, were input to the equations. This could result in, for example, the mean of the annual maximum series for a particular duration being larger than the value estimated for a longer duration. Thus, the concept of the slope between the mean of the annual maximum series and duration, for a range of selected durations, was introduced. It was noted from the observed data at numerous sites that, if changes in scaling do occur, they typically occur at durations of 15 min, 2 h, 1 day and 3 days. These durations were therefore used as pivotal durations, with the regression based approach used to estimate the mean of the annual maximum series at these durations, and the mean of the annual maximum series for intermediate durations scaled from these values. This application of the Regional L-Moment Algorithm, in conjunction with a Scale Invariance approach has been termed the RLMA&SI.

The performance of the RLMA&SI procedures have been assessed in a number of ways. At 10 sites located in different climatic regions of South Africa and which each have at least 40 years of daily rainfall data, and which were not used in the regionalisation process, the RLMA&SI procedures generally exceeded the design values estimated directly from the at-site data for return periods greater than 20 years. A similar trend was evident at all daily rainfall stations which have at least 40 years of record.

A comparison at 2184 daily rainfall stations between design rainfall estimated by Adamson (1981) and by the RLMA&SI procedures indicated that for return periods of less than 50 years, the differences between the two estimates were generally less than 20%, while for longer return periods the differences were greater, with the Adamson values generally exceeding the RLMA&SI design rainfalls. These differences are attributed to:

- the longer record lengths used in the regional approach;
- the stringent data quality control procedures developed by Smithers and Schulze (2000b) and used in this study;
- the different approaches to design rainfall estimation used in the two studies,
  - with Adamson (1981) using a single site approach with a censored LN distribution while
  - the regional approach using the RLMA&SI procedures adopted the GEV distribution; and
- the L-moments used in the RLMA&SI approach to fitting the GEV distribution being less influenced by outliers in the data.

However, it has been shown that design rainfall depths computed using the regional approach generally exceed the values computed directly from the at-site data. In addition, the regional approach has been shown in many international studies (e.g. Potter, 1987; Cunnane, 1989; Hosking and Wallis, 1997) to result in more reliable and robust estimates compared to design values computed using only single at-site data. Therefore, it is postulated that the 1 to 7 day design rainfall values computed using the RLMA&SI procedures may be used with confidence.

Further comparisons between design rainfall estimated using different approaches for durations $\leq$ 24 h were performed. The approaches included design rainfall estimated from the observed data, by the RLMA&SI procedures, by using the equation developed by Alexander (2001), using the equation developed by Adamson (1981) in DWAF Report TR102 and by using the results from Midgley and Pitman (1978) Contained in HRU Report HRU2/78. Generally, the design rainfalls estimated using the RLMA&SI and HRU2/78 procedures were similar and, where no obvious anomalies were evident in the data, follow the trends in design rainfalls estimated directly from the observed data. It was evident that the Alexander (2001) equation generally overestimates design rainfalls for durations ranging from 10 minutes to 24 h, with the maximum overestimation occurring at durations of approximately 1 h. Furthermore, inconsistencies between the estimated 24 h event estimated using Alexander (2001) and the TR102 1 day value, on which the equation is based, were evident. The functional relationship of the Alexander equation does not seem to accommodate the curvilinear relationship between design rainfall depth and log transformed duration, which is evident in the observed data at most stations investigated.

From the comparisons performed in this study is evident that, compared to the observed data and other approaches used for estimating design rainfalls, the RLMA&SI procedures developed generally result in estimates of design rainfall which are frequently more reasonable and consistent than other estimates. This is evident for 1 to 7 day durations where RLMA&SI values are generally similar to the values computed directly from the at-site data and display a consistent trend for these durations, whereas inconsistencies in both the TR102 values and observed data are evident. The RLMA&SI values are consistent over the entire range of durations, whereas, the other techniques considered are frequently inconsistent for durations shorter and longer than 24 h.

In summary, the RLMA&SI procedures utilise the more reliable, consistent and longer records of the daily rainfall database to estimate design rainfalls for shorter durations, thus compensating for deficiencies in the digitised rainfall database. It is thus concluded that the RLMA&SI

procedures may be used with confidence to estimate design rainfalls in South Africa for durations up to 7 days.

A graphical user interface has been developed in Java to facilitate the estimation of design rainfall depths for any location in South Africa. This software implements the procedures developed in this study and enables the estimation of design rainfalls at a spatial resolution of 1 arc minute and for durations ranging from 5 minutes to 7 days and for return periods of 2 to 200 years.

Design Flood Estimation

Design flood estimation may be performed by a frequency analysis of observed flows where these are available and adequate in both length and quality. The analysis may be performed at a single site, or preferably a regional approach should be adopted. The advantages of a regional approach to frequency analysis for design flood estimation are evident from the studies reviewed. This has led to the adoption of a regional approach as the recommended approach for design flood estimation by some countries (e.g. Australia and UK). Alexander (1990; 2001) advocates a regional approach for South Africa and details a methodology and provides software for the implementation of the regional approach, but states that overseas concepts of identifying homogeneous regions are not valid in South Africa. Using Alexander's approach, users are expected to visually interpret the data and decide subjectively which data can be used beneficially to improve the estimates of the parameters of the distribution being fitted to the data. This raises the question of inconsistency in the results between different users and places an onerous burden on each user, who has to collect the raw data for the stations in the region and then proceed with the analysis. Furthermore, it is probable that similar analyses would be performed by different users for the same regions and valuable human resource time would be wasted. It is argued that a research project, undertaken by respected experts, to develop a regional approach on a national scale could thus save significant effort by individual users and improve the consistency of results. An argument against this computerised "cook book" approach is that it may be applied by inexperienced designers outside of the bounds within which it was developed. However, it is postulated that far larger errors and inconsistencies will result when the current manual approaches are applied by inexperienced designers.

For direct statistical analysis Alexander (1990; 2001) recommends either the Method of Moments or Probability Weighted Moments for fitting distributions. The literature indicates that L-moments are widely used and have been adopted as a standard approach in, for example, the UK. Although some caution and criticism of the use of L-moments is also evident in the literature, further investigation of L-moments for possible general use in South Africa is warranted.

When no recorded streamflow data are available at the site of interest, or the records are inadequate, the recommended event-based rainfall : runoff methods for design flood estimation in South Africa include the unit hydrograph, Rational and SCS methods.

No development or refinement of the unit hydrograph methods for South Africa have been published since they were developed by the HRU (1972) in the late 1960s and early 1970s.

Subsequent to these studies, regional techniques for frequency analysis have become the standard and preferred approach in some countries. In addition, longer rainfall and streamflow records are currently available for analysis, computing power has expanded enormously and detailed databases of climatic and catchment physiographic characteristics are available at a national scale. While the regionalisation of South Africa into nine veld zone types, based on data from only 92 flow gauging stations, was pioneering work in the 1960s, it is postulated that a refined regionalisation of homogeneous hydrological response regions in the country is now possible. Furthermore, the event based methods are generally applied in a deterministic manner and hence suffer from the limitations of this approach, which includes both the uncertainty of the real exceedance probability associated with the computed design flood and the spatial and temporal distribution of rainfall and soil moisture conditions in the catchment prior to extreme events. Although a return period adjustment factor for the application of the Rational Method in South Africa is advocated, the method is still applied in a deterministic manner and the adjustment factor does not constitute a probabilistic approach. A probabilistic approach would enable the conversion of a design rainfall event into a design flood event with the same return period.

The calibrated Rational method developed by Alexander (2002), and termed the "Standard Flood", is a probabilistic-based approach which has the ingredients to overcome some of the deficiencies evident in the techniques currently used for design flood estimation in South Africa. In this study no in-depth analysis of the standard flood has been performed, but the use of a single rainfall site and outdated design rainfall values (TR102), the subjective adjustments made, the method of incorporation of variability within regions and the method of regionalisation are all aspects that could warrant further investigation.

The adaptations for southern African conditions to the SCS approach, as detailed by Schmidt and Schulze (1987), account for regional differences in median antecedent soil moisture conditions prior to large events and for the joint association between rainfall and runoff. However, improved computing power and currently available databases could be utilised to further refine the method. For example, the regionalisation of South Africa could be improved, at the broadest scale, to reflect the 1946 Quaternary Catchments into which South Africa has been delineated and, where necessary, could also reflect heterogeneity of soils and current land use within each Quaternary Catchment. The method used to account for regional differences in antecedent moisture conditions (AMC) could be improved by utilising improved modelling inputs. For example, estimates of reference potential evaporation as well as maximum evaporation (i.e. transpiration by vegetation and soil evaporation) could be improved by using currently available information. The use of median conditions to account for AMC needs to be re-evaluated and possibly improved by the use of continuous simulation modelling. It is probable that the soil moisture status could be a function of the exceedance probability of the intended design. The method used to account for the joint association between rainfall and runoff could also be improved by the use of a continuous simulation approach and could include events larger than those equivalent to the 20 year return period, to which the 1987 adaptation of the SCS technique for South Africa is currently limited.

An important aspect for design flood estimation is the need for consistency when each of the various methods are applied by different users, i.e. similar results should be obtained by different users when applying the same method. Alexander (1990) states that the subjectivity in the estimation of design storms is a major limitation in the consistent estimation of design floods in South Africa. For a specified catchment response time, the RLMA&SI procedures to estimate design rainfall will, when applied on a 1' x 1' gridded scale in South Africa, overcome the subjectivity in rainfall input. However, considerable inconsistency remains in the estimation of the catchment response time, and hence in the estimation of the critical duration of rainfall, and in the selection of other model inputs based on text book values for the Rational Method and, to a lesser extent, the SCS techniques.

Conclusions

The major contractual objectives of the project have been met. The development of the RLMA&SI procedures for design rainfall estimation in South Africa not only adopts a novel approach by utilising the scale invariance of growth curves with duration, but enables reliable and consistent estimates of design rainfall to be made in South Africa by means of a Java-based computer programme with a graphical user interface.

The inconsistencies in the growth curves developed in the studies by Smithers and Schulze (2000a; 2000b) was unexpected and resulted in the development of the RLMA&SI procedures. Therefore, the development of new regionalised areal reduction factors, design and actual hyetographs, rainfall erosivity map and the impacts of climate change on design rainfall estimates for South Africa, as stated in the project objectives, were not achieved in this study and are recommended for future research.

The secondary contractual objective related to design flood estimation has been largely achieved. Both the South Africa and international literature on design flood estimation was reviewed and a summary of research needs for South Africa has been compiled. Pilot studies on the use of an index-flood and a continuous simulation modelling approach to design flood estimation in South Africa has been completed. The effects of climate change on design flood estimation was not undertaken and is recommended for future research.

The gap between flood research and practice is emphasised by Cordery and Pilgrim (2000), with research required to improve the estimates of both specific and probabilistic floods. Although the gap between flood research and practice may not be large in South Africa, partially because relatively little research in design flood hydrology has been undertaken in the past 25 years, the need to refine existing methods and to evaluate new methods adopted for design flood estimation in other countries, currently requires urgent attention and funding in South Africa.

Recommendations for Further Research

It is frequently necessary to estimate a design hydrograph which, in turn, requires the estimation of a design hyetograph. The RLMA&SI procedures developed in this study enable the estimation of a design rainfall depth for a particular duration. Hence, regionalised procedures need to be developed to enable the disaggregation of the design rainfall depth into a design hyetograph. An additional requirement which could be a by-product of this investigation are regionalised relationships to disaggregate recorded daily rainfall data into a hyetograph with sub-daily time steps. These procedures are required when, for example, modelling certain sub-daily processes within a daily time step model (e.g. in flow routing or rainfall infiltration routines).

When estimating design flood hydrographs from a catchment it is necessary to convert the point rainfall measurements to areal rainfall depths using Areal Reduction Factors (ARF). These ARF relationships need to be re-investigated in the light of recent extreme events and as longer periods of record are now available for analysis, and also in the way in which ARF may vary in South Africa with recurrence interval and with rainfall producing mechanisms.

The following research needs in design flood hydrology for South Africa have been identified and are listed in a perceived priority which takes into account the need to introduce new and internationally accepted techniques and to refine existing techniques:

- A continuous simulation approach to design flood estimation should be further evaluated and developed. Such an approach overcomes many of the limitations of the design event models and can accommodate current and projected future conditions in a catchment, such as anticipated land use or climate change. Limitations of the gauged flow data and changes in catchment conditions within the period of gauging may be overcome using this approach. It may be necessary to combine this approach with, for example, unit hydrographs to estimate the peak discharge. The output from a continuous simulation approach could be pre-run and packaged for hydrologically homogeneous regions/Quaternary Catchments to enable simple and rapid use by practitioners.
- Areal Reduction Factors (ARFs), which convert design rainfall estimated at a point to an areal rainfall, need to be re-investigated in the light of recent extreme events and as longer periods of record are now available for analysis, and also in the way in which ARFs may vary in South Africa with recurrence interval and with rainfall producing mechanisms.
- Techniques for the temporal disaggregation and spatial estimation of daily rainfall need to be revised and refined.
- A joint probability approach to design flood estimation, which derives the flood frequency distribution by the incorporation of uncertainties in the inputs to the model, should be investigated.
- A revision and updating of the SCS method for design flood estimation on small catchments in South Africa should be undertaken to incorporate both the increased spatial resolution of information now available and the updated and improved design rainfall values, while simultaneously improving the technique to account for antecedent moisture conditions.
- A regional statistical approach for flood frequency should be developed, i.e. the identification of homogeneous regions, the development of growth curves for each reach and the development of algorithms to estimate the scaling factor at ungauged sites. Regionalisation based both on a cluster analysis of site characteristics and the region of influence approach, as adopted by the Flood Estimation Handbook (FEH) for the UK (Reed, 1999), should be investigated.
- Improved and consistent methods to estimate catchment lag should be evaluated.
- A probabilistic approach to the use of the Rational Method should be investigated. The observed streamflow data required for this approach could be supplemented with the output of the continuous simulation approach, i.e. this could constitute one of the simple approaches which could be synthesised from the output of the continuous simulation approach. Alexander (2002) has developed a “standard design flood” using this approach, which may require further refinement.

- The run-hydrograph technique should be re-evaluated and, if necessary, further refined for use by practitioners.
- The unit hydrograph approach including the estimation of storm losses should be refined, utilising longer records, improved regionalisation and currently available detailed databases and geographic information systems.

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Dr GC Green	Water Research Commission
Mrs L KcKune/ Dr LJ du Preez	Water Research Commission (Secretary)
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LIST OF ACRONYMS

AMC	Antecedent Moisture Conditions
AMS	Annual Maximum Series
ARF	Areal Reduction Factor
BLRP	Bartlett-Lewis Rectangular Pulse
BLRPG	Bartlett-Lewis Rectangular Pulse Gamma
BS	Bootstrap
CN	Curve Number
EMA	Expectation Maximisation Algorithm
FEH	Flood Estimation Handbook
GEV	General Extreme Value
L_l_{1day}	Mean of AMS for 1 day duration
LM	Linear Moments
LP3	Log-Pearson Type 3
MAP	Mean Annual Precipitation
MLP	Maximum Likelihood Procedure
MM	Method of Moments
OBS	Observed
PWM	Probability Weighted Moments
RD	Relative Difference
RLMA	Regional L-Moment Algorithm
RLMA&SI	Regional L-Moment Algorithm and Scale Invariance procedures
SE	Standard Error

CHAPTER 1

INTRODUCTION

The estimation of design flood events are necessary for the planning and design of engineering projects (Rahman *et al.*, 1998). Hence, flood frequency analysis remains a subject of great importance owing to its economical and environmental impact (Pilgrim and Cordery, 1993; Bobee and Rasmussen, 1995). However, reliable estimates of flood frequency in terms of peak flows and volumes remain a current challenge in hydrology (Cameron *et al.*, 1999). Cordery and Pilgrim (2000) express the opinion that the demands for improved estimates of floods have not been met with any increased understanding of the fundamental hydrological processes.

Standard techniques for flood estimation have been developed for many countries. These generally include statistical analysis of observed peak discharges, where these are available, and event modelling using rainfall-runoff techniques. Observed streamflow data are often not available at the site of interest and frequently rainfall event-based methods have to be used. This requires a probabilistically based estimate of rainfall, generally referred to as design rainfall, to be made at the site of interest. The frequently used term design rainfall is thus the rainfall depth and duration, or intensity, associated with a given probability of exceedance, which in turn is inversely related to the commonly used term, return period.

Design rainfall depths for various durations are thus required for the many engineering and conservation design decisions made annually in South Africa and which result in many millions of Rands of construction. For example, engineers and hydrologists involved in the design of hydraulic structures (e.g. culverts, bridges, dam spillways and reticulation for drainage systems) need to assess the frequency and magnitude of extreme rainfall events in order to generate design flood hydrographs. Hence, Depth-Duration-Frequency (DDF) relationships, which utilise recorded events in order to predict future exceedance probabilities and thus quantify risk and maximise design efficiencies, are a key concept in the design of hydraulic structures (Schulze, 1984).

The duration of design rainfall which is required for design flood estimation may range from as short as 5 minutes for small urban catchments which have a rapid hydrological response, to a few days for large regional flood studies. One of the requirements for undertaking frequency analyses is long periods of records. Given that the data at a site of interest will seldom be sufficient, or available for frequency analysis, it is necessary to use data from similar and nearby locations (Stedinger *et al.*, 1993). This approach is known as regional frequency analysis and utilises data from several sites to estimate the frequency distribution of observed data at each site (Hosking and Wallis, 1987; Hosking and Wallis, 1997). Thus, the concept of regional analysis is to supplement the limited length of record by the incorporation of spatial randomness, using data from different sites in a region (Schaefer, 1990; Nandakumar, 1995). A regional approach has been shown in many studies (e.g. Potter, 1987; Cunnane, 1989; Hosking and Wallis, 1997) to result in more reliable and robust design values.

Regional approaches are not new in frequency analyses of hydrological data and many different techniques are available. The development of a regional index-flood type approach to frequency analysis, based on L-moments (Hosking and Wallis, 1993; 1997) and termed the Regional L-Moment Algorithm (RLMA), has many reported benefits and has been successfully used by Smithers and Schulze (2000a; 2000b) to estimate short (≤ 24 h) and long (1 to 7 day) duration design rainfall depths in South Africa.

The objectives of this project, as stated in the contract, consisted of major objectives related to design rainfall and design flood estimation and are detailed below.

Design Rainfall Estimation in South Africa:

- linking techniques developed during project K5/681 (Short design rainfall estimates for South Africa) to results from project K5/811 (Long duration design rainfall estimates for South Africa), thus increasing spatial resolution of short duration design rainfall estimates in South Africa,
- further verification of techniques, developed during project K5/681, for the estimation of design rainfall for durations 1 h and development, if necessary, of techniques using reliable data for these very short durations,
- development of new regionalised areal reduction factors for South Africa,
- development of new regionalised design and actual hyetographs for South Africa,
- development of revised rainfall erosivity map for South Africa,
- investigation into the effect of climate change on design storm estimates, and the
- production of comprehensive design rainfall user manual/computer package for short and long duration design storm estimation in South Africa.

Design Flood Estimation in South Africa:

- critical review of existing techniques,
- investigation into and development of regionalised index-flood based design storm estimation methodology using L-moments at selected catchments,
- further evaluation and development of techniques for design flood estimation using a continuous simulation modelling approach at the selected catchments,
- investigation into the effect of climate change on design flood estimates at selected catchments,
- production of a report summarising the results from selected catchments of the feasibility of applying the index-flood and continuous simulation modelling approaches to design flood estimation in South Africa.

The major objective of this study was thus to further refine and link the results obtained independently in the studies by Smithers and Schulze (2000a; 2000b) and to be able to provide reliable and consistent estimates of design rainfall, for durations ranging from 5 minutes to 7 days, at any location in South Africa. Associated with this objective is the requirement to produce a user manual/computer package for the estimation of short and long duration design rainfalls in South Africa. Appendix A of this report contains a user manual for the Java-based computer program which implements the procedures developed in this study and enables a user to estimate design rainfalls at any location in South Africa for return periods of 2 to 100 years and for durations ranging from 5 minutes to 7 days.

The techniques developed to link and further refine the methodologies outlined by Smithers and Schulze (2000a; 2000b) for design rainfall estimation in South Africa are contained in Part A of this report which consists of Chapters 2 to 5. The approach developed utilises the daily rainfall database, which is considered to be more reliable, and has many more stations with longer record lengths when compared to the digitised short duration rainfall database. For example, approximately 1 800 rainfall stations in South Africa have more than 40 years of daily records while fewer than 200 automatically recording rainfall stations have more than 10 years of record.

The regional approaches to design rainfall estimation in South Africa developed by Smithers and Schulze (2000a; 2000b) are summarised in Chapter 2. The differences in the growth curves which relate design rainfall, scaled by an index value, to duration, developed using the digitised and daily rainfall databases, is investigated in Chapter 3 and the use of scale invariance of the growth curves with duration is proposed. The development of relationships to estimate the index value at any location is South Africa is reported in Chapter 4 and the methodology which was developed scales the index values for all durations from the daily value, which is estimated as a function of site characteristics using regionalised relationships. The procedures developed are summarised in Chapter 5 and comparisons between design rainfalls estimated using the procedures developed in this study and previous studies are presented.

A secondary objective of this project was to review practices and research trends in techniques for design flood estimation, both in South Africa and internationally. In addition, the use of both a regionalised index flood and a continuous simulation modelling approaches for design flood estimation was to be evaluated for application in South Africa.

Recent reviews of approaches to design flood estimation are contained in Cordery and Pilgrim (2000), Smithers and Schulze (2001a) and in Chapter 6 of this report. These indicate that, relative to other countries, little new research into techniques for design flood estimation has been conducted in South Africa since the early 1970s and that the methodologies used in practice in South Africa require updating and refinement.

Part B of this document focusses on design flood estimation and contains the results of work undertaken as part of this study. Chapter 6 contains a brief overview of methodologies currently used to estimate design floods both in South Africa and internationally and presents perceived deficiencies in the techniques currently used to estimate design floods in South Africa. In addition, research needs to improve the estimation of design floods in South Africa are identified. The use of continuous simulation modelling for design flood estimation, which is finding increasing support internationally, is illustrated by means of case studies in the Mgeni and Sabie River catchments. The use of regional approaches to improve the reliability of design estimates is illustrated in Chapter 7 by a case study of the application of an index flood based approach to design flood estimation in KwaZulu-Natal. Chapter 8 contains a discussion of the contents of this document and draws some conclusions while Chapter 9 lists the references used in this study.

PART A

ESTIMATION OF DESIGN RAINFALL IN SOUTH AFRICA: THEORY

CHAPTER 2

A REVIEW OF REGIONAL APPROACHES TO DESIGN RAINFALL ESTIMATION IN SOUTH AFRICA

Numerous regional and national scale studies in South Africa have focused on estimating design rainfalls for durations ≤ 24 h. These include those of Vorster (1945), Woolley (1947), SAWB (1956), Reich (1961), Reich (1963), Bergman and Smith (1973), SAWB (1974), Adamson (1977), Alexander (1978), Midgley and Pitman (1978), Van Heerden (1978), Henderson-Sellers (1980), Schulze (1980), Adamson (1981), Sinske (1982), Op Ten Noort (1983), Schulze (1984), Weddepohl *et al*. (1987), Weddepohl (1988), Smithers (1996), Smithers and Schulze (2000a) and Alexander (2001). Studies in South Africa which have estimated design rainfalls for durations of one day and longer include those by SAWB (1956), Schulze (1980), Adamson (1981), Pegram and Adamson (1988) and Smithers and Schulze (2000b). With the exception of the research by Smithers and Schulze (2000a; 2000b), the other studies have all utilised point design rainfall values using at-site data only and no regionalisation was performed in an attempt to increase the reliability of the design values at gauged sites and for the estimation of design values at ungauged sites.

Regional frequency analysis assumes that the standardised variate has the same distribution at every site in the selected region and that data from a region can thus be combined to produce a single regional rainfall, or flood, frequency curve that is applicable anywhere in that region with appropriate site-specific scaling (Cunnane, 1989; Gabriele and Arnell, 1991; Hosking and Wallis, 1997). This approach can then also be used to estimate events at ungauged sites where no rainfall or runoff data exists at the site (Pilon and Adamowski, 1992).

In nearly all practical situations a regional method has been found to be more efficient than the application of an at-site analysis (Potter, 1987). This view is also shared by both Lettenmaier (1985; cited by Cunnane, 1989), who expressed the opinion that "regionalisation is the most viable way of improving flood quantile estimation", and by Hosking and Wallis (1997) who, after a review of recent literature, advocate the use of regional frequency analysis based on the belief that a "well conducted regional frequency analysis will yield quantile estimates accurate enough to be useful in many realistic applications". Where slight statistical heterogeneity exists within a region, regional analysis yields more accurate design estimates than at-site analysis (Lettenmaier and Potter, 1985; Cunnane, 1989; Hosking and Wallis, 1997). Even in heterogenous regions, regional frequency analysis may still be advantageous for the estimation of extreme quantiles (Cunnane, 1989; Hosking and Wallis, 1997).

The extrapolation to return periods beyond the record length introduces much uncertainty which can be reduced by regionalisation procedures which relate the observed rainfall or flood at a particular site to a regional response (Ferrari *et al.*, 1993). Nathan and Weinmann (1991) illustrate the effect of record length on quantile estimates and show that the combined at-site/regional estimates are far more robust in relation to length of record than those based only on at-site data, particularly when only short record lengths are available.

Regional approaches are not new in frequency analysis and many different techniques are available. The development of a regional index-flood type approach to frequency analysis based on L-moments (Hosking and Wallis, 1993; 1997), termed the Regional L-Moment Algorithm (RLMA), has many reported benefits and has been used successfully by Smithers and Schulze (2000a; 2000b) to estimate short (≤ 24 h) and long (1 to 7 day) duration design rainfall in South Africa. The following section summarises the regional approach adopted in these studies.

2.1 Regional L-Moment Algorithm

Hosking and Wallis (1993; 1997) developed a regional frequency analysis procedure based on L-moments. While being similar to ordinary product moments, the purpose of L-moments is to summarise theoretical probability distributions and observed samples (Vogel *et al.*, 1993a). Hence, L-moments can be used for parameter estimation, interval estimation and hypothesis testing. L-moments have several important advantages over ordinary product moments (Vogel *et al.*, 1993b). In order to estimate the sample variance and sample skewness, ordinary product moments require the squaring and cubing of the observations respectively. Sample estimators of L-moments are linear combinations of the ranked observations and do not require squaring and cubing of the observations. Thus L-moments are subject to less bias than ordinary product moments (Wallis, 1989; Pearson *et al.*, 1991; Vogel *et al.*, 1993a; Karim and Chowdhury, 1995).

An index storm approach assumes that within a homogeneous region the frequency distribution of observations from all the sites in the region are identical, apart from a site-specific scaling factor. Assuming that N sites form a homogeneous cluster, with site i having a record length n_i, sample mean $l_1^{(i)}$ and sample L-moment ratios $t^{(i)}$, $t_3^{(i)}$, $t_4^{(i)}$, then the regional average L-moment ratios t^R, t_3^R, t_4^R, which are weighted in proportion to the sites' record length, are computed as:

$$t^R = \sum_{i=1}^{N} n_i t^{(i)} / \sum_{i=1}^{N} n_i \qquad ...1$$

$$t_r^R = \sum_{i=1}^{N} n_i t_r^{(i)} / \sum_{i=1}^{N} n_i \ , \ r = 3,4,.... \qquad ...2$$

The regional average mean is set to 1 (i.e. $l_1^{(R)} = 1$) and the selected distribution is fitted by equating the theoretical L-moment ratios to $l_1^{(R)}$, t^R, t_3^R, t_4^R calculated in Equations 1 and 2. As shown in Equation 3, the quantile, with non-exceedance probability F, may be estimated by combining the quantile function of the fitted distribution ($\hat{q}$), commonly referred to as a growth curve, with the at-site mean.

$$\hat{Q}_i(F) = l_1^{(i)} \hat{q}(F) \qquad ...3$$

The strength of regional frequency analysis using the RLMA is that it is useful even when not all of its assumptions are satisfied (Hosking and Wallis, 1997). The RLMA has many reported advantages, including robustness, and is relatively simple to apply. Routines obtained from Hosking (1996) were utilised for the identification of discordant stations, testing of clusters for homogeneity and for the implementation of the RLMA in South Africa.

The identification of homogeneous regions is usually the most difficult of all the stages in a regional frequency analysis and requires the most subjective judgment (Hosking and Wallis, 1997). This step aims at forming groups, or clusters, of sites that are approximately homogeneous, i.e. the frequency distribution at each site within the cluster is nearly identical, apart from a site-specific scale factor.

Data available for the formation of regions are site statistics (quantiles calculated from measurements) and site characteristics such as latitude, longitude, elevation, mean annual precipitation (MAP) and other rainfall characteristics. Hosking and Wallis (1997) recommend that the site characteristics, and not the site statistics, be used for regionalisation. The at-site statistics should be used for independent testing of proposed homogeneous regions. Some statistics (e.g. MAP, rainfall seasonality) which are estimated from measurements may be included in the site characteristics, provided that the statistics are not too highly correlated with the variable of interest. This approach would also enable the estimation of quantiles at ungauged sites where site characteristics are available.

The results from the application of the above methodology in South Africa for durations ≤ 24 h, using digitised rainfall data, and for 1 to 7 day durations, using daily rainfall, is summarised in the following section.

2.2 Application of Regional L-Moment Algorithm in South Africa

The RLMA has been applied to estimate design rainfalls in South Africa and full details of the theory and methodology adopted are contained in Smithers and Schulze (2000a; 2000b).

2.2.1 Data utilised

Smithers and Schulze (2000a) utilised digitised rainfall data from 172 sites in South Africa, which have at least 10 years of record, to estimate short duration design rainfall. As illustrated by Smithers (1993) and Smithers and Schulze (2000a), many of the digitised rainfall data are viewed as unreliable, as many errors in the digitisation process are evident in the data. In addition, comparisons between the 24 h rainfall totals, computed from the digitised rainfall data, and daily rainfall, as measured at 08:00 every day using standard non-recording raingauges at the same site, indicated numerous significant discrepancies in the two values. Hence, Smithers and Schulze (2000a) utilised the scaling characteristics and stochastic modelling of the rainfall process to complement the regional approach to design rainfall estimation for durations < 24 h. The approach adopted in this study to overcome the deficiencies in the digitised rainfall data is to utilise, as far as possible, the more abundant and reliable daily rainfall data which generally have longer record lengths than the digitised rainfall data.

Data from 1806 rainfall stations in South Africa which have at least 40 years of quality controlled daily records were utilised by Smithers and Schulze (2000b) to estimate design rainfalls for 1 to 7 day durations in South Africa. Details of the regionalisation procedure are contained in the following section.

2.2.2 Identification of homogeneous clusters

Regionalisation of sites using only site characteristics was performed by cluster analysis. The most subjective aspect of the RLMA is the cluster analysis and it may be necessary to relocate sites or create new clusters subjectively, but based on geographical and physical considerations (Hosking and Wallis, 1997). In the cluster analysis, a vector of site characteristics is associated with each site and standard multivariate statistical analysis is performed to group sites according the similarity of the vectors (Hosking and Wallis, 1997).

The site characteristics used in the cluster analysis were latitude (°), longitude (°), altitude (m), a monthly index of the concentration of precipitation (%), MAP (mm), an index of rainfall seasonality (category) and distance from sea (m). The regions identified in the cluster analysis of site characteristics were tested for homogeneity using a heterogeneity test developed by Hosking and Wallis (1993), which compares the between-site variability (dispersion) of L-moments with that which would be expected for a homogeneous region. The distribution of the 15 relatively homogeneous short duration rainfall clusters identified by Smithers and Schulze (2000a) are shown in Figure 1 and the 78 long duration rainfall clusters identified by Smithers and Schulze (2000b) are shown in Figure 2.

2.2.3 Growth curves

The General Extreme Value (GEV) distribution was determined to be the most appropriate distribution to use for design rainfall estimation in South Africa (Smithers, 1996; Smithers and Schulze, 2000a; 2000b). Growth curves, which depict the relationship between a growth factor (ratio of design storm and an index storm) and return period, were derived for each cluster and for durations ranging from 15 minutes to 7 days. Examples of growth curves with their 90% error bounds are shown in Figure 3. The mean of the Annual Maximum Series (AMS) was utilised as the index storm. Hence, in order to estimate design rainfall depths at an ungauged location, it is necessary to estimate the mean of the AMS for the required duration at the desired location.

2.3 Assessment of Regional Approaches to Design Rainfall Estimation in South Africa

The study by Smithers and Schulze (2000a) to estimate design rainfalls for ≤24 h was undertaken and completed before the project to estimate 1 to 7 day design rainfalls was initiated. At the time that the first project was proposed, it was deemed that the estimates of short duration design rainfall required more urgent updating than the daily rainfall values. In retrospect, the studies may have been more compatible had the daily design rainfall study, which utilised more reliable data from a larger number of stations with longer record lengths available for analysis, been undertaken first. Subsequent analyses highlighted inconsistencies in the growth curves derived from the two studies. This issue is addressed in the following chapter.

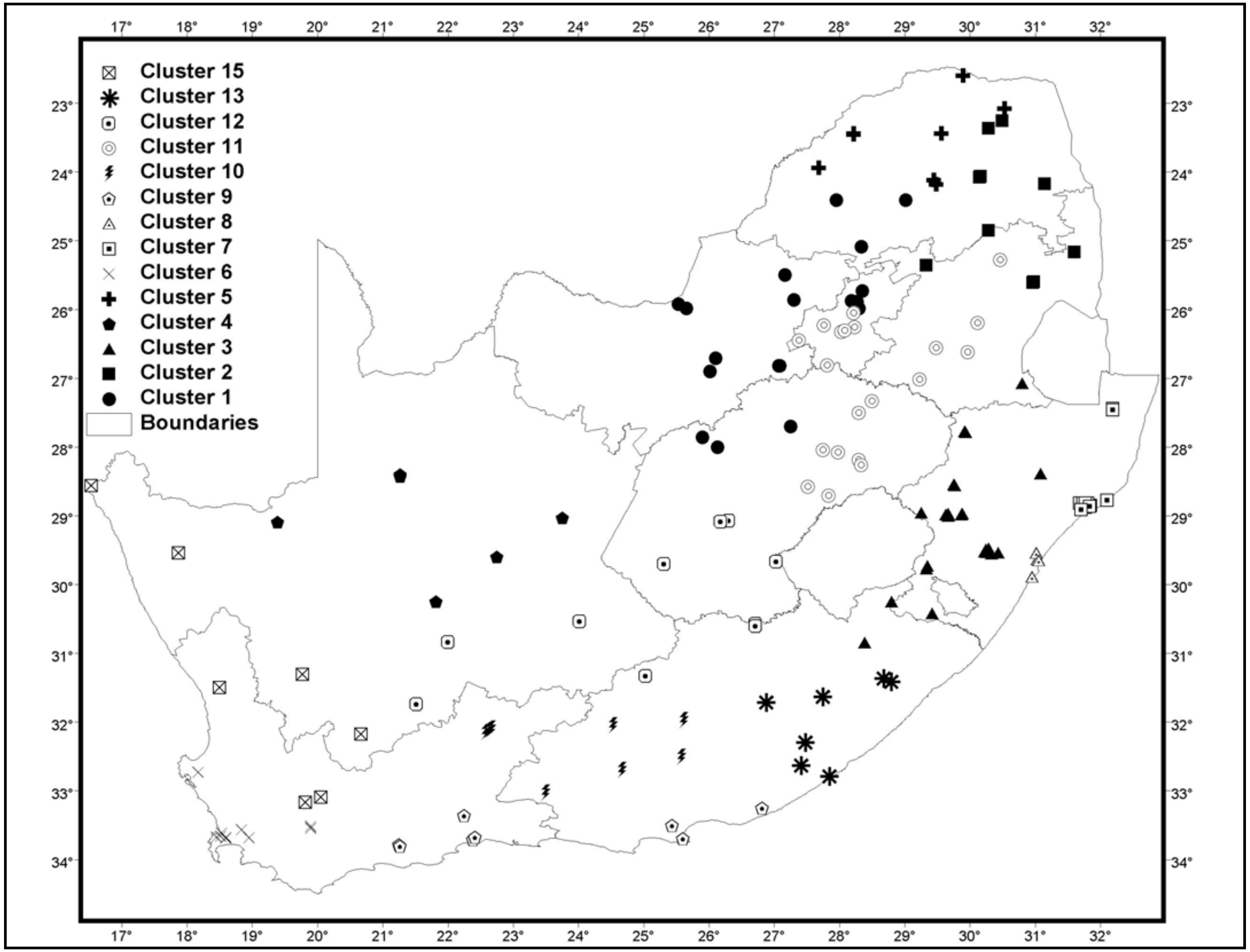


Figure 1 Distribution of 15 clusters of relatively homogeneous extreme short duration (≤ 24 h) rainfall in South Africa (Smithers and Schulze, 2000a)

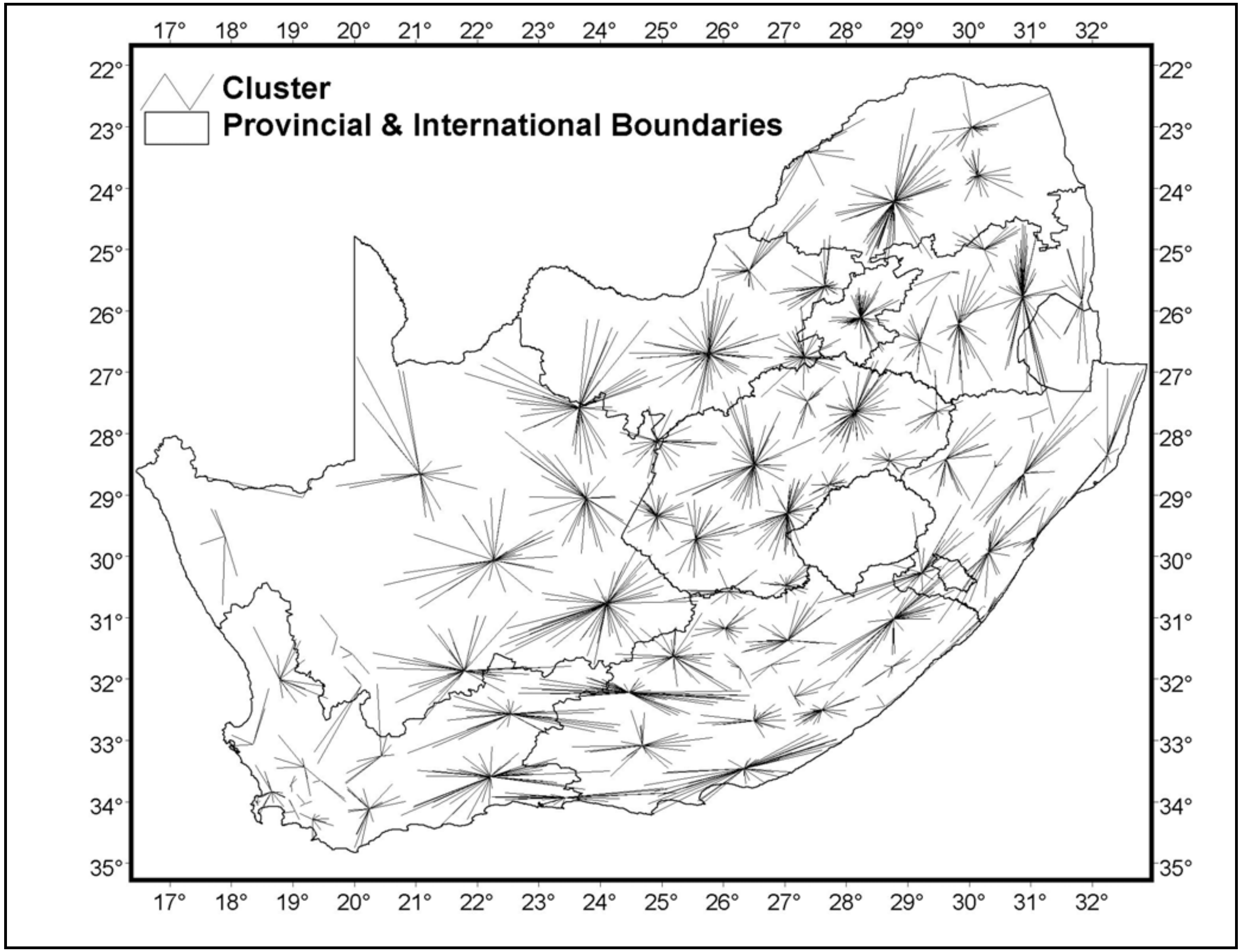


Figure 2 Distribution of 78 clusters of relatively homogeneous extreme daily rainfall in South Africa (Smithers and Schulze, 2000b)
(Each line and the centre point of each cluster represents the location of a daily rainfall station which has at least 40 years of record)

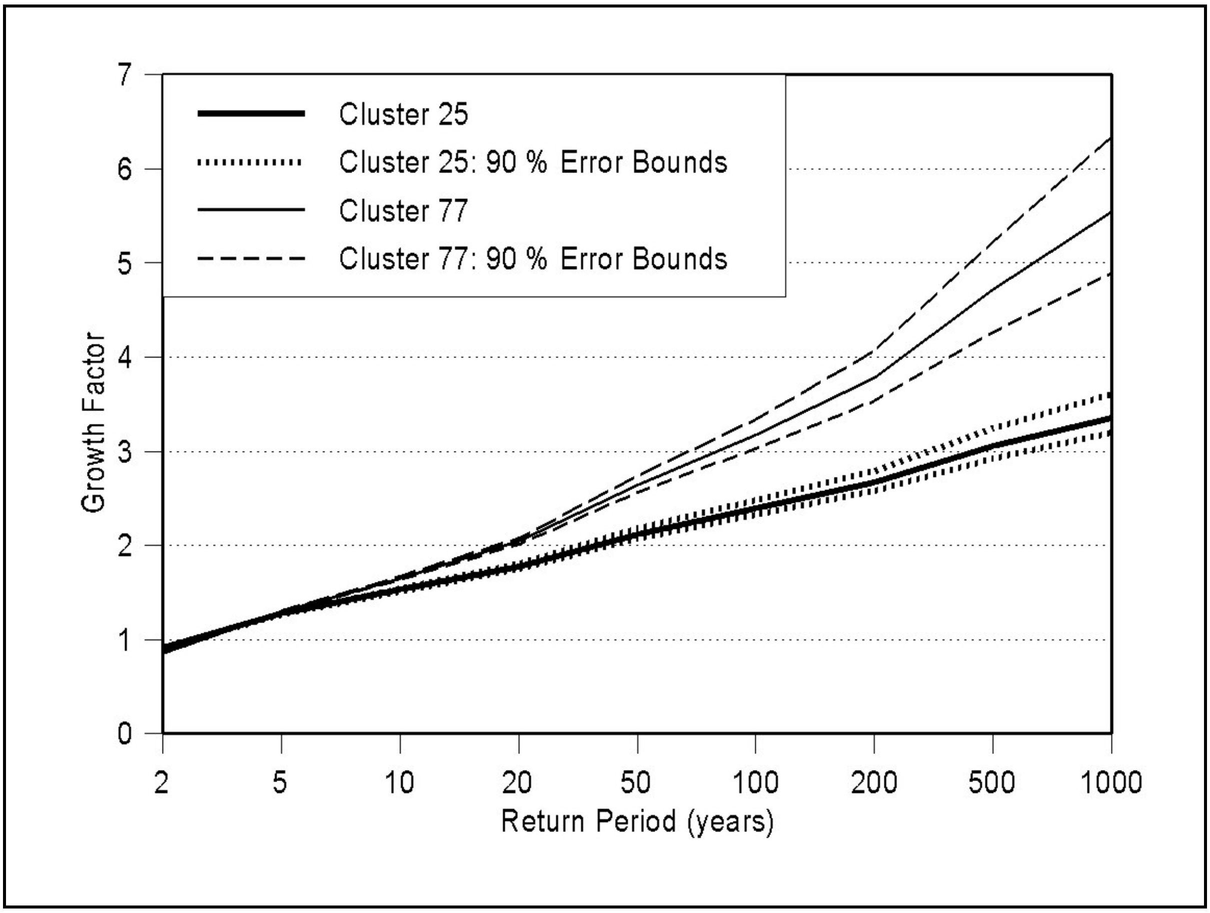


Figure 3 Examples of 1 day regional growth curves and their 90 % error bounds (Smithers and Schulze, 2000b)

CHAPTER 3

INCONSISTENCIES IN GROWTH CURVES DERIVED FROM DIGITISED AND DAILY DURATION RAINFALL DATA

Growth curves for durations ≤ 24 h were derived by Smithers and Schulze (2000a) using digitised rainfall data and for durations ≥ 24 h by Smithers and Schulze (2000b) using daily rainfall data. As illustrated in Figure 4 for a location in South Africa which has membership of short duration Cluster 9 and long duration Cluster 4, the use of the different databases results in inconsistencies in the growth curves for the 24 h duration. It is expected that the design values for the 24 h duration derived from the digitised data, which utilises a sliding 24 h window to extract the AMS from continuously recorded rainfall data, should exceed the value computed from the daily data, which utilises a fixed 24 h window to extract the AMS from data recorded at fixed 24 h intervals. For the example shown in Figure 4, the 24 h 100 year return period event computed using the growth curve derived from the daily rainfall data would exceed the design rainfall computed using the growth curve derived from the digitised rainfall data. Short duration rainfall Cluster 9 consists of 24 sites each with at least 10 years of record and the long duration Cluster 4 consists of 39 stations each of which has at least 40 years of record. Smithers and Schulze (2000a) showed that the digitised rainfall data were frequently unreliable, which may explain some of the inconsistencies outlined above.

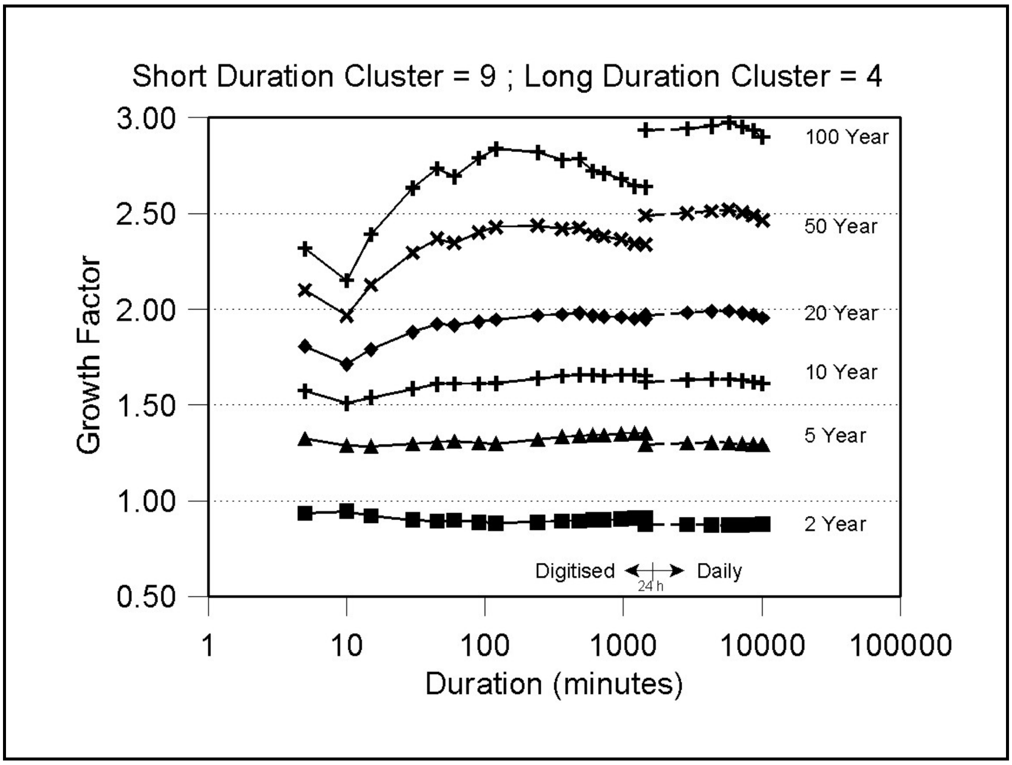


Figure 4 Example of inconsistencies between growth curves derived from digitised and daily rainfall data for 2 to 100 year return periods

A large degree of scale invariance is exhibited, particularly by the growth curves computed from the daily rainfall data for durations of 1 to 7 days, with a relatively constant growth factor for each return period over a range of durations. However, the scale invariance of the growth curves for durations < 24 h is only clearly evident for return periods of < 20 years and generally for durations > 2 h.

The parameters of the GEV distribution for the example shown in Figure 4 are presented in Figure 5. Similar trends to those noted for the growth curves are evident for the parameters of the GEV.

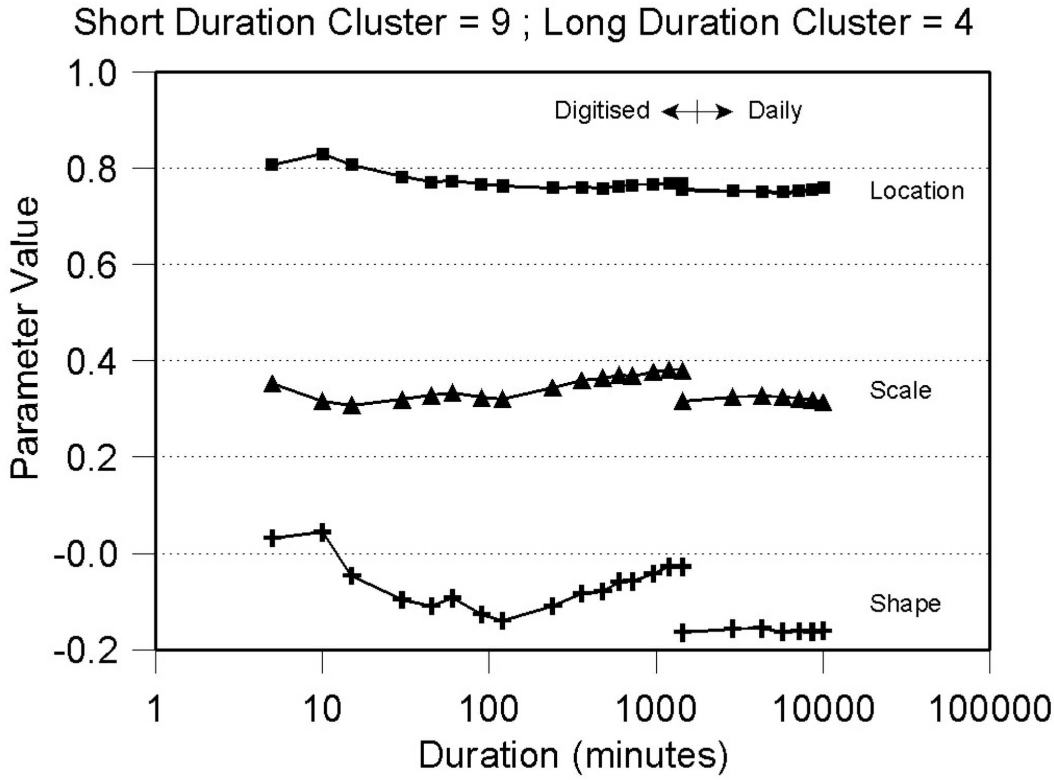


Figure 5 Example of inconsistencies between parameters of the GEV distribution derived from digitised and daily rainfall data

The index value used in the RLMA is the mean of the AMS. Hence, the regional record length weighted mean of the scaled AMS for all stations in a cluster is 1. The second and third order L-moment ratios, i.e. L-CV and L-skewness of the AMS, are not affected by the scaling of the AMS. The L-moment ratios are illustrated in Figure 6 for the short duration Cluster 4 and long duration Cluster 9. The concept of scale invariance is further investigated in the following section as a means to improve the reliability of the estimates of design rainfalls and to overcoming the inconsistencies between the digitised and daily rainfall data.

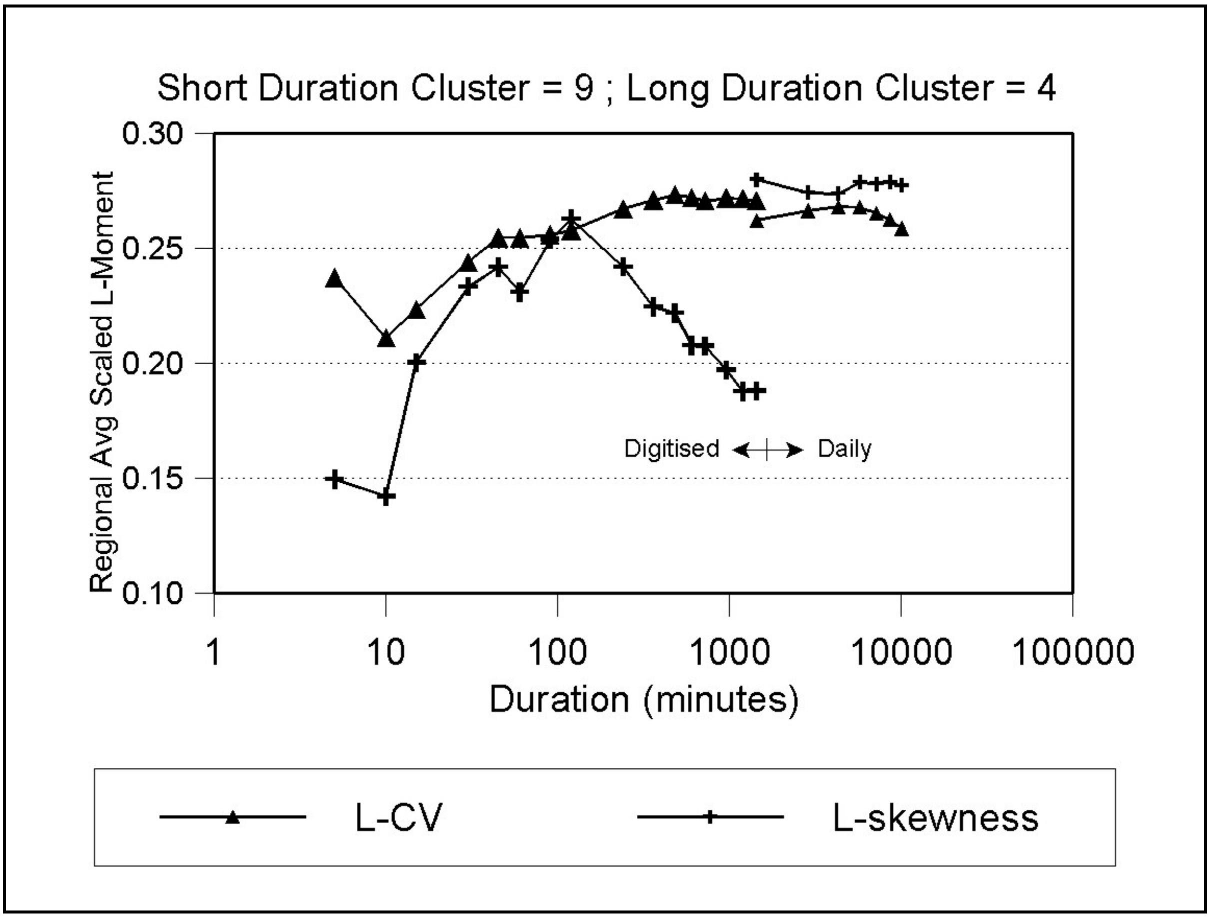


Figure 6 Example of inconsistencies between regional average scaled L-moment ratios derived from digitised and daily rainfall data

3.1 Scale Invariance Characteristics of Rainfall Data

The scale invariance characteristics of both the digitised and daily rainfall data are investigated in this section.

3.1.1 Digitised rainfall data

The regional L-moment ratios computed from the digitised rainfall data for the 15 short duration clusters are shown in Figure 7. Generally, scale invariance of L-CV is a characteristic displayed in most clusters for durations ranging from as short as 10 minutes to 4 days. Exceptions to this trend are the ratios in Clusters 2, 3, 7 and 8. More deviation from scale invariance was evident and expected for L-skewness. It is noted that the trends in L-CV and L-skewness for durations shorter and longer than 24 h were similar and no distinct shifts in L-CV and L-skewness are evident between 24 and 48 h durations. Deviations from scale invariance for L-CV and L-skewness are postulated to be the result of either one, or a combination of, sampling variability, some heterogeneity within a cluster and missing periods of data.

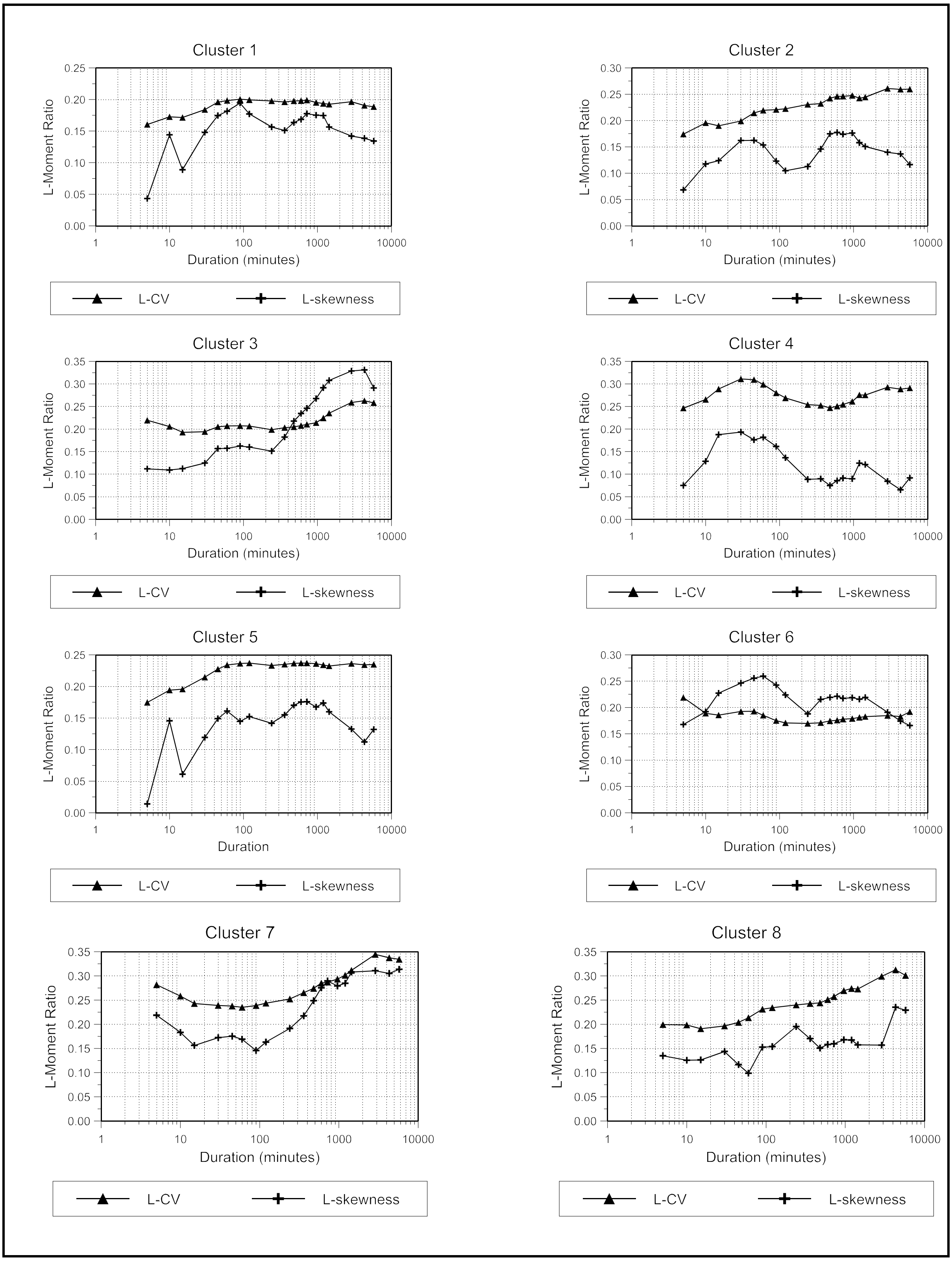


Figure 7 Regional L-moment ratios vs duration for short duration clusters

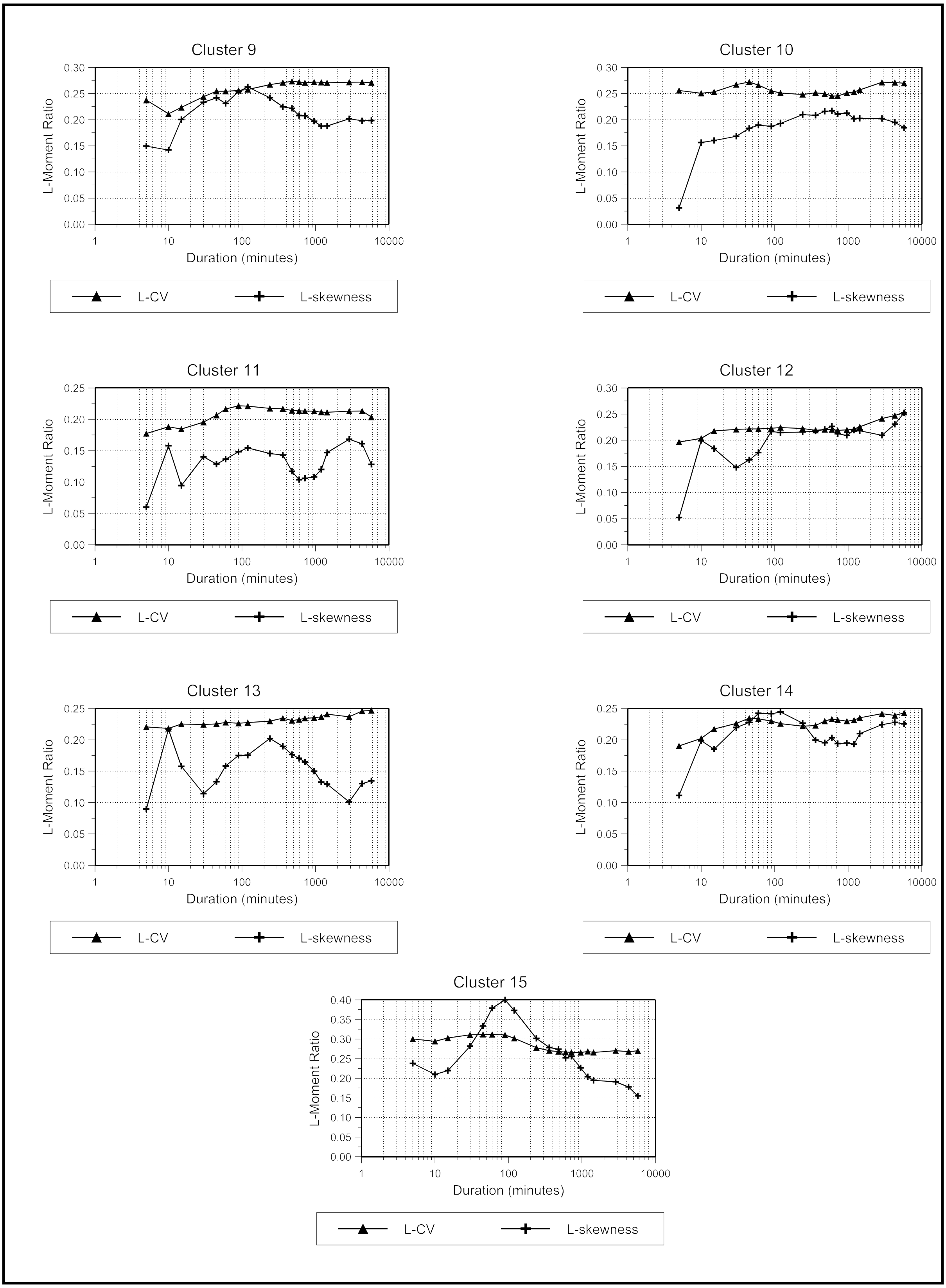


Figure 7 (cont) Regional L-moment ratios vs duration for short duration clusters

3.1.2 Daily rainfall data

The regional average L-moment ratios, computed from the daily rainfall data, for selected long duration clusters are shown in Figure 8. From these examples it is evident that scale invariance of both L-CV and L-skewness with duration is a characteristic of daily rainfall for durations ranging from 1 to 7 days in a range of climatic regimes. Deviations from scale invariance for L-CV and L-skewness are postulated to be the result of either one, or a combination of, sampling variability, some heterogeneity within a cluster and missing periods of data.

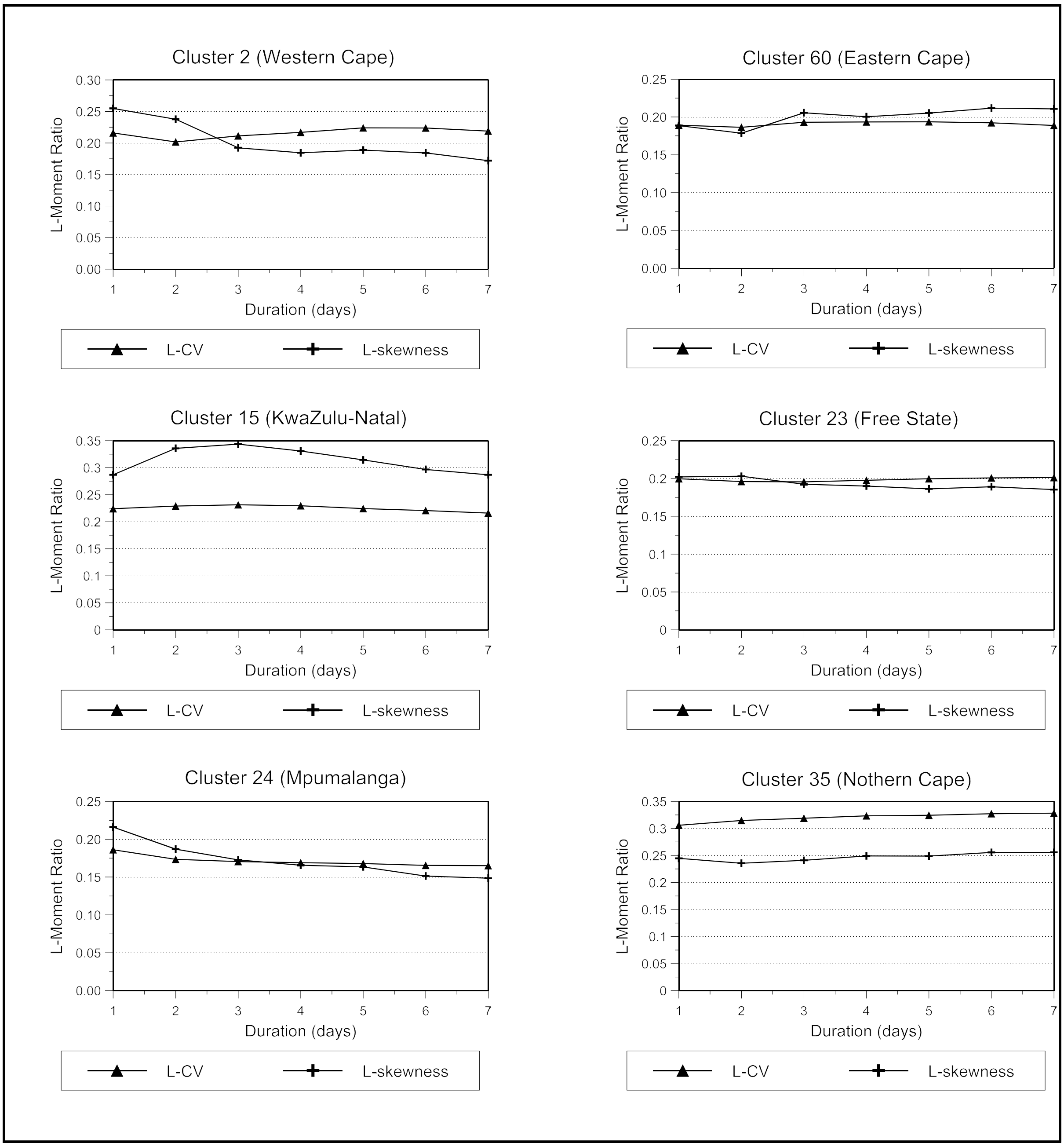


Figure 8 Regional average L-moment ratios vs durations for selected short duration clusters located in different climate regions of South Africa

3.1.3 Slope of L-moment ratio vs duration

The degree of scale invariance within the digitised and daily rainfall databases is illustrated by computing the slope of the relationship between the regional L-moment ratios and duration for each cluster and for both databases. Durations ranging from 5 minutes to 24 h were used in calculating the slope for the 15 short duration clusters and from 1 to 7 days for the 78 long duration clusters. A frequency analysis of the 15 and 78 slopes for the second (L-CV) and third (L-skewness) regional L-moment ratios was performed and the results are shown in Figure 9. A scale invariance hypothesis assumes that the slope should be zero.

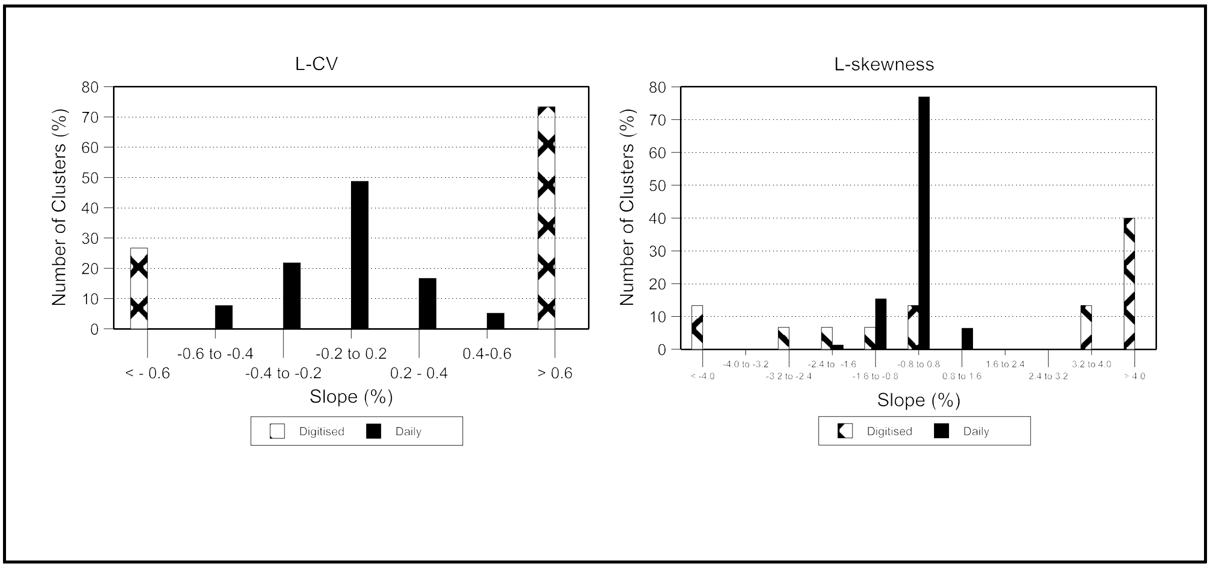


Figure 9 Frequency analysis of the slope of regional average L-moments vs duration computed for short (Digitised) and long duration (Daily) rainfall clusters

The mean of the slopes of the relationship between the regional L-moment ratios and duration for durations of 5 minutes to 24 h and for 1 to 7 days computed for the short and long duration clusters respectively, are not significantly different from zero. Hence, it is postulated that the variation in the slopes displayed in Figure 9 are the result of a combination of sampling variability, some heterogeneity within the clusters and periods of missing data.

Rainfall events for durations longer than 1 day are computed by scanning the daily data sequentially, with each day forming the beginning of a potential rainfall event. A day of missing data will therefore form part of a number of events for durations longer than one day, each of which includes the missing day within its' duration. Hence, a single day of missing data will result in the exclusion of more longer duration than 1day events, each of which may be a potential extreme event. It is therefore postulated that the 1 day regional L-moment ratios are more reliable than the average L-moments for durations longer than 1 day. Thus, based on the assumption of scale invariance, the parameters of the GEV distribution fitted to the 1 day regional average L-moment ratios may be used to estimate growth curves for durations ranging from 1 to 7 days.

Similarly, the deviations from scale invariance exhibited by the L-moment ratios in some of the 15 short duration clusters are also postulated to be the result of sampling variability, heterogeneity within the clusters, errors and periods of missing digitised rainfall data. As shown in Figure 7, which is based on the digitised rainfall data, there are no jumps or discontinuities (inconsistencies) between rainfall for durations of 24 h and for durations longer than 24 h. Hence, the regional L-moment ratios computed from the digitised and daily rainfall databases should be consistent for 24 h durations. Based on these obervations, the inconsistencies between the regional L-moments are assumed not to be an inherent characteristic of the rainfall and are hypothesised to be caused by:

- the quality of the data, and
- the differing periods or records used in the analyses.

This hypothesis is investigated in the following sections.

Both short (≤ 24 h) and long (1 to 7 days) duration growth curves, which relate design rainfall depths, scaled by the mean of the AMS, to return period, have been developed for South Africa (Smithers and Schulze, 2000a; Smithers and Schulze, 2000b). Inconsistencies between 24 h and 1 day growth curves, derived from digitised and daily rainfall respectively, have been illustrated. In the derivation of these growth curves, the full period of available rainfall data were utilised, resulting in differing periods of records used in the computation of the respective growth curves. Growth curves are derived using L-moment ratios computed from the observed rainfall data. The objectives of the following sections are to:

- compare the L-moment ratios and derived growth curves for rainfall computed using fixed time periods and sliding windows to extract the AMS, and to
- investigate the scaling properties of rainfall L-moment ratios with duration, using data for *concurrent* periods of record for rainfall data recorded continuously and at fixed 24 h time intervals.

3.2 L-moment Ratios and Growth Curves Derived from Fixed and Sliding AMS

At selected stations which were deemed have reliable digitised rainfall data and which are located in different geographic and climatic regions in South Africa, L-moment ratios were computed from the digitised rainfall data by (i) sampling at fixed periods, as would be observed at daily raingauges, and (ii) using a sliding window. The results, shown in Figure 10, indicate no systematic differences in the either the L-CV and L-skewness of the fixed and sliding data. This concurs with results obtained by Dwyer and Reed (1995) who could not discern any systematic differences between higher order moments computed from annual maxima extracted using fixed and sliding windows. Hence, it is concluded that growth curves derived from annual maxima extracted using fixed and sliding windows should be equivalent. Differences in the short and long duration growth curves, as noted previously, are thus hypothesised to be attributed to differences in the rainfall recorded in the digitised and daily rainfall data and to the different periods of rainfall used to derive the growth curves. Details of the stations are listed in Table 1.

Table 1 Locations and available rainfall record lengths for stations analysed in Figure 10

Station and Location	Period of Record	Years of Record	Climate	MAP (mm)
CP6 (Cathedral Peak)	1953-1985	32	Summer rainfall, interior, mountainous	1046
N23 (Ntabamhlope)	1964-1995	29	Summer rainfall, interior, plateau	900
SAL10 (La Mercy)	1983-1995	12	Summer rainfall, coastal	937
Jn19A (Jonkershoek)	1945-1997	50	Winter rainfall, mountainous	1095
Moko3A (Mokobulaan)	1956-1984	27	Summer rainfall, interior	1004

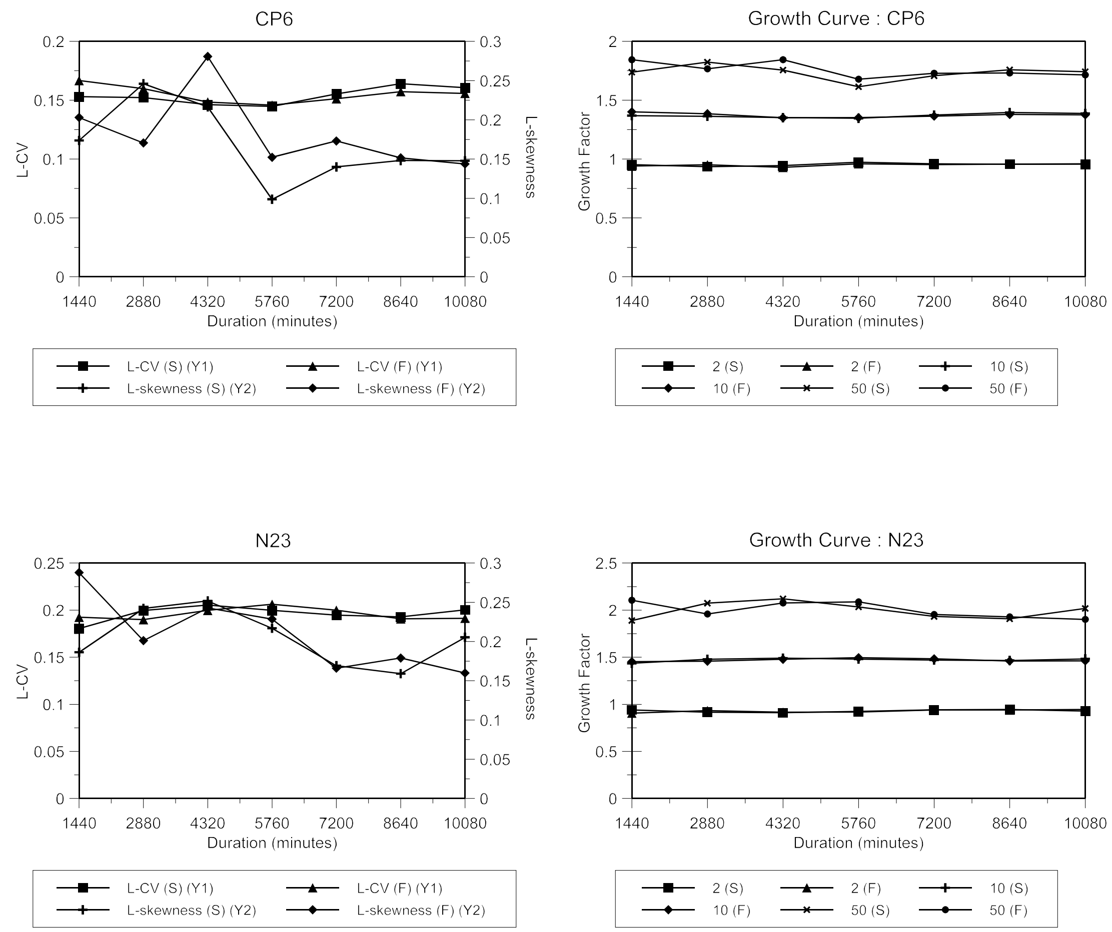


Figure 10 Examples at selected sites in different climatic regions of South Africa of L-moment ratios and 2, 10 and 50 year return period growth curves derived from annual maximum series extracted from digitised rainfall data using fixed (F) and sliding (S) windows

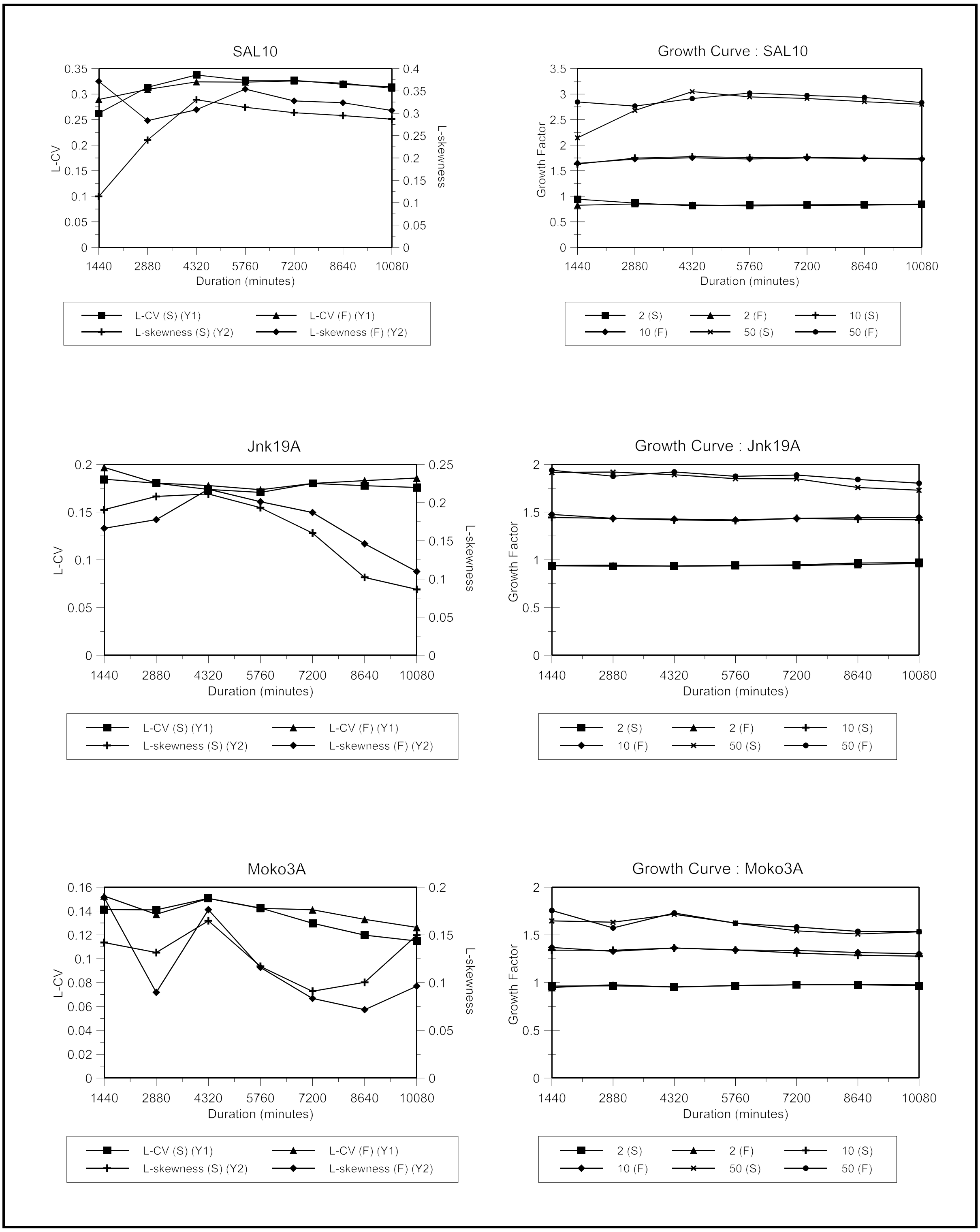


Figure 10 (cont) Examples at selected sites in different climatic regions of South Africa of L-moment ratios and 2, 10 and 50 year return period growth curves derived from annual maximum series extracted from digitised rainfall data using fixed (F) and sliding (S) windows

3.3 Scaling Properties of L-Moment Ratios and Growth Curves with Duration

In order to examine the scaling properties of L-moment ratios and growth curves, growth curves for individual stations were derived independently for all durations between 15 minutes and 7 days. Thus, the use of independent growth curves for each duration ensures that the design rainfall estimates are consistent for individual durations. However, as shown in Figure 11 for selected stations in different climatic regions of South Africa, considerable variations with duration in both the growth curves and L-moment ratios are evident. The large variations between durations in the L-moment ratios, particularly in L-skewness, are not evident in rainfall data published, for example, by Dwyer and Reed (1995). These variations in the observed data may be attributed to:

- The sampling variability
  The variations are not the true characteristics of the rainfall data, but are an artefact of the sample period and length of sample. This idea is explored in the following section.
- Errors in the digitised rainfall data
  It is possible that missing periods in the digitised rainfall data may have some influence on the AMS for various durations, and hence result in the variations in the L-moment ratios with duration.
- Limitations in the resolution of measurement and processing of autographically recorded rainfall data
  The finest resolution of the rainfall data recorded autographically and retrieved at weekly intervals is approximately 15 minutes. Hence, the digitised values for durations shorter than 15 minutes are associated with a lower degree of confidence and any variations in the L-moment ratios for durations shorter than 15 minutes may be attributed to the resolution in the analysis of chart recorded rainfall.

3.4 Sampling Variability of Rainfall Data

The sampling variability of the annual maximum rainfall series was estimated using three approaches. The first considered windows of data extracted from the entire period of record, the second utilised stochastic modelling of the rainfall process and the third approach implemented a bootstrapping technique.

3.4.1 Approach 1: Use of windows of observed data

The variability of L-CV and L-skewness with sample period and record length was established by computing these higher order statistics from the following periods of observed record:

- the full period of record,
- the first third of the record,
- the second third of the record,
- the last third of the record,
- the first two-thirds of the record, and
- the second two-thirds of the record.

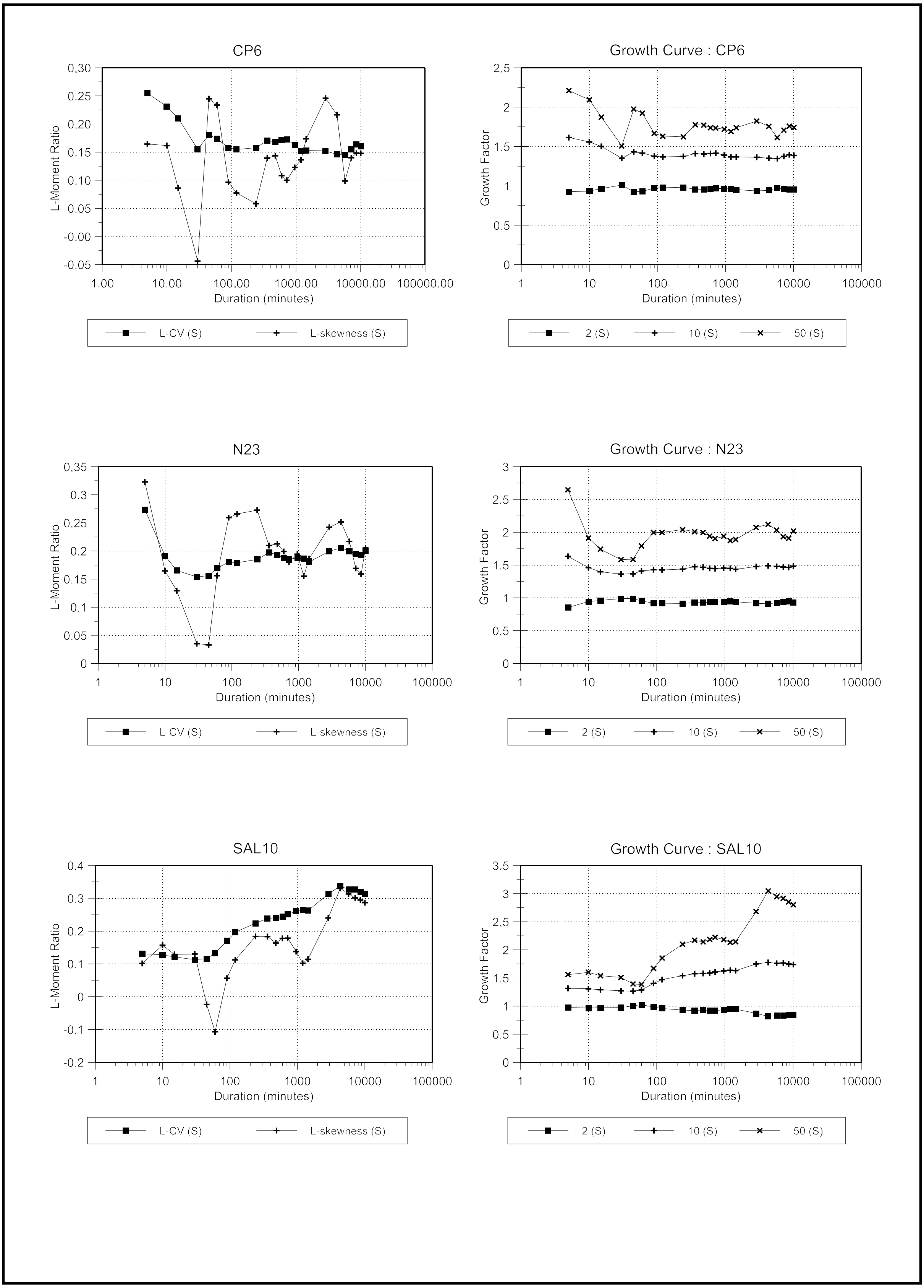


Figure 11 Variations of L-moment ratios and 2, 10 and 50 year return period growth curves with duration at selected sites in different climatic regions of South Africa ('S' indicates sliding window used to extract AMS)

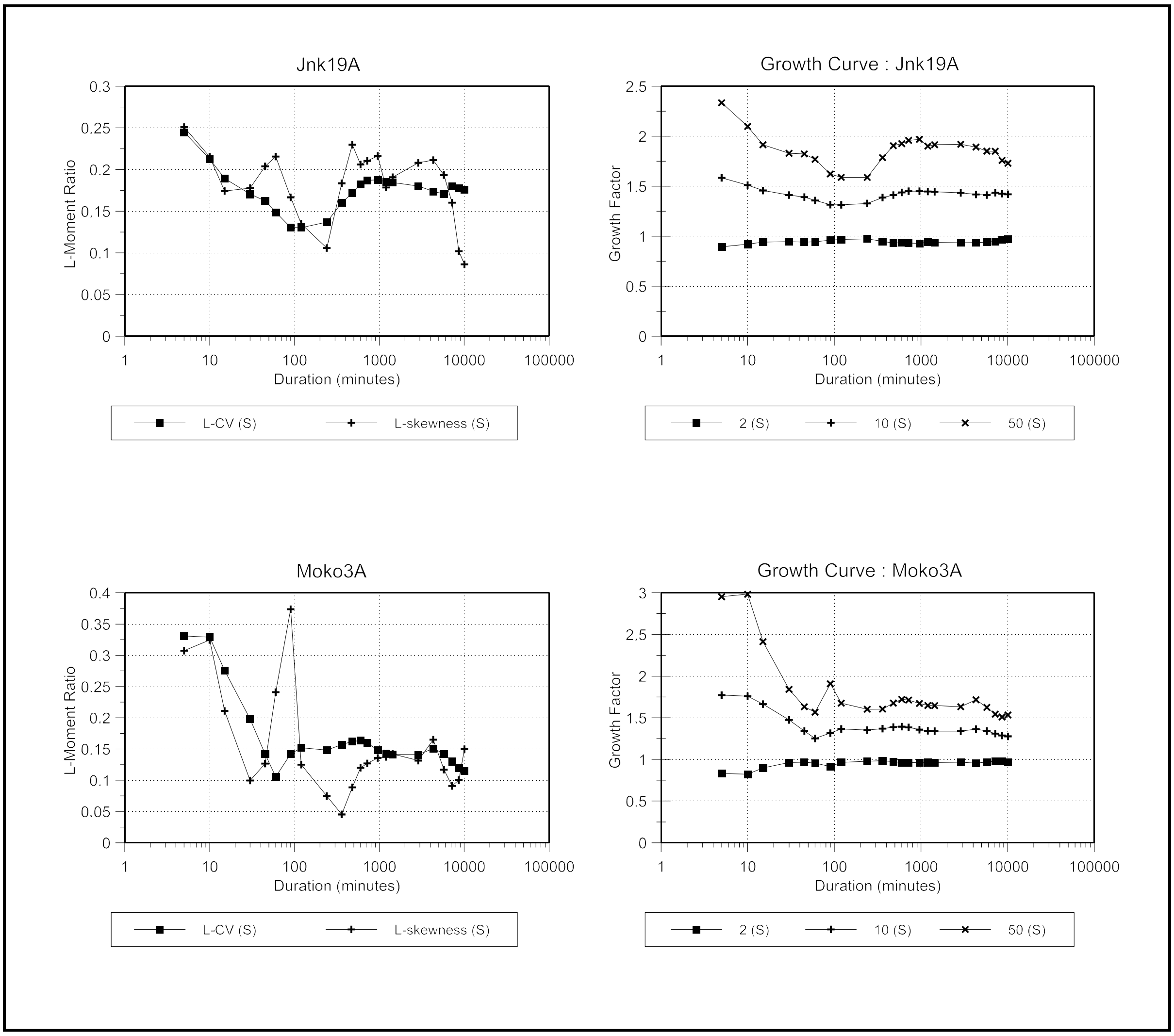


Figure 11 (cont) Variations of L-moment ratios and 2, 10 and 50 year return period growth curves with duration at selected sites in different climatic regions of South Africa ('S' indicates sliding window used to extract AMS)

For the stations listed in Table 1, the L-CV and L-skewness are depicted in Figure 12 for the 6 periods listed above. It is evident that there is considerable variation over the durations considered, particularly in L-skewness, which is more apparent at stations with shorter record lengths (e.g. SAL10).

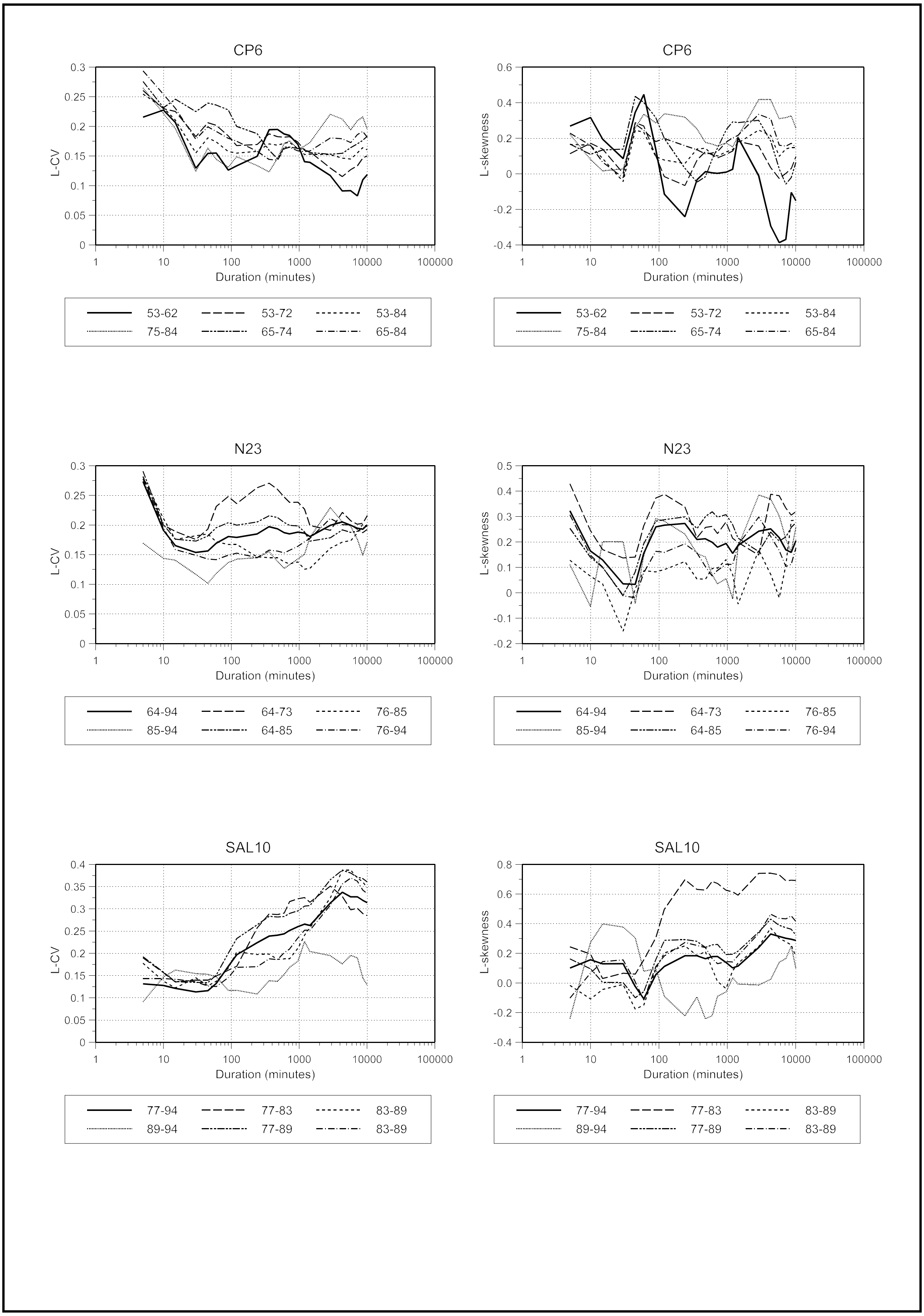


Figure 12 L-moment ratios computed for varying periods and lengths of record at selected stations in different climatic regions in South Africa

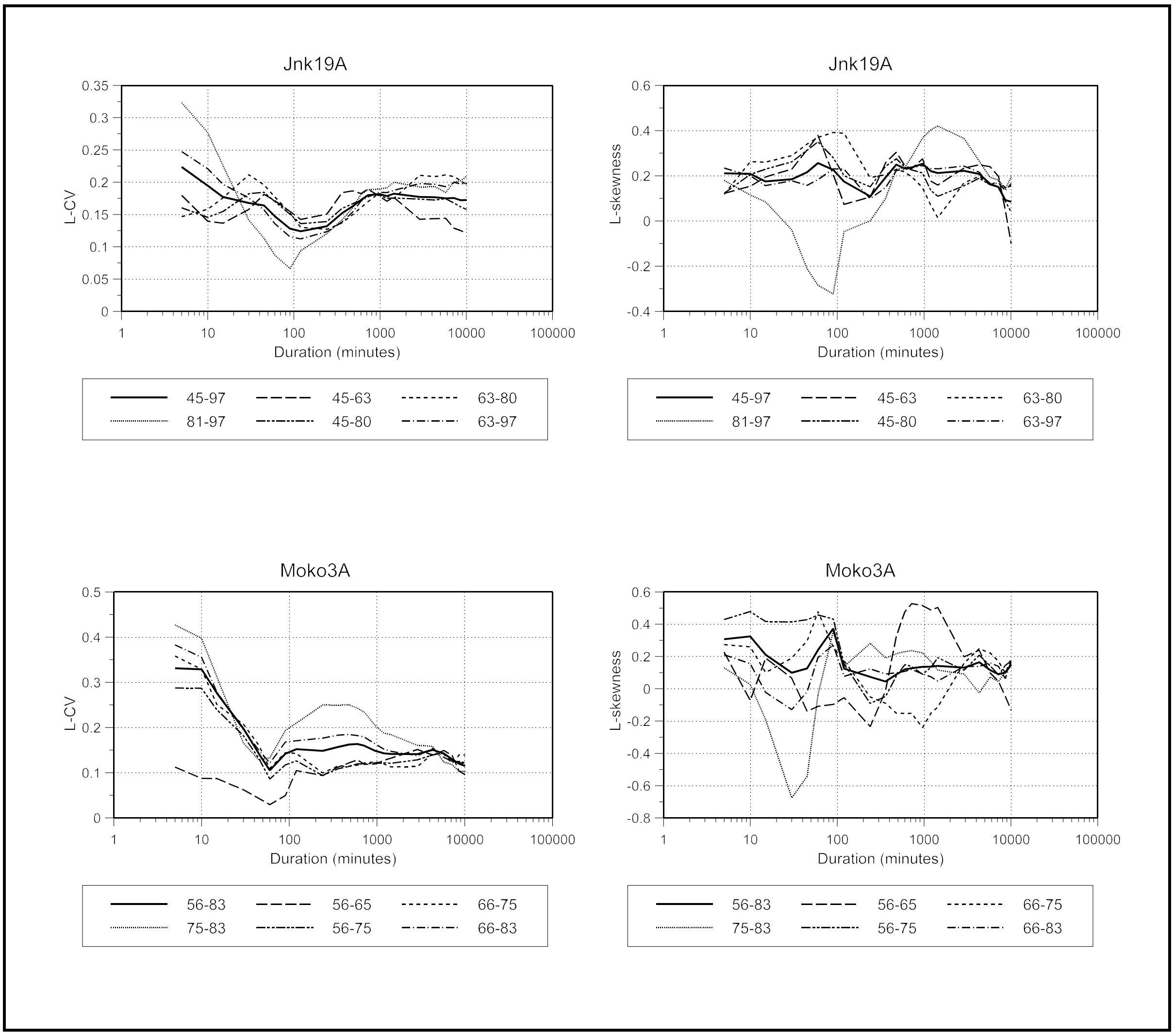


Figure 12 (cont) L-moment ratios computed for varying periods and lengths of record at selected stations in different climatic regions in South Africa

Thus six estimates of L-CV and L-skewness were computed, based on different periods and record lengths as shown in Figure 12, and used to establish confidence intervals as shown in Equation 4. The use of Equation 4 assumes that the values are distributed normally. The 95 % confidence interval calculated using Equation 4 are depicted in Figure 13 for selected stations in South Africa.

$$\hat{y}_{U,L} = \bar{y} \pm t \times s_y \qquad ...4$$

where

$\hat{y}_{U,L}$ = upper and lower limit of confidence interval,

$\bar{y}$ = mean of statistic,

t = Student's t, and

s_y = standard deviation of statistic.

Included in Figure 13 is the mean (MEAN) of the 6 values computed for varying periods and record lengths, the statistic computed using the full observed record (Full Rec), the 95% Confidence Intervals (CI) and the moment computed using fixed 1 day intervals, i.e. as would be computed from daily rainfall data. It has already been established that there are no systematic trends in the moments computed using fixed and sliding windows and the differences in Figure 13 between the 1 day and 24 h value are the result of sampling variability. It is evident in Figure 13 that at most stations and generally for durations > 15 minutes, both the 1 day L-CV and L-skewness (i.e. as would be computed from daily rainfall data) fall within the computed 95% confidence interval. An exception to this generalisation is Station SAL10, the analysis of which is based on only 12 years of record and where the 1 day values for L-CV fall outside of the 95% confidence interval for durations < 120 minutes.

3.4.2 Approach 2: Use of stochastic rainfall series

Smithers (1998), Smithers and Schulze (2000a) and Smithers *et al*. (2002) evaluated the performance of Bartlett-Lewis Rectangular Pulse (BLRP) rainfall models for estimating design rainfalls in South Africa. Their results indicate that BLRP models, and in particular the modification which modelled rainfall intensity with an exponential distribution (Onof and Wheater, 1994) and which is termed the Bartlett-Lewis Rectangular Pulse Gamma (BLRPG) model, was shown to be able to reproduce the characteristics of observed rainfall and extreme events reasonably well for durations ranging from 1 h to 24 h.

The BLRPG model was used in this study to simulate 100 synthetic series of rainfall, each equal in length to the observed period of record. For each series and for durations ranging from 15 minutes to 7 days, the AMS was extracted and L-moments and L-moment ratios were computed. A frequency analysis of the 100 L-moments was performed and the 25th, 50th, 75th percentiles and mean values were extracted. These values are shown in Figures 14 to 16 for selected stations in South Africa. Included in Figures 14 to 16 are the observed values, the simulated 25th and 75th percentiles indicated as I-beams, the mean of the simulated series and a series (Sim 24h) which assumes that the 24 h value is applicable to all durations, i.e. the assumption of scale invariance. As evident in Figure 14, the BLRPG model simulated the mean of the AMS well at most locations considered, although there appears to be some consistent bias at Jnk19A. As shown in Figure 15, the inter-quartile range of L-CVs of the rainfall series simulated by the BLRPG model encompass the 24 h value for durations ranging from 60 minutes to at least 2 days at most stations considered. An exception is noted at Moko3A where there is a marked decrease in L-CV of the simulated series for durations < 240 minutes. At all stations considered, and as shown in Figure 16, the inter-quartile range of L-skewness of the synthetic rainfall series simulated by the BLRPG include the 24 h value for durations ranging from 15 minutes to at least 7 days.

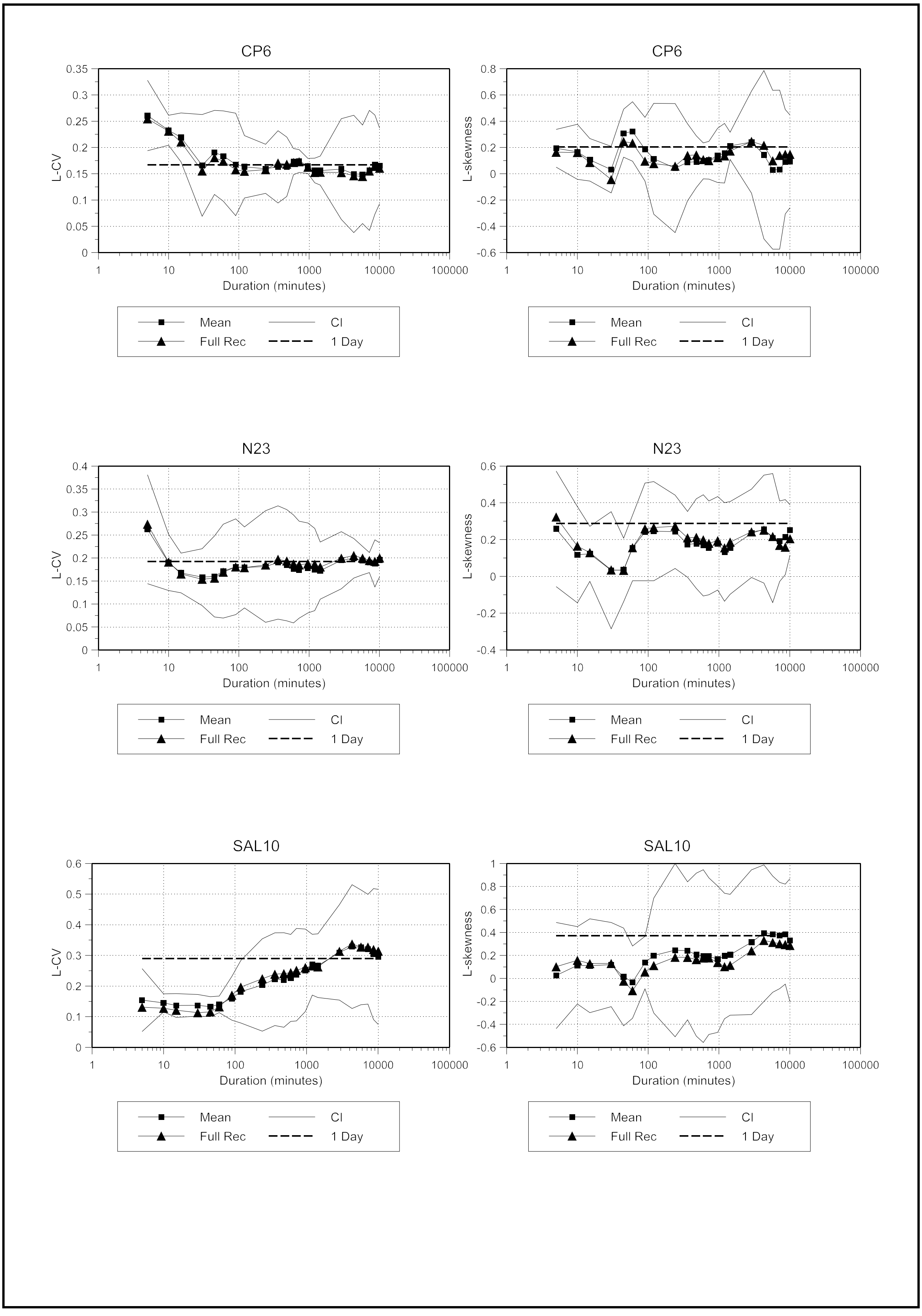


Figure 13 L-moment ratios and 95% confidence intervals (CI) computed using observed data from selected stations in different climatic regions in South Africa

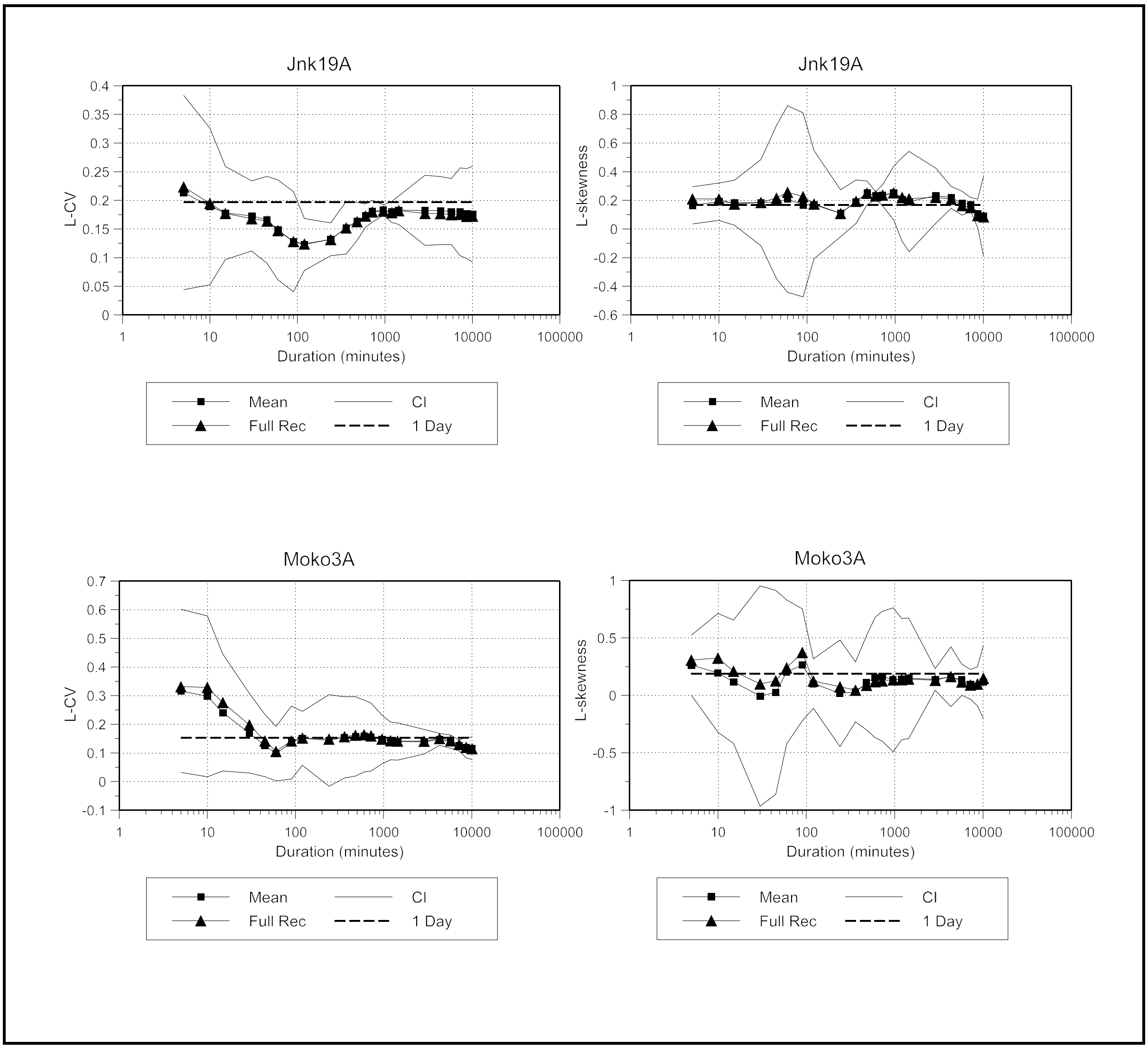


Figure 13 (cont) L-moment ratios and 95% confidence intervals (CI) computed using observed data from selected stations in different climatic regions in South Africa

The range of L-CV is (0,1) and for L-skewness is (-1,1). Hence, the range of variation in these values with duration as shown in detail in Figures 15 and 16 is relatively small. These results indicate that, assuming the BLRPG model to be able to reproduce the rainfall characteristics realistically, the assumption of scale invariance (i.e. that the 24 h L-CV and L-skewness can be used for durations < 24 h) appears to be plausible.

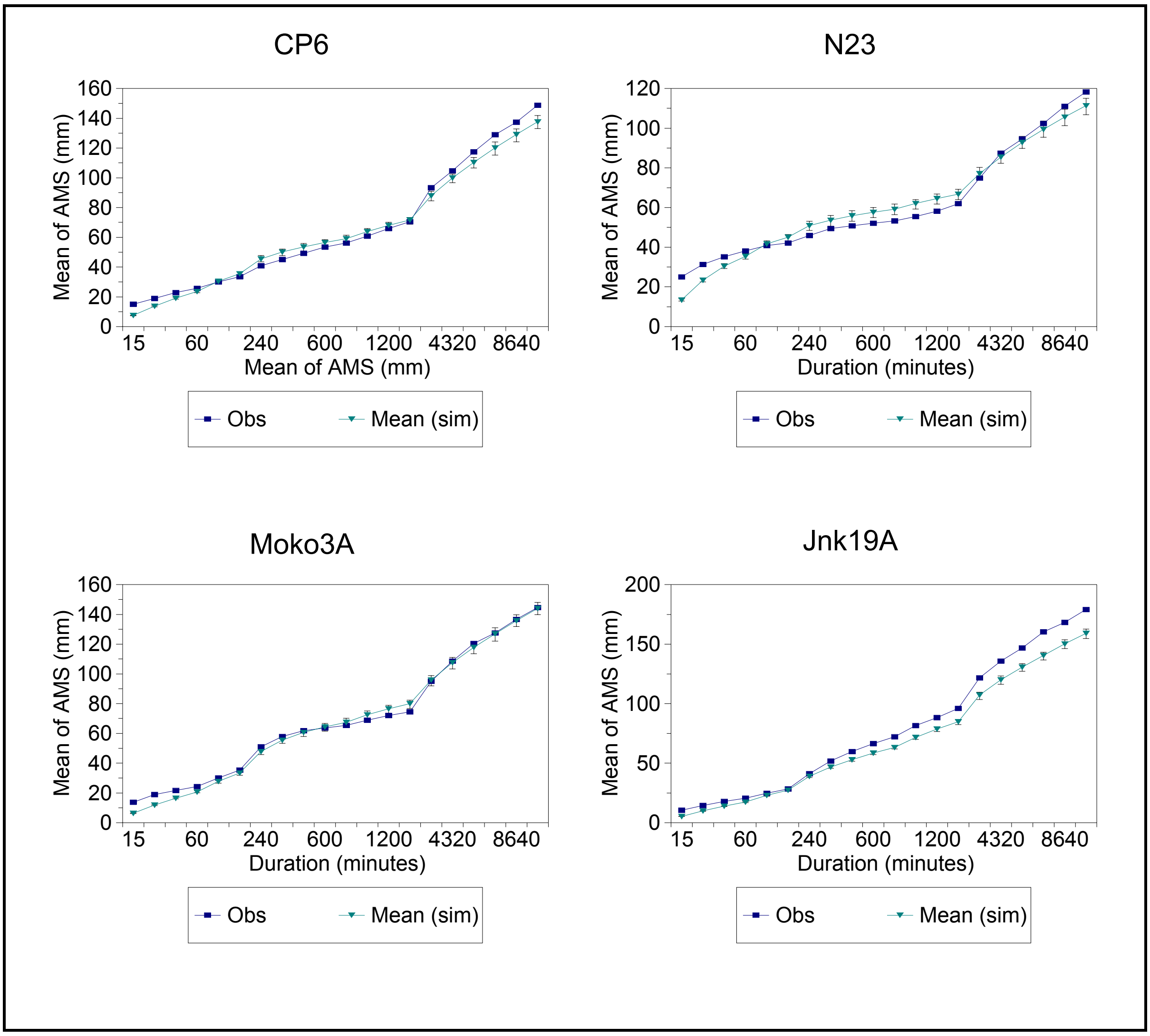


Figure 14 Observed and simulated mean of AMS at selected rainfall stations in South Africa (I-beams indicate inter-quartile range of simulated values)

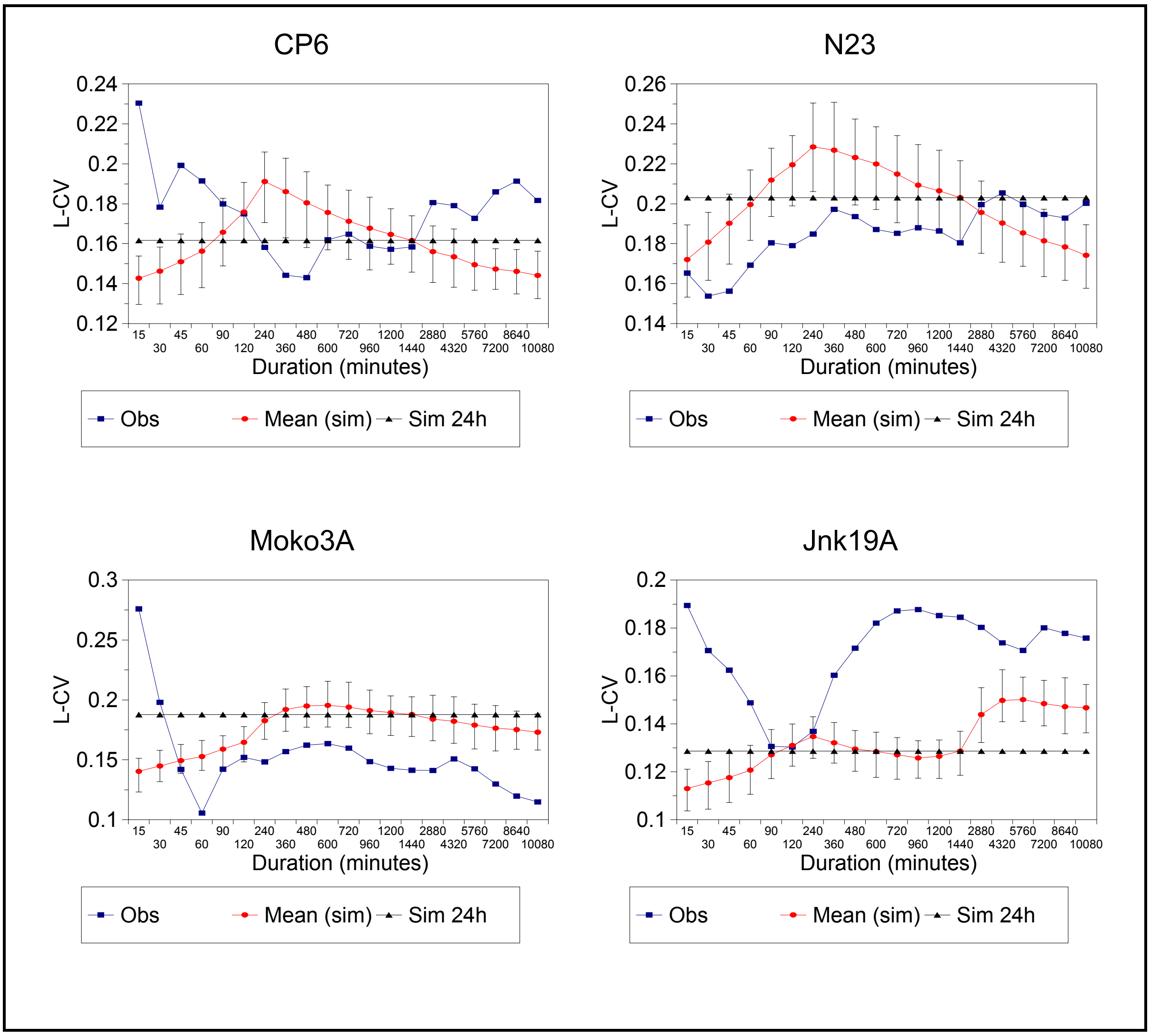


Figure 15 Observed and simulated L-CV at selected rainfall stations in South Africa (I-beams indicate inter-quartile range of simulated values)

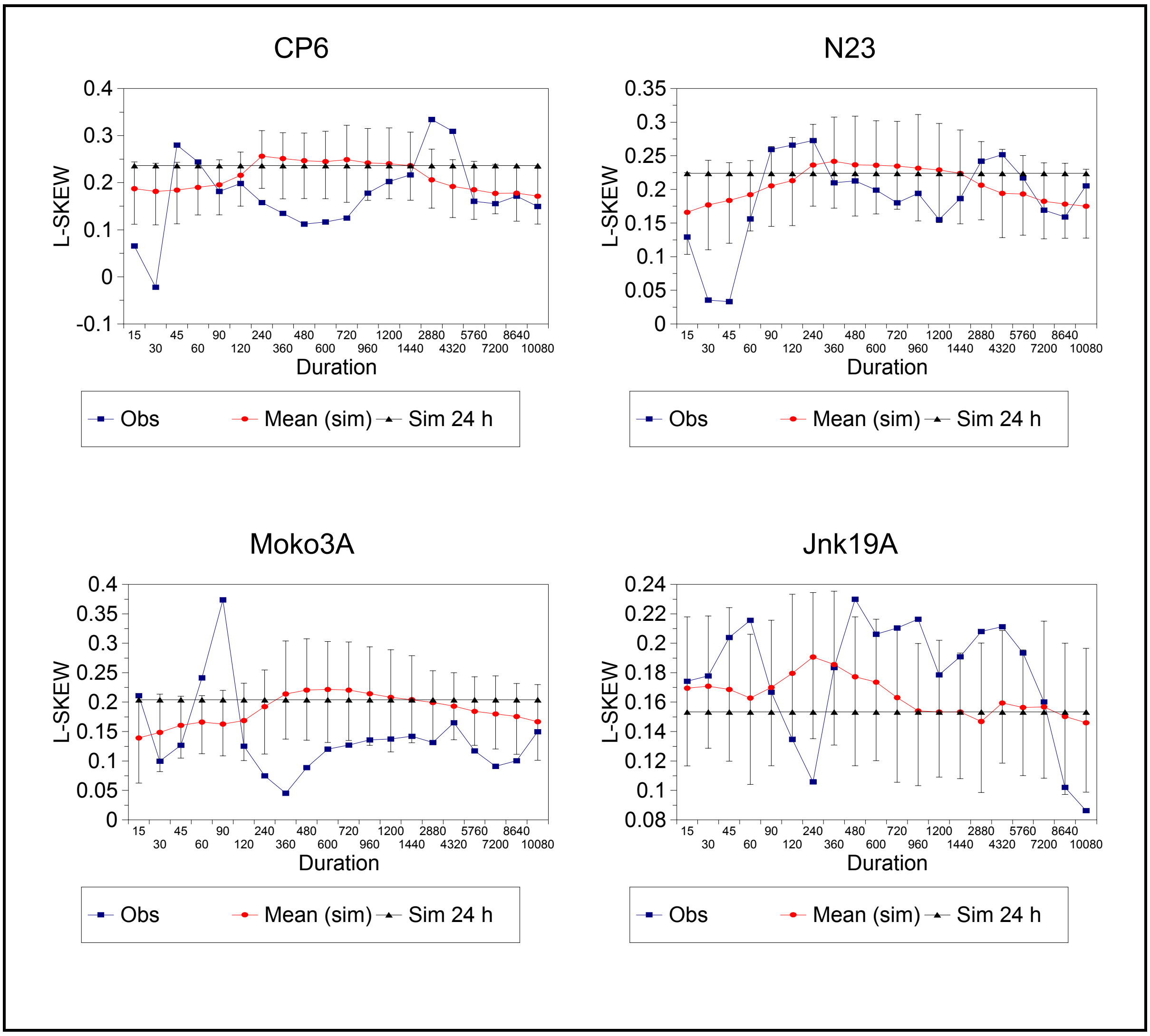


Figure 16 Observed and simulated L-skewness at selected rainfall stations in South Africa (I-beams indicate inter-quartile range of simulated values)

3.4.3 Approach 3: Use of bootstrapping

The bootstrapping algorithm described by Adamson *et al*. (1984) and Zucchini and Adamson (1989) was utilised to estimate the sampling variability of the L-moment ratios and hence the errors in the growth curves, based on the assumption of scale invariance. One thousand random samples extracted from the AMS were used to estimate the 90 % confidence intervals. These are illustrated in Figure 17 for Raingauge N23.

As expected and evident in Figure 17, the mean of the 1000 bootstrapped samples (bs) correlates well with the mean of the AMS extracted from the observed data (obs). In addition, at Raingauge N23, both the 24 h L-CV and 24 h L-skewness fall within the 90% confidence interval for durations ranging from 10 minutes to 7 days. Hence, the 24 h growth factors also generally fall within the 90% growth factor confidence intervals for a wide range of durations, as shown for the 2 and 50 year return period rainfalls in Figure 17.

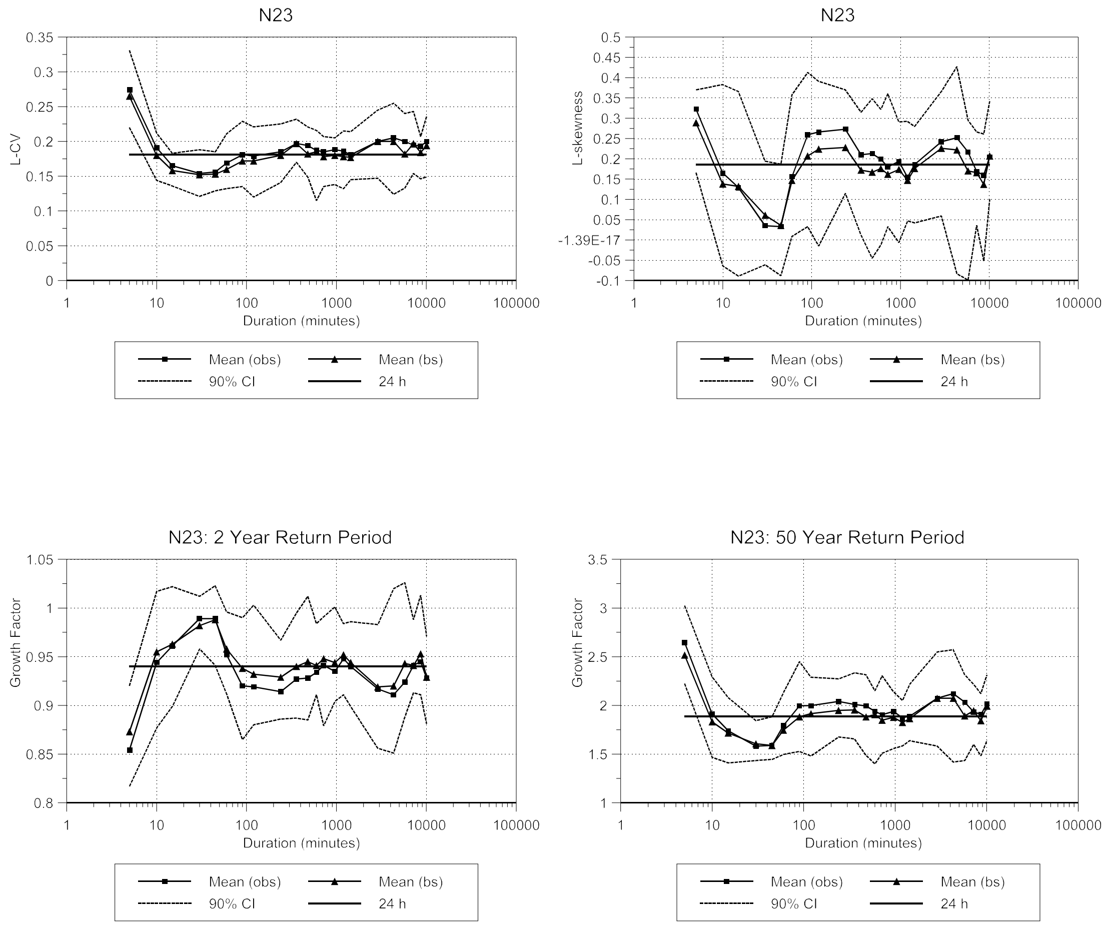


Figure 17 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge N23 (Ntabamhlope)

The results of a similar analysis at Cathedral Peak are contained in Figure 18, where the assumption of scale invariance is valid for durations ranging from 30 minutes to 7 days, i.e. the 24 h L-CV and L-skewness, and hence the growth factors for return periods < 200 years, fall within the 90% confidence interval for durations ranging from 30 minutes to 7 days.

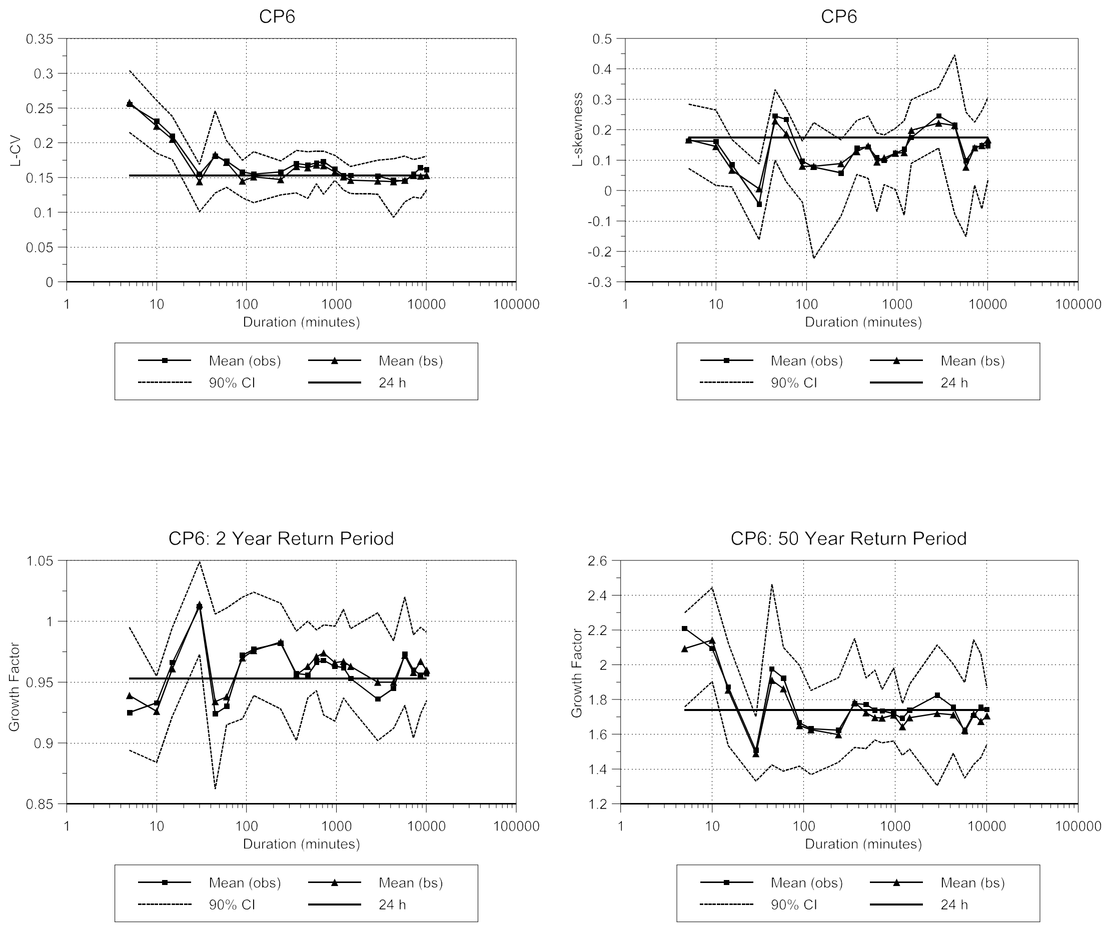


Figure 18 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge CP6 (Cathedral Peak)

The results for Raingauge C182 at Cedara are contained in Figure 19. Considerable variation in both L-CV and L-skewness with duration is evident at C182 and the assumption of scale invariance is not valid there for durations ranging from 30 minutes to 7 days.

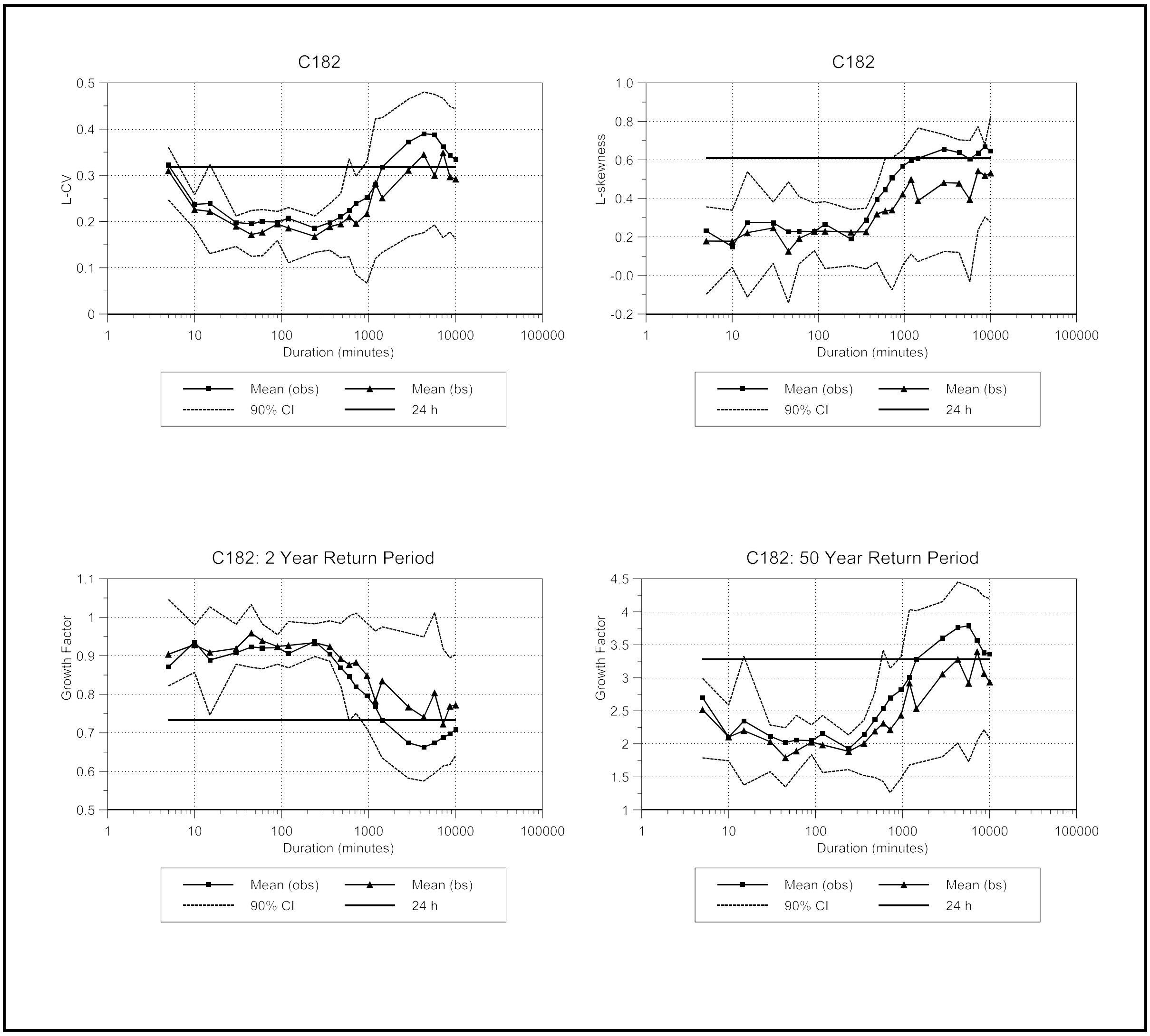


Figure 19 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge C182 (Cedara)

However, as shown in Figure 20, the assumption of scale invariance is generally valid at Cedara over a wide range of durations when the data from the September 1987 extreme rainfall event are excluded from the analysis.

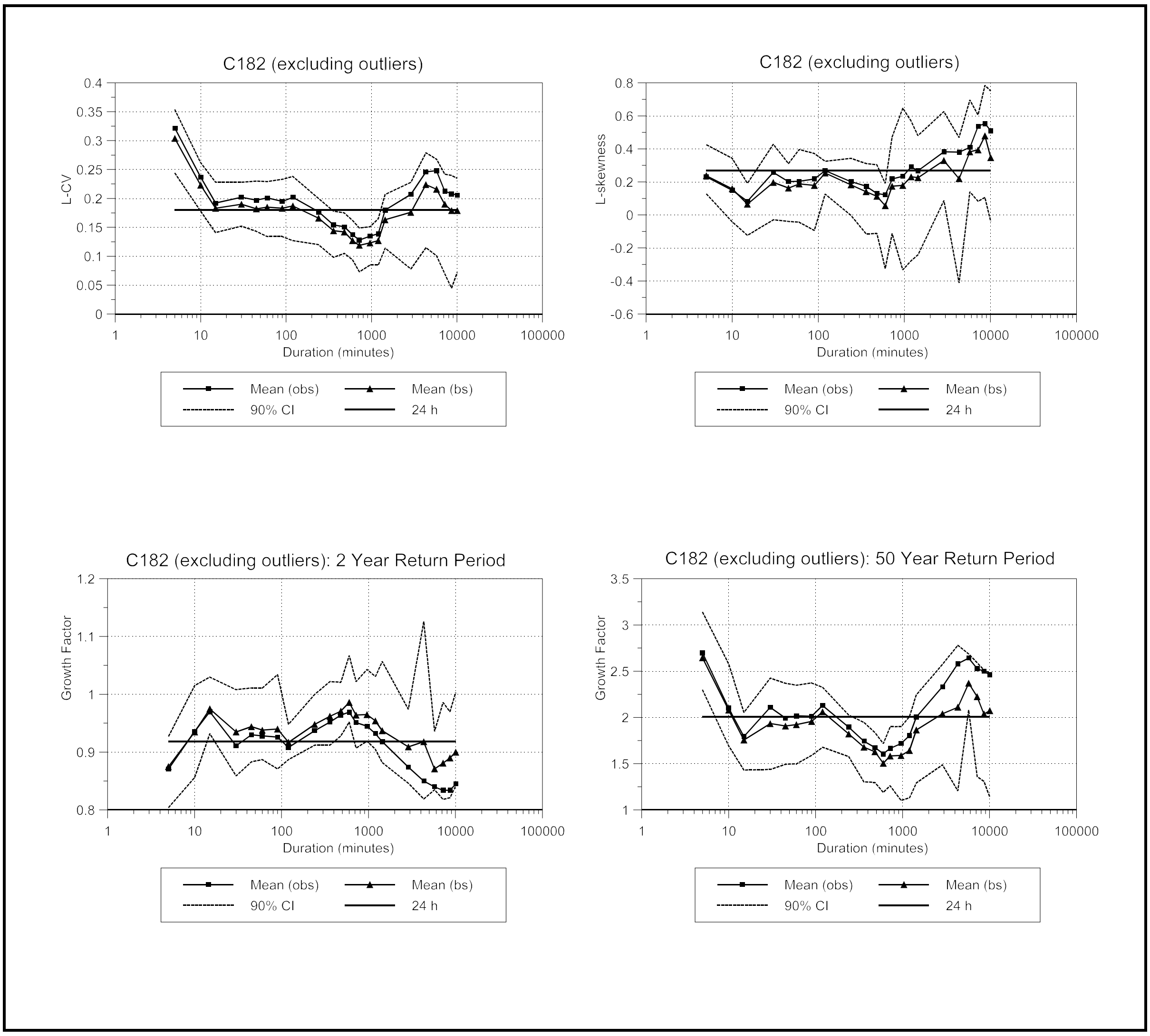


Figure 20 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge C182 (Cedara), with outliers excluded

The results of the analysis at SAWS Raingauge 0240808 at Durban International Airport, based on 35 years of record, are contained in Figure 21. Although there is an increase of L-CV with duration and the 24 h L-CV falls outside of the 90% confidence intervals for durations < 2 h, the growth factors for the 2 and 50 year return periods generally fall within their 90% confidence interval for durations > 30 minutes. Similar results were obtained using data from Mount Edgecombe and La Mercy, both with 17 years of data.

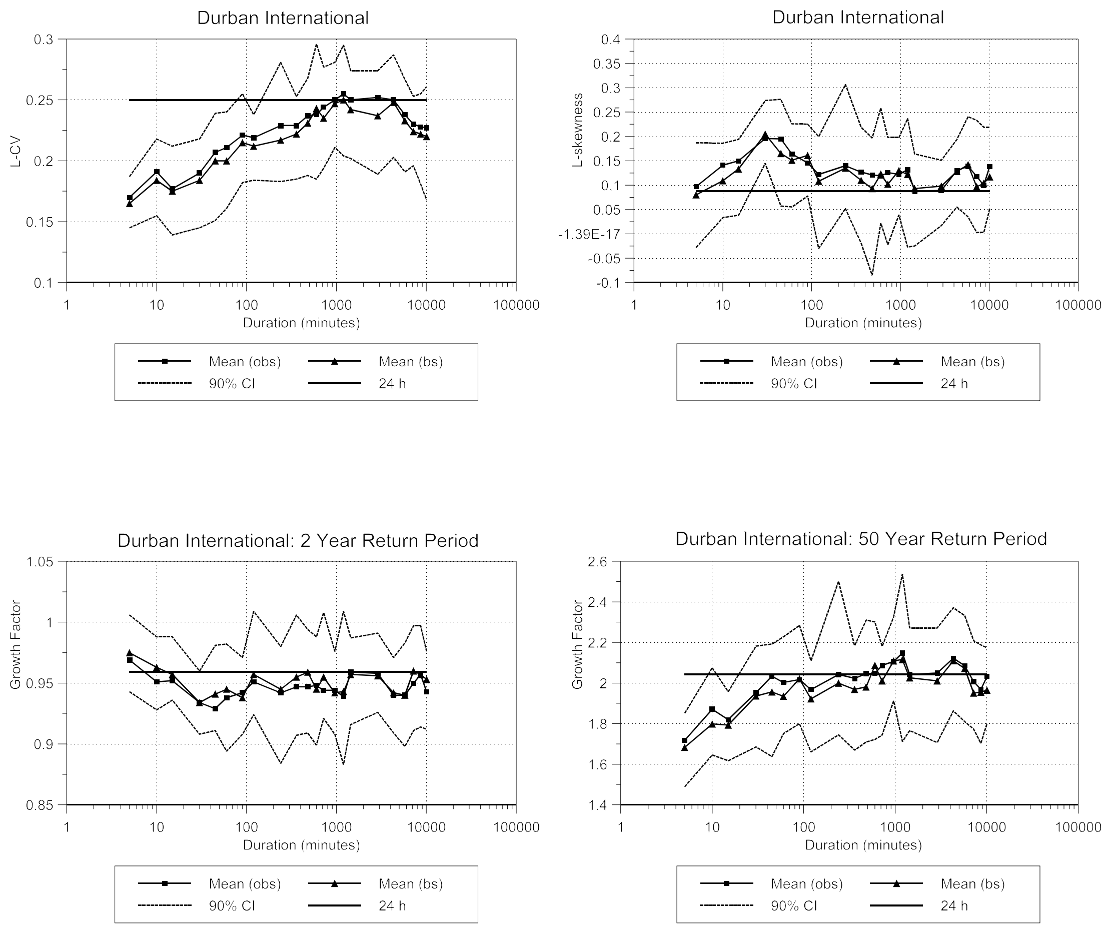


Figure 21 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge 0240808 (Durban International Airport)

The results for SAWS Raingauge SAWB 0059572at East London, based on 50 years of record, are contained in Figure 22. The 24 h L-CV exceeds the 90% confidence limits for durations < 2 h, but both the 2 and 50 year return period 24 h growth factors generally fall within the 90% confidence intervals for durations ranging from 30 minutes to 7 days.

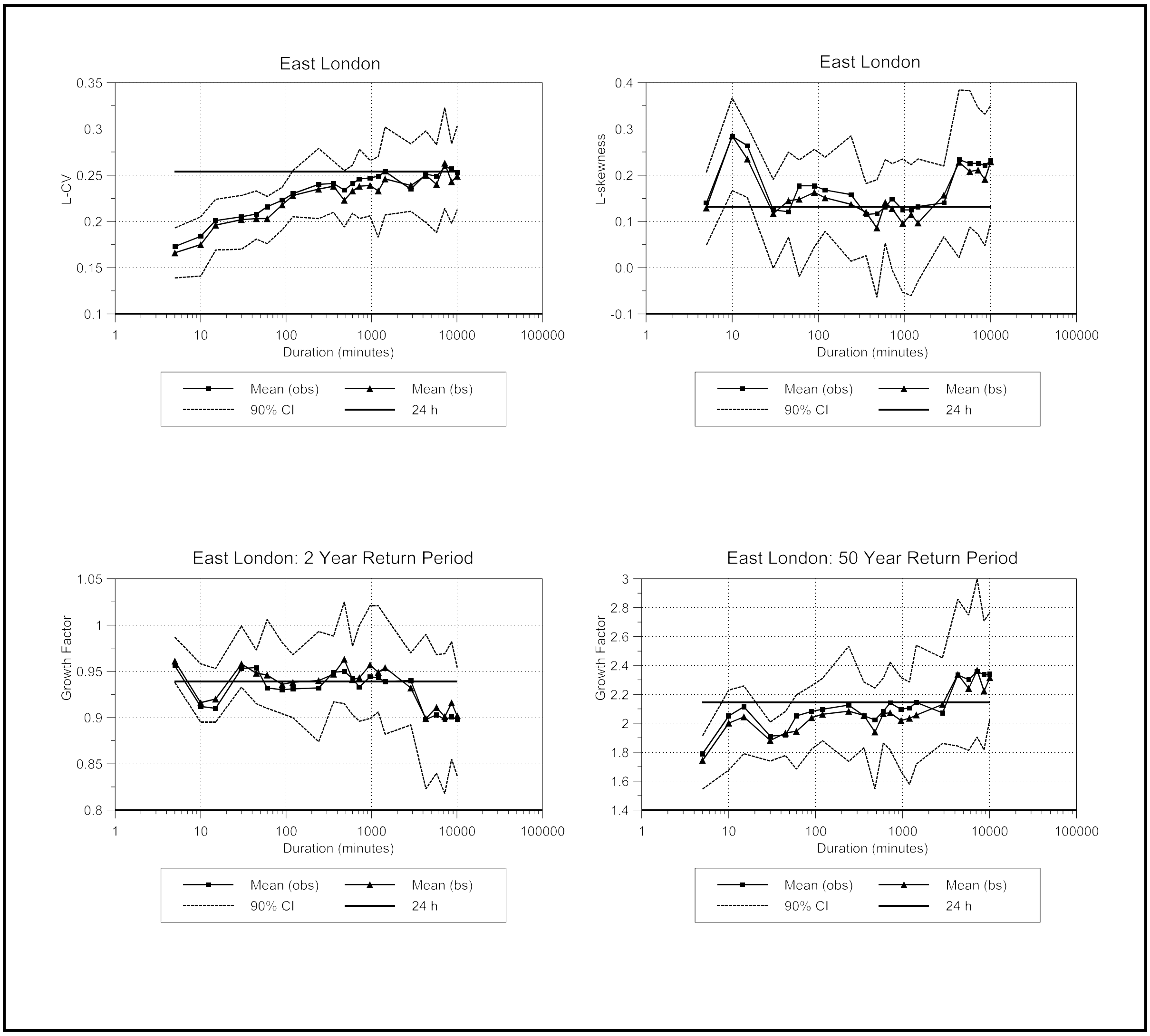


Figure 22 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge 0059572 (East London)

The results for SAWS Raingauge 0035179 with 52 years of record at Port Elizabeth are contained in Figure 23. The 24 h L-CV exceeds the 90% confidence limits for durations < 15 minutes, but both the 2 and 50 year return period 24 h growth factors fall within the 90% confidence intervals for durations ranging from 15 minutes to 7 days.

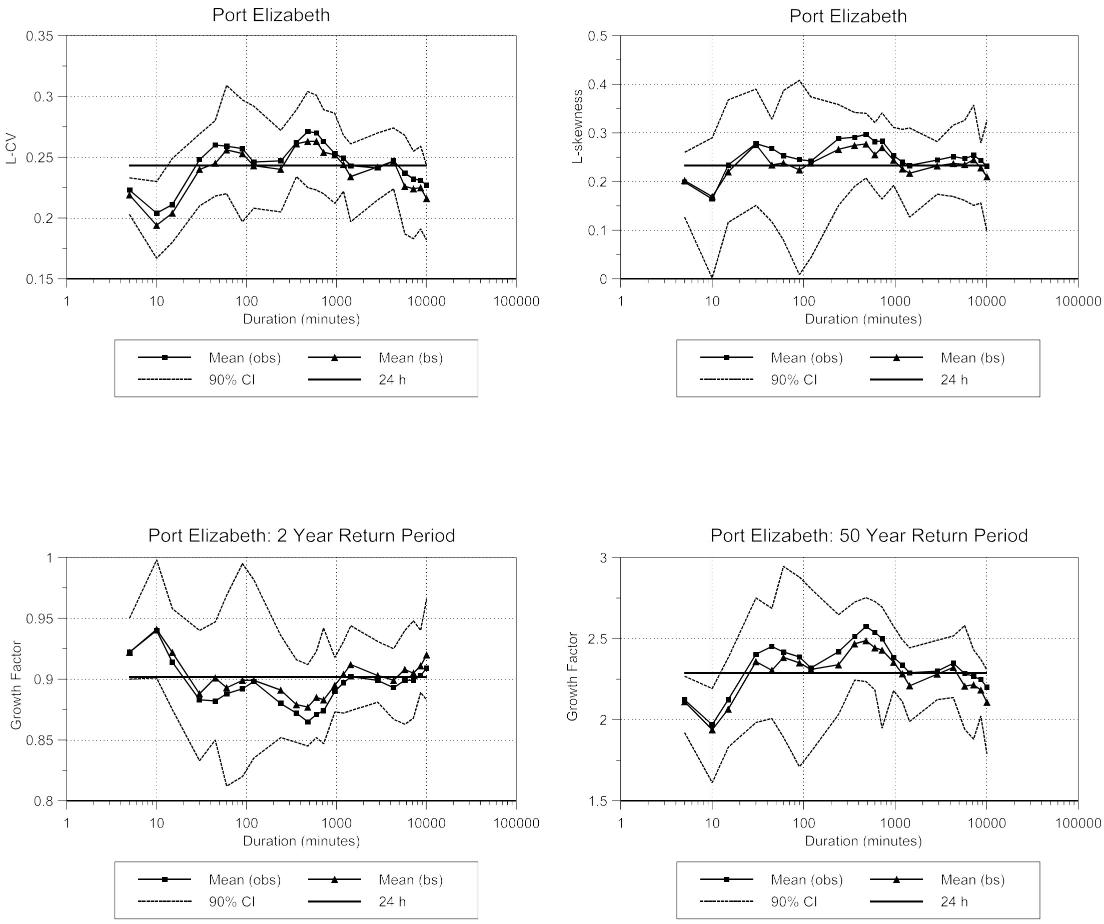


Figure 23 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge 0059572 (Port Elizabeth)

The results for Raingauge Jnk19A with 54 years of record at Jonkershoek (Western Cape) are contained in Figure 24. Although the L-CV falls outside of the 90% confidence limits for durations ranging from 2 to 6 h, the 2 and 50 year return period growth curve generally fall within the 90% confidence for most durations.

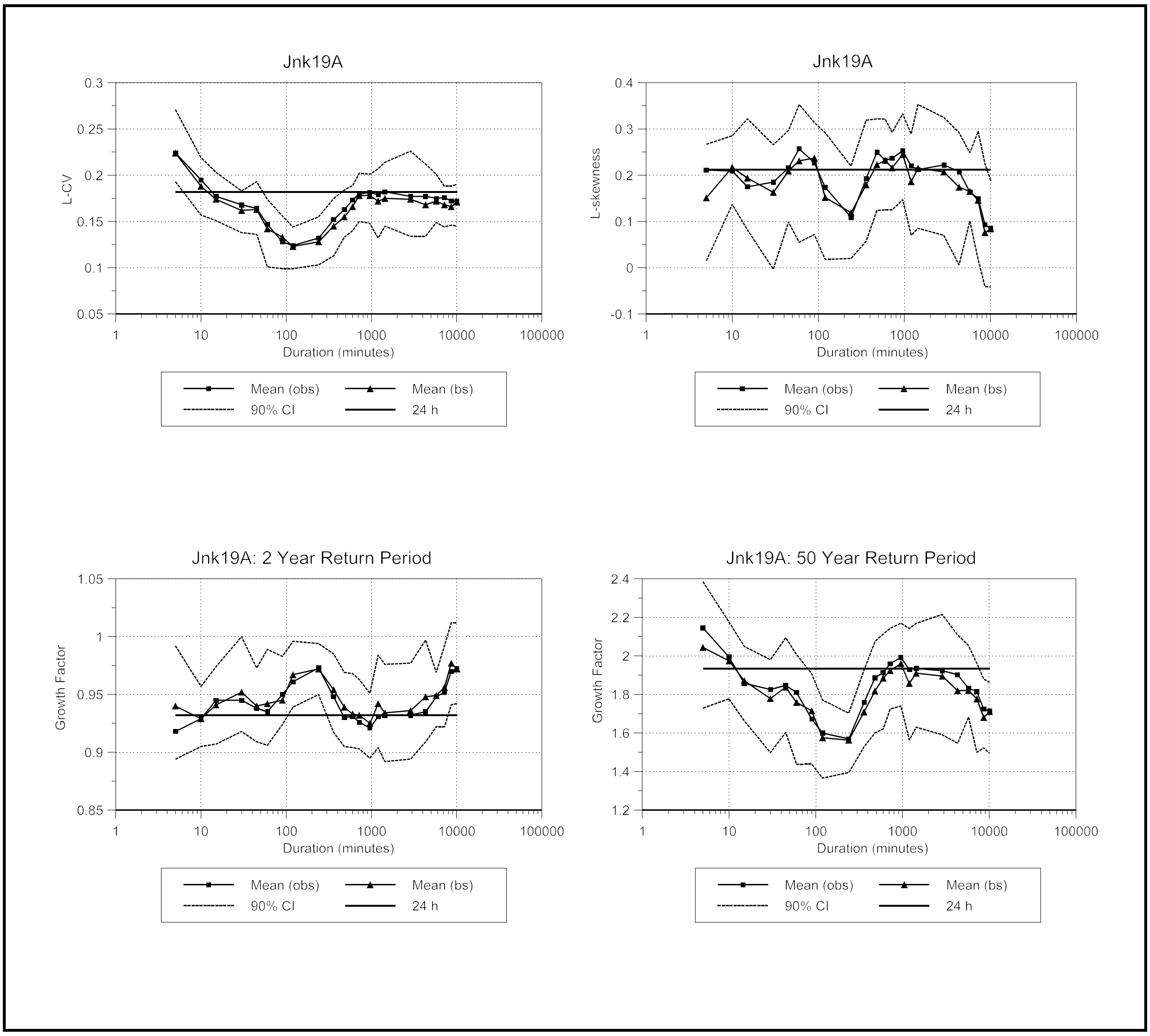


Figure 24 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge Jnk19A (Jonkershoek)

The results for SAWS Raingauge 0290468 with 41 years of record at Kimberley are contained in Figure 25. Again, the 24 h L-CV falls outside the 90% confidence limits over a wide range of durations. The variation of L-CV and L-skewness with duration results in large variations in the growth curves with duration which, when combined with mean of the AMS for individual duration, results in a decrease in design rainfall depths for longer durations. Similar results are obtained from the estimation of design rainfalls for the individual durations directly from the observed data. This clearly indicates a problem with the digitised rainfall data.

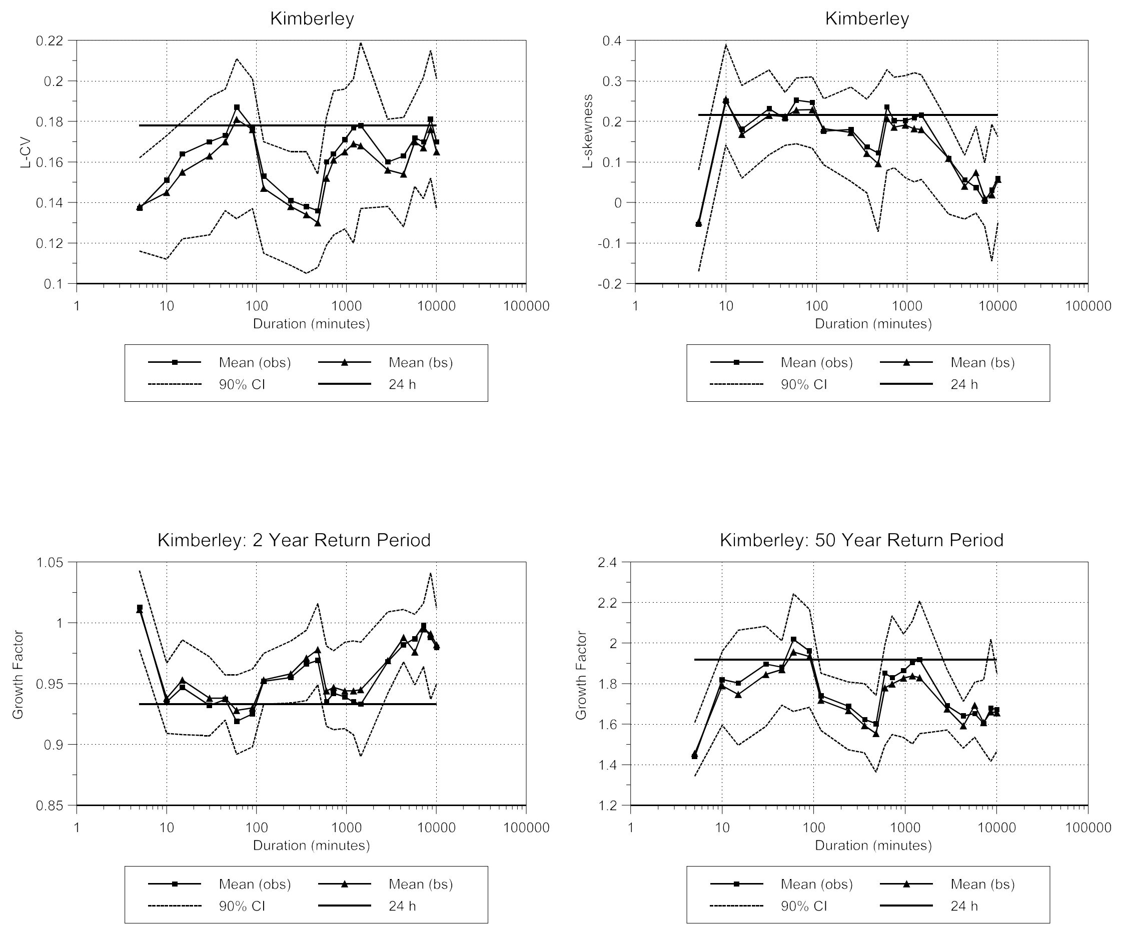


Figure 25 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at SAWS Raingauge 0290468 (Kimberley)

The results for Raingauge Moko3A which has 27 years of record at Mokobulaan are contained in Figure 26. Both the 24 h L-CV and 24 h L-skewness fall within the 90% confidence limits over a wide range of durations. Thus the 2 and 50 year 24 h growth curves generally fall within the 90% confidence limits for durations > 30 minutes.

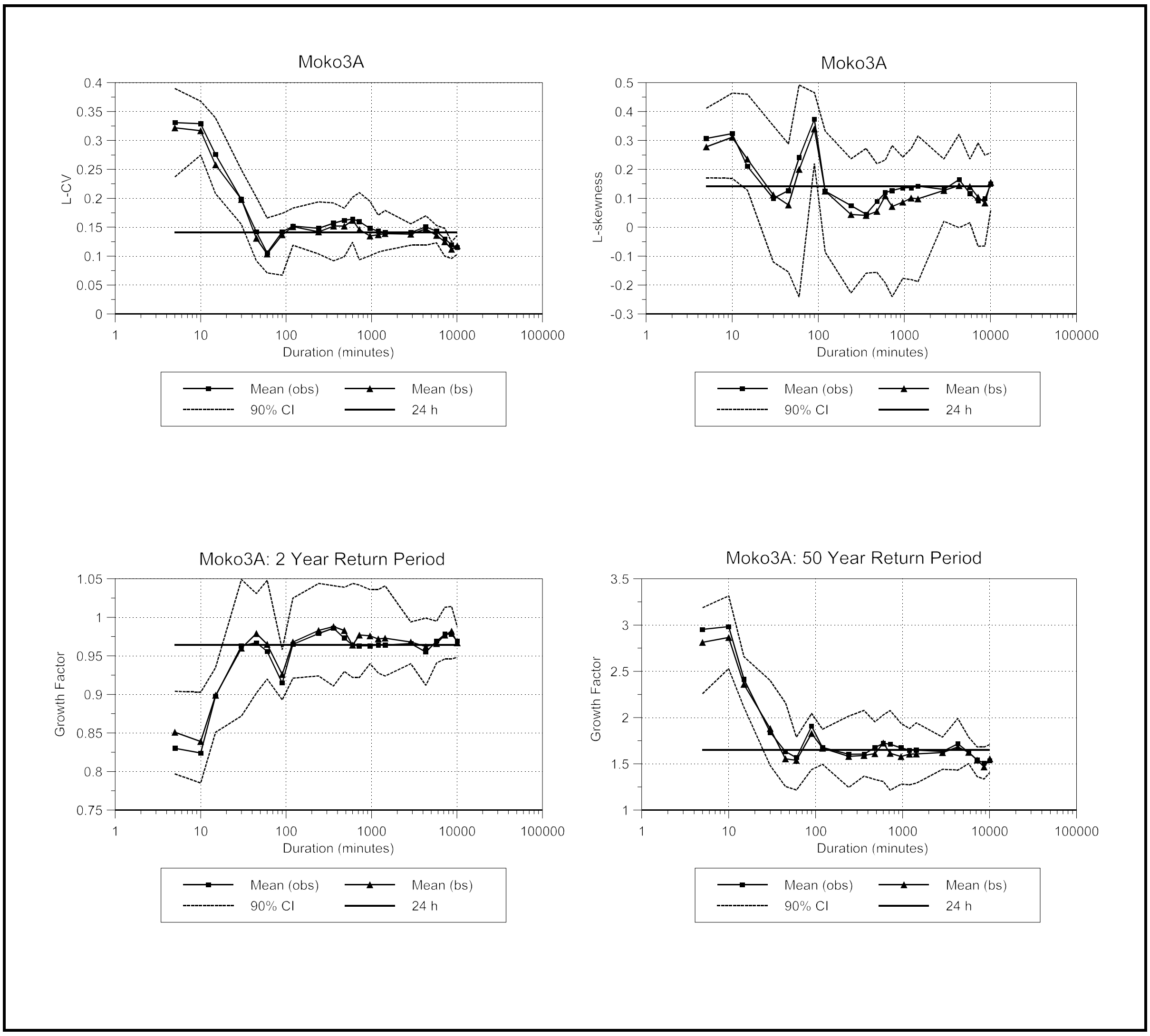


Figure 26 90% Confidence limits for L-moment ratios, 2 and 50 year return period growth factors established from 1000 bootstrapped samples at Raingauge Moko3A (Mokobulaan)

For the stations considered, which are located in different climatic regions in South Africa, the assumption of scale invariance and the use of the 24 h duration growth curve, which is assumed to be the most reliable, can be reasonably confidently applied to durations ranging from 30 minutes to 7 days. Although some exceptions to this assumption are evident (e.g. Kimberley), the autographically recorded data from these sites appear to be suspect. At some sites the removal of a single outlier event (e.g. at C182) improved the validity of scale invariance at the site.

Where changes in the trends of the L-moment ratios with duration are evident (e.g. at Jnk19A and Kimberley), the design rainfalls computed from the observed data for individual durations occasionally decrease with longer durations. Again, this clearly indicates poor and inconsistent data.

3.4.4 Errors in growth curves using a scale invariance approach

Based on the assumption of a scale invariance approach and that the 24 h growth factor is the most reliable value as it can be estimated from the daily rainfall database, Figure 27 contains the results of the differences between the *D* h and 24 h duration growth factors for selected sites in South Africa. At the sites considered, the differences between the *D* h and 24 h duration growth factors for return periods of up to 100 years are generally less than 20% for durations > 15 minutes. Exceptions to this generalisation are evident at Kimberley and Jnk19A, where the data are considered to be suspect, as explained previously.

3.5 Other Evidence

Burlando and Rosso (1996) developed a distribution free framework for scaling DDF curves which assumed that the coefficient of skewness and coefficient of kurtosis are invariant with duration. Menabde *et al.* (1999) tested the scaling concepts on rainfall data from two stations, one in New Zealand and the other in South Africa, and concluded that simple scaling was applicable at both sites and postulated that the scaling exponent was related to the local climate.

Durrans and Brown (2000) revised design rainfall values for Alabama, USA, for durations ranging from 15 minutes to 48 hours and they constrained the L-CV and L-skewness for all durations to be constant at a site.

3.6 Chapter Conclusions

Based on the above evidence it is concluded that:

- There are no systematic differences between higher order L-moment ratios for annual maximum series extracted using fixed and sliding windows. Hence, the differences in the short and long duration growth curves are attributed largely to the different periods and length of record used in the analyses and to a lesser extent to the errors in the digitised rainfall data.
- It is evident that there is considerable variation with duration in observed higher order L-moments. This is associated with the sampling variability and length and period of record.
- The most reliable estimates of the L-moment ratios are computed from the daily rainfall data which are more abundant and have longer record lengths than the digitised rainfall data.
- For durations ranging from 60 minutes to 2 days, both the 24 h L-CV and L-skewness, computed from rainfall series simulated by the BLRPG model, generally fell within the inter-quartile range at most locations considered. The variability of the simulated L-CV and L-skewness with duration is relatively small.

- For durations > 15 minutes, the 1 day L-moment ratios generally fell within the 95% confidence intervals computed for each duration from the observed digitised rainfall data.
- For durations ranging from 30 minutes to 7 days, the 1 day L-moment ratios generally fell within the 90% confidence intervals computed for each duration from the observed digitised rainfall data using a bootstrapping technique.

It is thus concluded that the 1 day L-moment ratios, and hence growth curves, are the most reliable estimate of the L-moment ratios for all durations. Design rainfall estimates for all durations may thus be estimated as the product of the 1 day growth curves and an estimate of the mean of the AMS (index value) for the duration in question. The methodology developed for estimating the mean of the AMS at ungauged location in South Africa is detailed in Chapter 4.

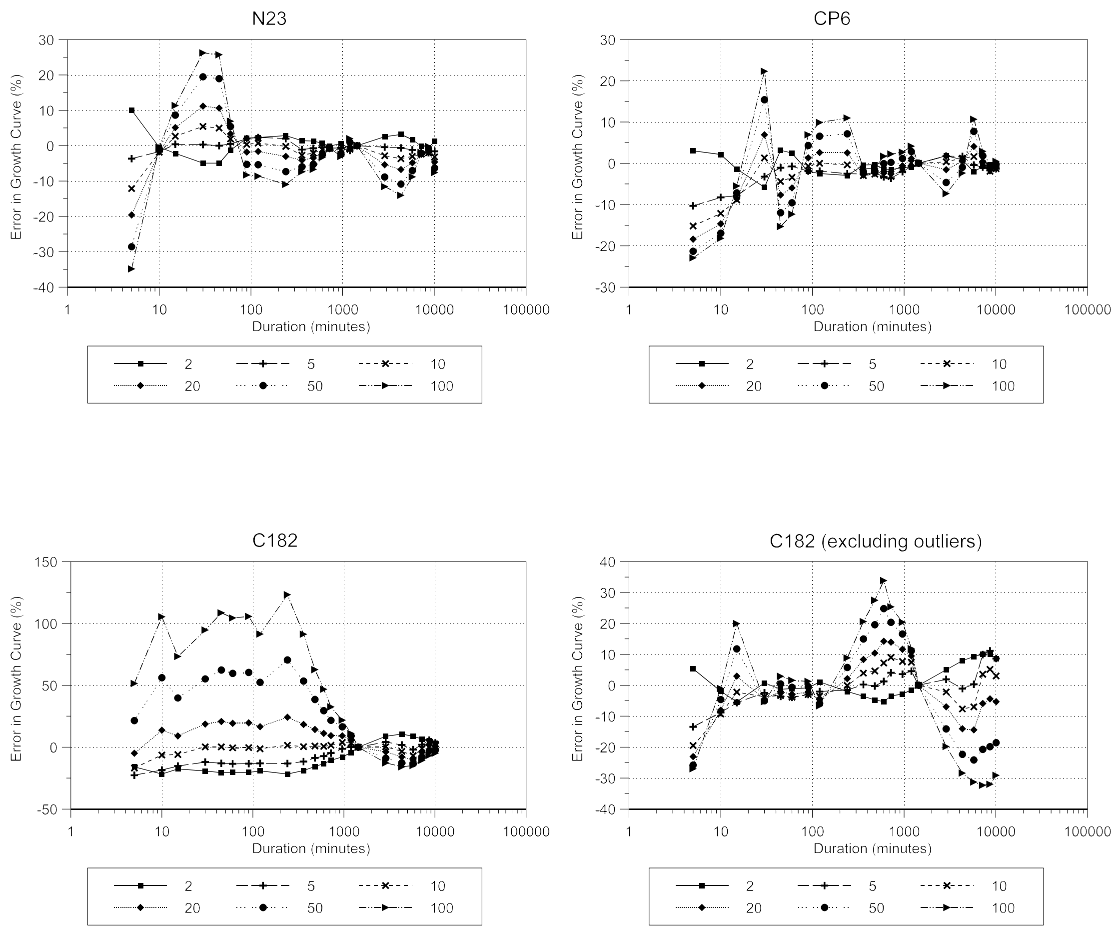


Figure 27 Differences in 24 h and *D* h growth curves, expressed as percentage of the *D* h value at selected stations in different climatic regions of South Africa

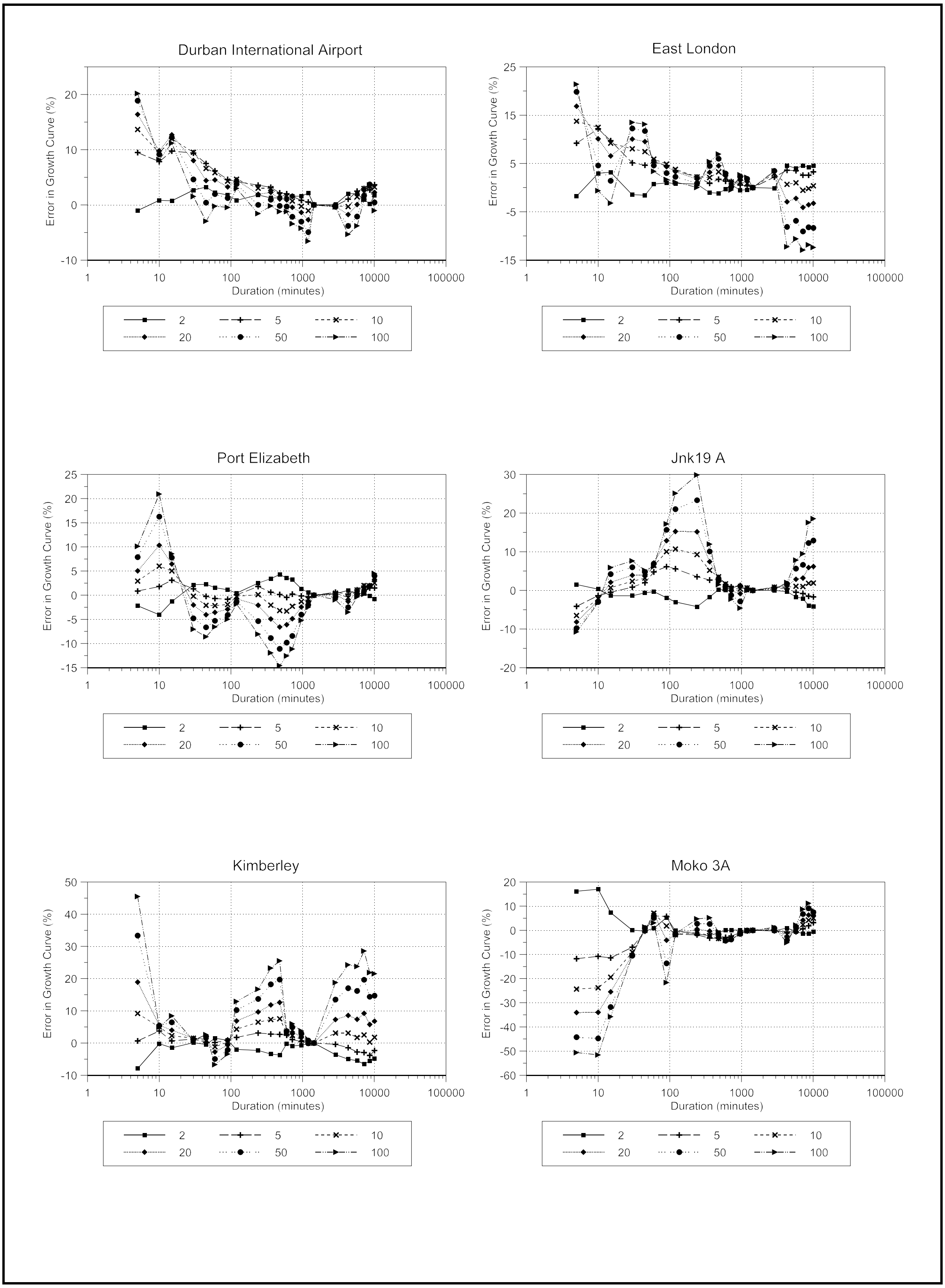


Figure 27 (cont) Differences in 24 h and *D* h growth curves, expressed as percentage of the *D* h value at selected stations in different climatic regions of South Africa

CHAPTER 4

ESTIMATION OF THE MEAN OF THE ANNUAL MAXIMUM SERIES AT UNGAUGED LOCATIONS IN SOUTH AFRICA

4.1 Estimation of the Mean of the 1 Day AMS

The regional growth curves developed for each of the 78 relatively homogeneous clusters, as shown in Figure 2, were scaled by the mean of the 1 day AMS (L_1_{1d}). Hence, in order to estimate the 1 day design rainfall values at an ungauged site, it is necessary to estimate the mean of the AMS at the required location.

4.1.1 Generalised relationships

As shown in Figure 28 for daily rainfall data from 1 806 stations which have at least 40 years of record, a strong correlation ($R^2 = 0.72$) exists between the mean of the 1 day AMS and Mean Annual Precipitation (MAP). The relationship between the median of the 1 day AMS and MAP was very similar with, $R^2 = 0.71$. The values of MAP used in Figure 28 were derived from a study by Dent *et al.* (1987).

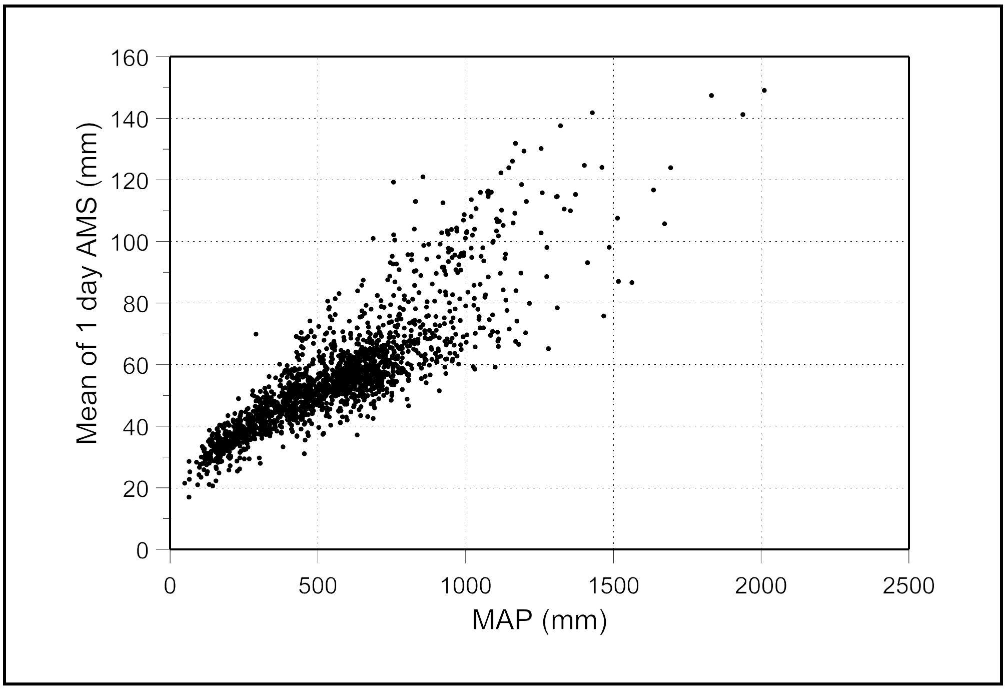


Figure 28 Relationship between the mean of 1 day AMS and MAP (from Dent *et al.*, 1987) for 1 806 stations in South Africa which have at least 40 years of observed daily rainfall record

It has been shown in previous studies, for example by Smithers and Schulze (2001b), that the MAP values mapped by Dent *et al.* (1987) may be erroneous at some locations. MAP values for each of the sites were thus also derived using the observed record which had missing daily rainfall data infilled using the Expectation Maximisation Algorithm (Smithers *et al.*, 1999). The relationship between the mean of the 1 day AMS and the concurrent "observed" MAP is shown in Figure 29. The mean of the 1 day AMS has a slightly stronger correlation with the observed MAP values (R^2 = 0.73) compared to the MAP values (R^2 = 0.71) derived from Dent *et al.* (1987). This is not unexpected, as the mean of the 1 day AMS and observed MAP values were derived using the same period of record which had missing and outlier values infilled using the EMA, whereas the MAP values derived by Dent *et al.* (1987) excluded missing daily rainfall values and were computed using a shorter period of record. Hence, statistics computed from the same data as used in the calculation of the mean of 1 day AMS values were used in the regression analyses.

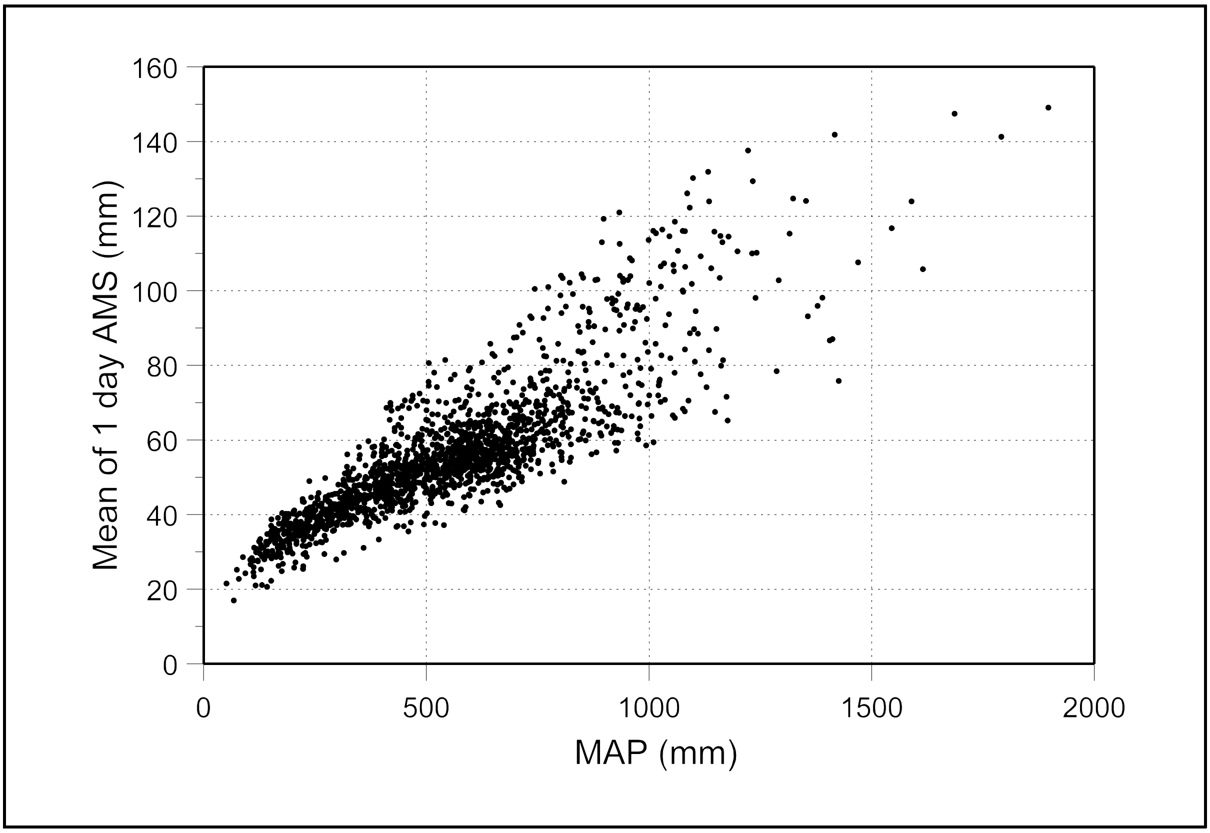


Figure 29 Relationship between the means of 1 day AMS and MAP (computed from the observed data) for concurrent periods calculated using records from 1 806 daily rainfall stations in South Africa which have at least 40 years of observed record

The relationship between the mean of the 1 day AMS and MAP derived from stations in South Africa which have at least 40 years of record is too general to be applied on a local scale to estimate the mean of the 1 day AMS. For example, at a site with a MAP of 1500 mm, the mean of the 1 day AMS value would be estimated as 110 mm, while the observations indicate that the range of the mean of the 1 day AMS, for a MAP of 1500 mm, is from 80 mm to more than 140 mm. Clearly, this range indicates that growth curves re-scaled using the estimated mean of the 1 day AMS could result in large errors in design rainfall values at some locations. Therefore, regionalised relationships to estimate the mean of the 1 day AMS in South Africa were developed. A spatial plot of the error residuals between the observed and estimated means of the 1 day AMS values, as shown in Figure 30, indicates strong regional differences where the generalised equation to estimate the mean of the 1 day AMS as a function of only MAP does not perform adequately.

4.1.2 Regionalised relationships

For each of the 78 relatively homogenous daily rainfall clusters identified by Smithers and Schulze (2000b), the average of the site characteristics (latitude, longitude, MAP, altitude, distance to sea, concentration and seasonality of rainfall) of all rainfall station sites making up the cluster were computed. In addition, an index of rainfall intensity (*XINDEX*) was computed using Equation 5 and values from individual sites were averaged for each cluster.

$$XINDEX = \frac{MAP}{100 - PPTCONC} \qquad ...5$$

where

PPTCONC = index of concentration of monthly rainfall as defined by Markham (1970) and mapped for South Africa by Schulze (1997).

The average latitude, longitude and *XINDEX* site characteristics for each cluster were normalised and used in a cluster analysis to group clusters into regions which could be used establish relationships between the mean of the 1 day AMS and MAP. An alternative approach would be to derive relationships for each of the 78 clusters. This would result in 78 relationships which may not be significant in clusters which have only a few daily rainfall stations.

A cluster analysis of these averaged site characteristics using Ward's minimum variance hierarchical algorithm (SAS, 1989), which tends to form clusters of roughly equal size (Hosking and Wallis, 1997), was performed. The number of clusters to form is subjective and initially four regions were identified. In regions where the regression relationships resulted in poor estimates of the mean of the 1 day AMS, further subdivision of regions was performed using a similar cluster analysis. This resulted in 6 regions being identified, the locations of which are shown in Figure 31. Further subdivision into more clusters did not markedly improve the Predicted Residual Sum of Squares (PRESS) statistic for the estimation of the mean of the 1 day AMS. A spatial plot of the error residuals between observed and estimated means of the 1 day AMS, as shown in Figure 32, indicates a significant improvement in the estimation of the mean of the 1 day AMS compared to using a single regression for the entire country.

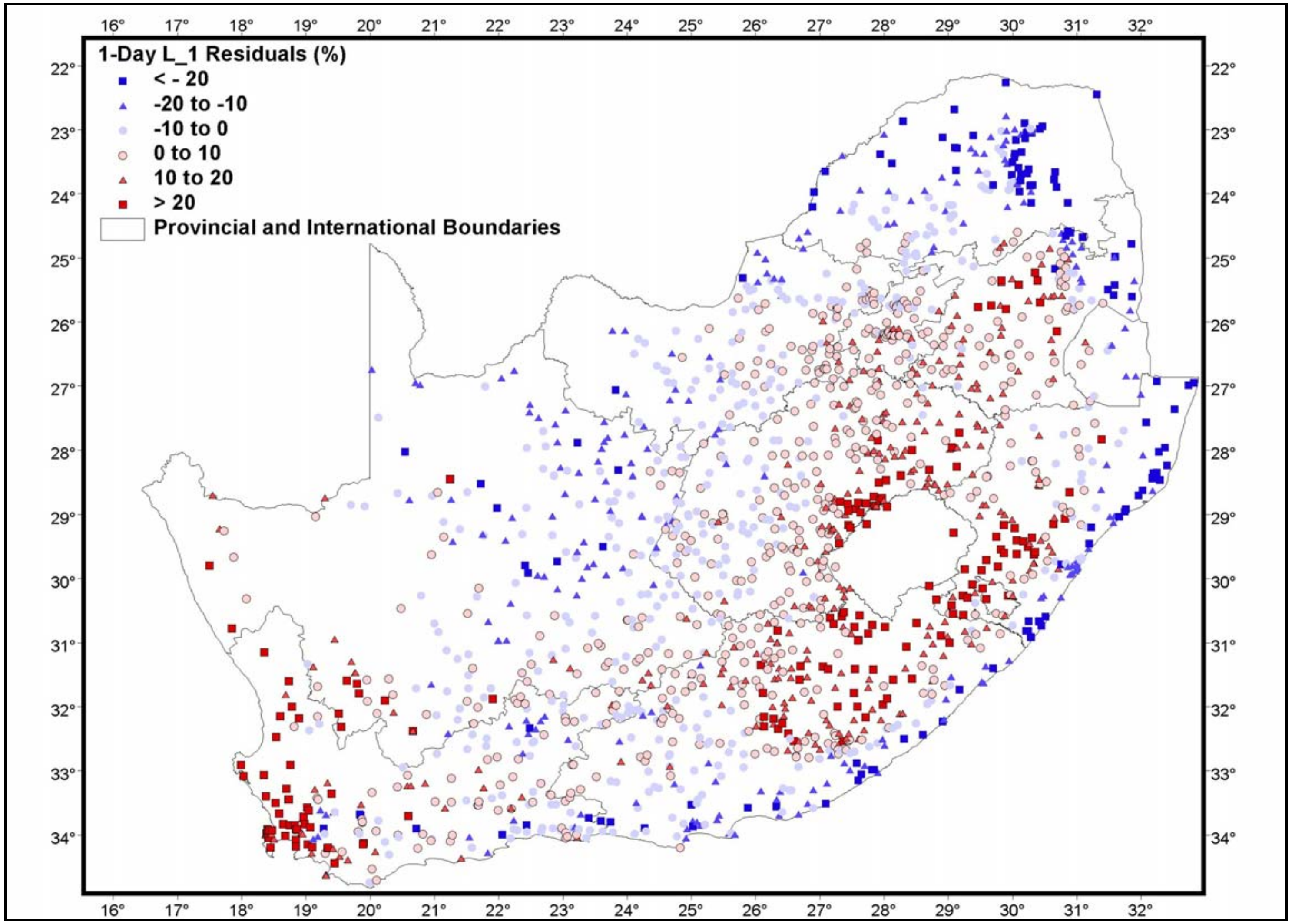


Figure 30 Percentage errors between the mean of the 1 day AMS ($L\_1_{1\,d}$) computed from observed data and estimated using a generalised 1 day *L_1*:MAP relationship for South Africa

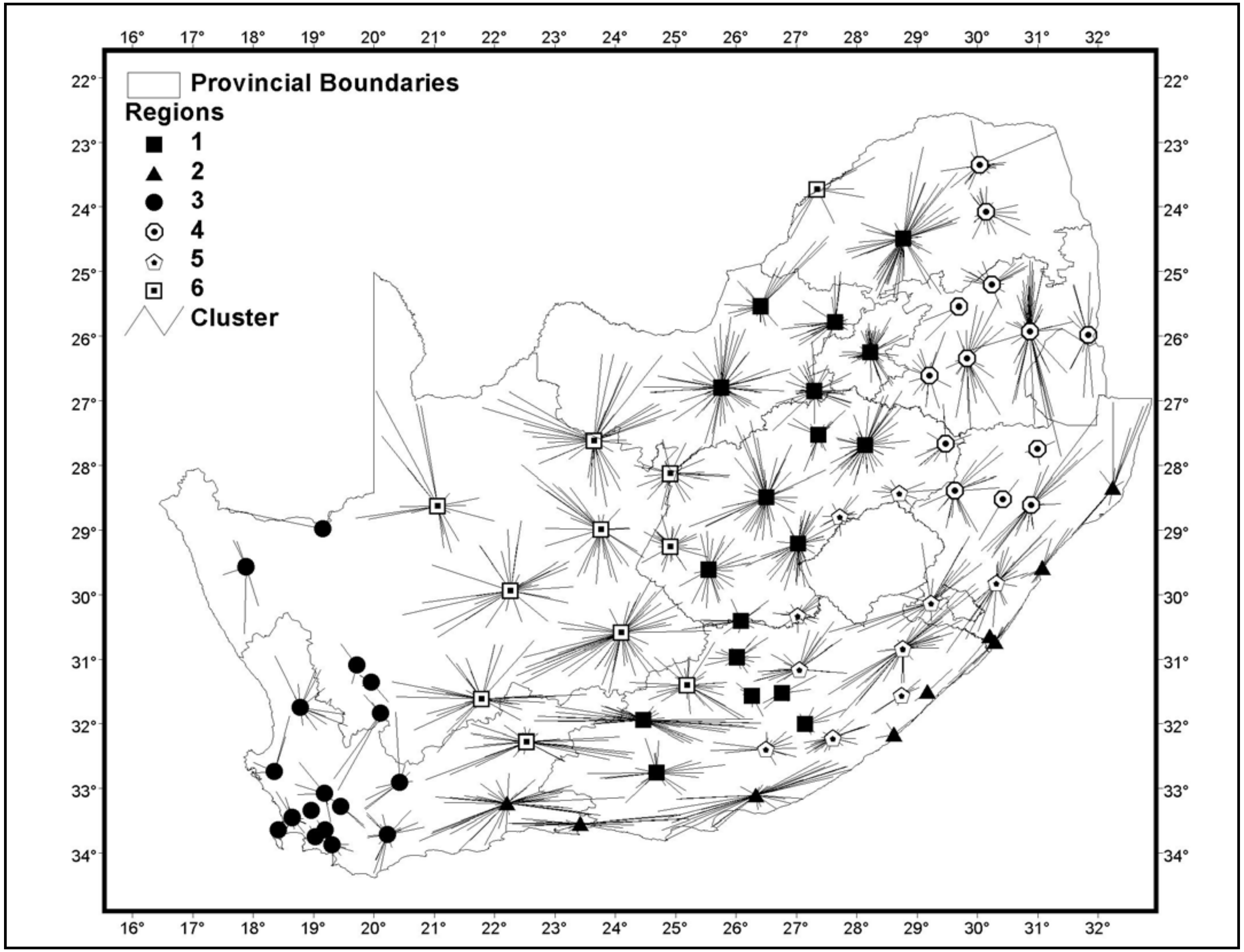


Figure 31 Regions of clusters used for the estimation of the mean of the 1 day ($L\_l_{1\,d}$) AMS as a function of site characteristics

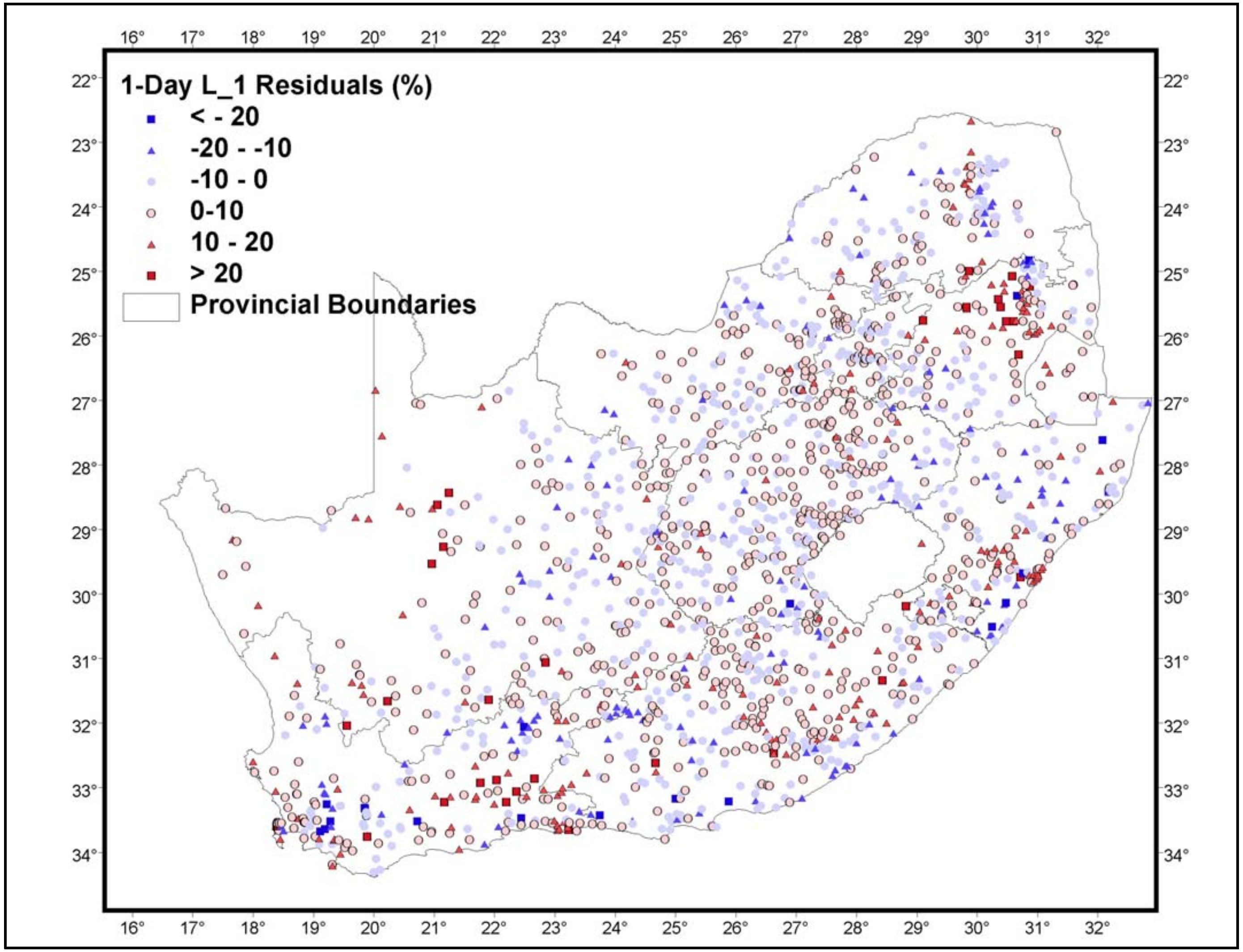


Figure 32 Percentage errors between the mean of the 1 day AMS (L_1_{1d}) computed from observed data and estimated using the six regionalised 1 day L_1_{1d} : MAP relationship for South Africa

The correlation matrix between site characteristics which could potentially be used as independent variables to estimate the mean of the 1 day AMS is shown in Table 2. Some degree of correlation exists between MAP and longitude, between latitude and distance from sea, between latitude and concentration of rainfall and between altitude and concentration of rainfall. Hence three models were considered to estimate the mean of the 1 day AMS with the following independent variables:

Model 1: MAP, latitude, altitude and seasonality,
Model 2: MAP, distance from sea, altitude and seasonality, and
Model 3: MAP, concentration of rainfall, altitude and seasonality.

Table 2 Correlation matrix between site characteristics of raingauge locations which have more than 40 years of record in South Africa

	MAP	Latitude	Longitude	Altitude	Distance from sea	Concentration of rainfall	Seasonality	*XINDEX*
MAP	1.00	0.07	0.40	0.00	0.06	0.00	0.12	0.10
Latitude		1.00	0.37	0.18	0.43	0.60	0.06	0.08
Longitude			1.00	0.08	0.02	0.07	0.00	0.00
Altitude				1.00	0.35	0.27	0.08	0.12
Distance from sea					1.00	0.48	0.09	0.14
Concentration of rainfall						1.00	0.05	0.38
Seasonality							1.00	0.20
XINDEX								1.00

Based on the summed PRESS statistics for the 6 regions, with independent variables retained in the model if significant at the 0.1 level, Model 1 was found to be the best model. Seasonality was found not to be a significant independent variable in any of the regions. The derived intercept and coefficients determined using multiple regression analysis are contained in Table 3.

Correlation between independent variables can lead to unstable and unreliable regression coefficients (Hirsch *et al.*, 1993). Hence, the Variance Inflation Factor (*VIF*), as defined in Equation 6, is included in Table 3.

$$VIF_j = \frac{1}{1-r_j^2} \qquad ...6$$

where

VIF_j = variance inflation factor for *j*-th independent variable, and
r_j^2 = coefficient of determination of regression of *j*-th independent variable on all other independent variables.

According to Hirsch *et al.* (1993) an ideal VIF_j is1 and a value of $VIF_j > 10$ could result in "serious problems" in the regression equations. As indicated in Table 3, the selection of independent variables appears to be adequate with the maximum $VIF_j < 3$. Ordinary Least Squares (OLS) were used in the regression analyses.

Table 3 Intercept and regression constants derived to estimate the mean of the 1 day AMS in South Africa for six regions shown in Figure 31

Region		1	2	3	4	5	6
Number of sites		596	173	137	264	234	343
R^2		0.81	0.90	0.79	0.85	0.71	0.82
Intercept	Parameter	81.2180	138.6769	-36.2028	122.6264	38.3667	75.4432
	SE	2.4193	13.3008	20.7785	6.9071	2.1599	3.3459
MAP	Parameter	0.0334	0.0683	0.0464	0.0609	0.0466	0.0484
	SE	0.0018	0.0026	0.0026	0.0019	0.0024	0.0020
	Variance Inflation	2.67	1.42	1.42	1.00	1.01	1.35
Latitude	Parameter	-1.4447	-3.4343	1.6616	-3.1778	0.0000	-1.6015
	SE	0.0689	0.3788	0.6329	0.2684	n/a	0.1007
	Variance Inflation	1.75	1.42	1.76	1.12	n/a	1.35
Altitude	Parameter	-0.0041	0.0000	0.0077	-0.0143	-0.0107	0.0000
	SE	0.0007	n/a	0.0020	0.0012	0.0009	n/a
	Variance Inflation	1.72	n/a	1.35	1.12	1.01	n/a

In a number of regions (1, 2, 5 and 6) the regression relationships tended to overestimate smaller values of the mean of the observed 1 day AMS and underestimate the larger values of the mean of the observed 1 day AMS found within a region. Further investigation indicated that these sites, from the perspective of estimating the mean of the 1 day AMS, seem to fit better with an adjacent cluster, which has a different regional membership to the site in question. Hence, although the distribution of the scaled annual maximum series at all the sites which form a particular cluster are relatively homogeneous, the relocation of some sites to different clusters may have resulted in improved estimates of the mean of the 1 day AMS. However, it is postulated that the results obtained do not warrant the added complexity of sites having a different cluster membership for the estimation of growth curves and for the estimation of the mean of the 1 day AMS. The influence of the errors in the estimated means of the 1 day AMS on design rainfall is presented in Section 4.1.6.

4.1.3 Revision of Region 3

The large prediction errors and large SE of the intercept for Region 3 resulted in this region being subdivided into two regions, *viz.* Regions 3 and 7 as shown in Figure 33. The results of the regression analyses in the 7 regions are contained in Table 4.

Table 4 Intercept and regression constants derived to estimate the mean of the 1 day AMS in South Africa for seven regions shown in Figure 33

Region		1	2	3	4	5	6	7
Number of sites		596	173	62	264	234	343	75
R^2		0.81	0.90	0.79	0.85	0.71	0.82	0.81
Intercept	Parameter	81.2180	138.6769	19.7865	122.6264	38.3667	75.4432	14.259
	SE	2.4193	13.3008	1.5983	6.9071	2.1599	3.3459	2.211
MAP	Parameter	0.0334	0.0683	0.0583	0.0609	0.0466	0.0484	0.0502
	SE	0.0018	0.0026	0.004	0.0019	0.0024	0.0020	0.003
	Variance Inflation	2.67	1.42	1	1.00	1.01	1.35	1.02
Latitude	Parameter	-1.4447	-3.4343	0	-3.1778	0.0000	-1.6015	0
	SE	0.0689	0.3788	n/a	0.2684	n/a	0.1007	n/a
	Variance Inflation	1.75	1.42	n/a	1.12	n/a	1.35	n/a
Altitude	Parameter	-0.0041	0.0000	0	-0.0143	-0.0107	0.0000	0.0123
	SE	0.0007	n/a	n/a	0.0012	0.0009	n/a	0.003
	Variance Inflation	1.72	n/a	n/a	1.12	1.01	n/a	1.02

The results of using the derived relationships to estimate the mean of the 1 day AMS are shown in Figures 34 to 39. Included in these figures are 90 % prediction intervals which incorporates both parameter uncertainty and unexplained variability of the dependent variable (Hirsch *et al.*, 1993). Equation 7 was used to calculate the prediction interval.

$$\left(\hat{y} - ts\sqrt{1 + \frac{1}{n} + \frac{\left(x - \bar{x}\right)^2}{S_{xx}}},\ \hat{y} + ts\sqrt{1 + \frac{1}{n} + \frac{\left(x - \bar{x}\right)^2}{S_{xx}}} \right), \qquad ...7$$

where

$\hat{y}$	=	value estimated using regression equation,
n	=	number of values,
t	=	Student's t with n-1 degrees of freedom,
s	=	standard error of the regression, and
S_{xx}	=	$\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2$.

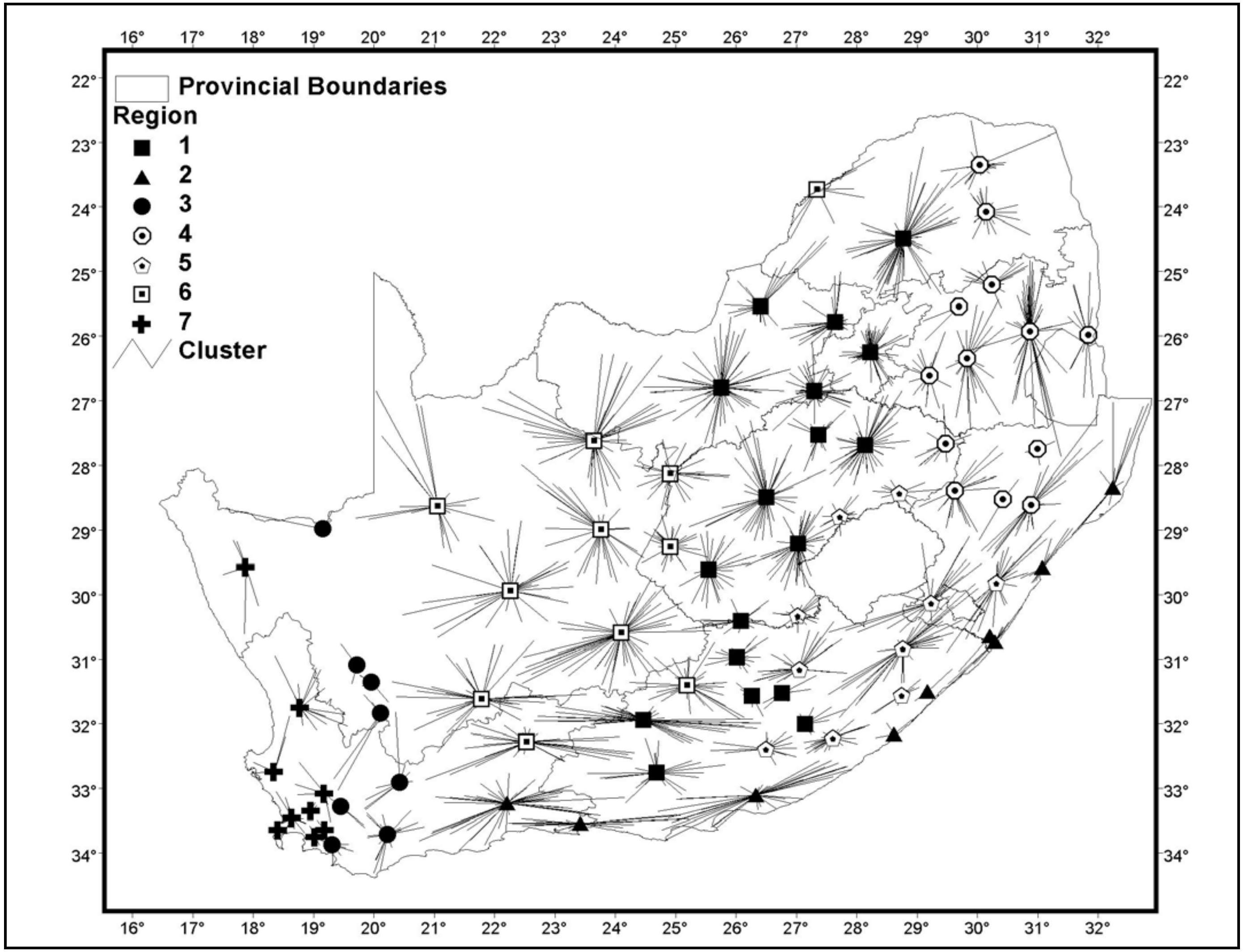


Figure 33 Revised regions of clusters used for the estimation of the mean of the 1 day ($L\_1_{1\,d}$) AMS as a function of site characteristics

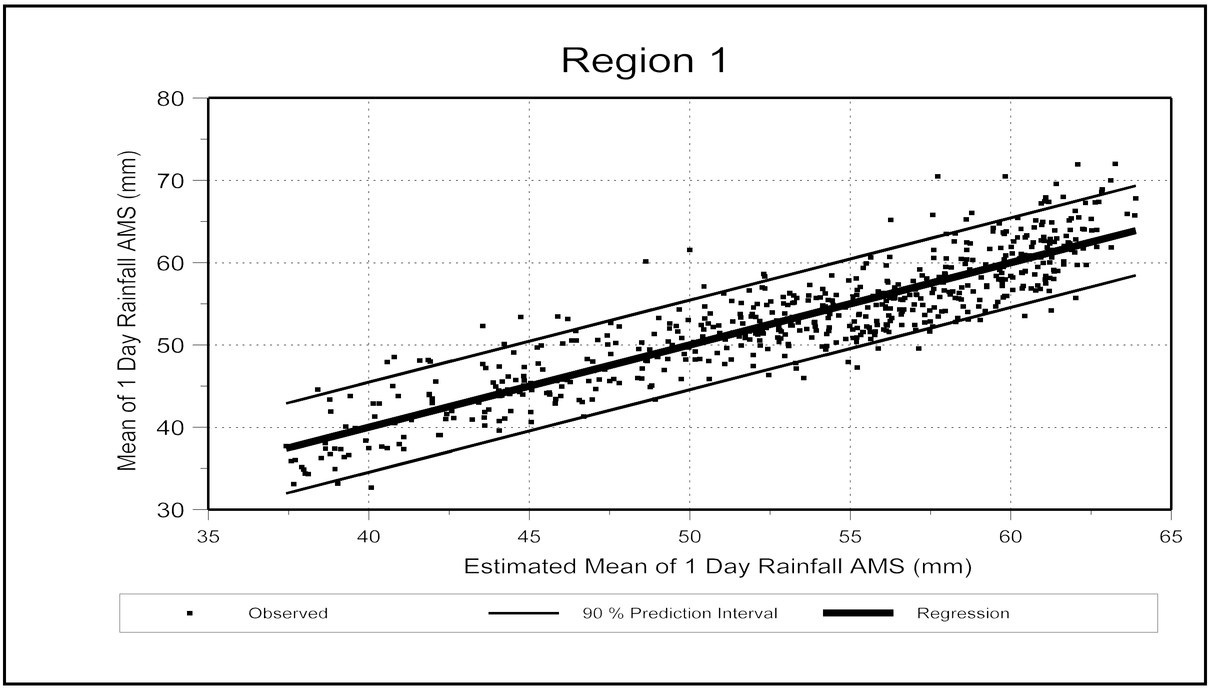


Figure 34 Estimated vs observed means of the 1 day AMS for Region 1, located as shown in Figure 33

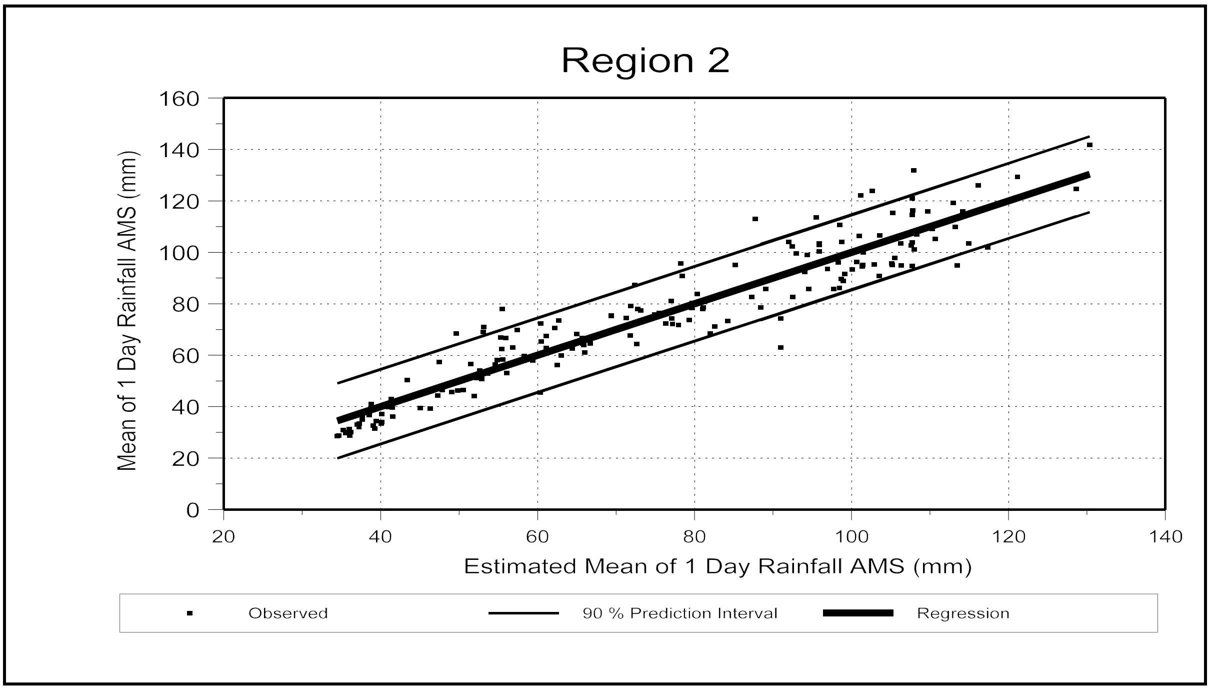


Figure 35 Estimated vs observed means of the 1 day AMS for Region 2, located as shown in Figure 33

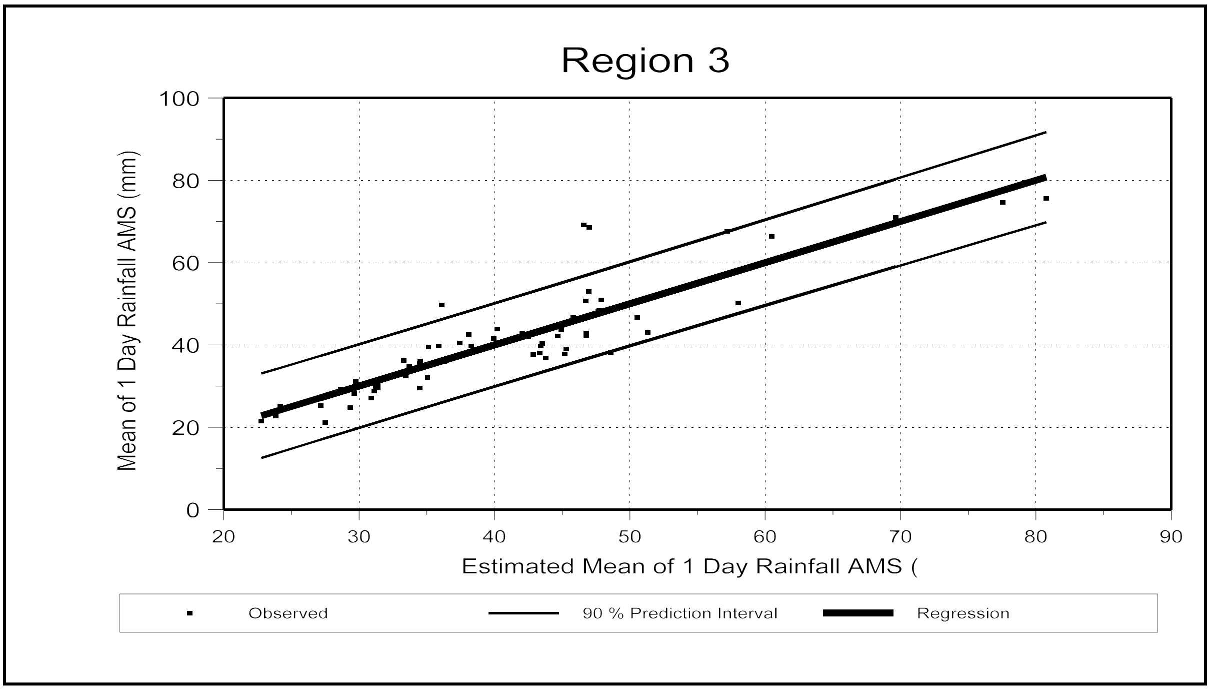


Figure 36 Estimated vs observed means of the 1 day AMS for Region 3, located as shown in Figure 33

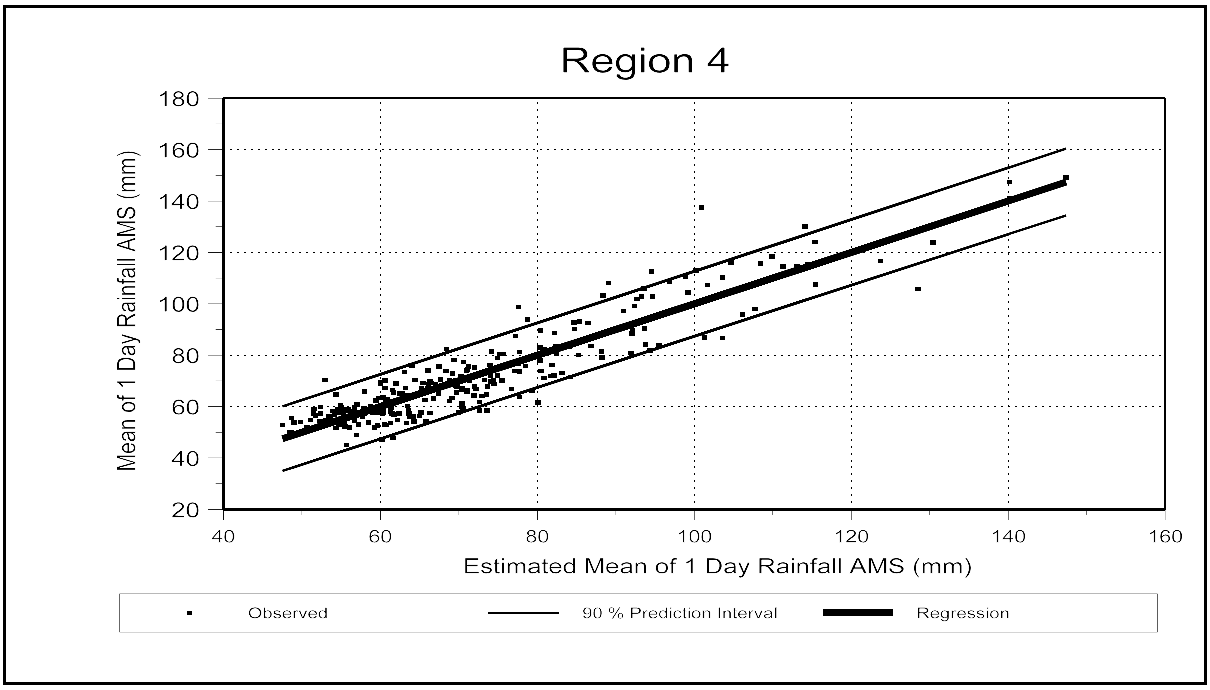


Figure 37 Estimated vs observed means of the 1 day AMS for Region 4, located as shown in Figure 33

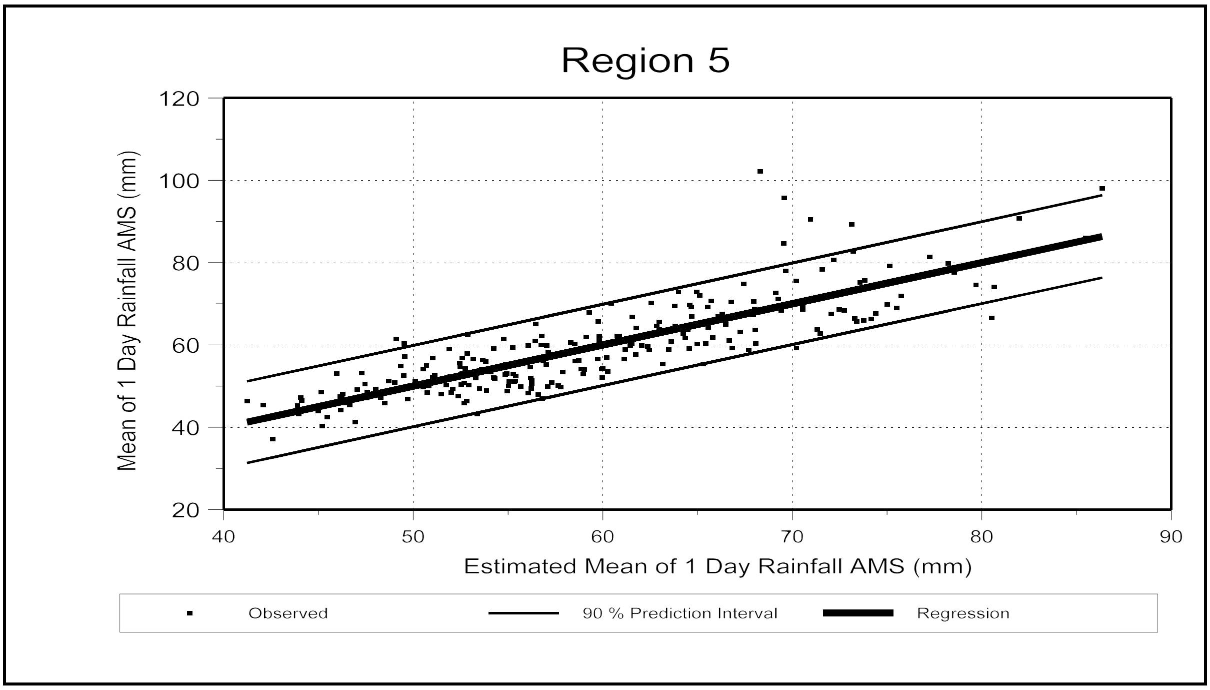


Figure 38 Estimated vs observed means of the 1 day AMS for Region 5, located as shown in Figure 33

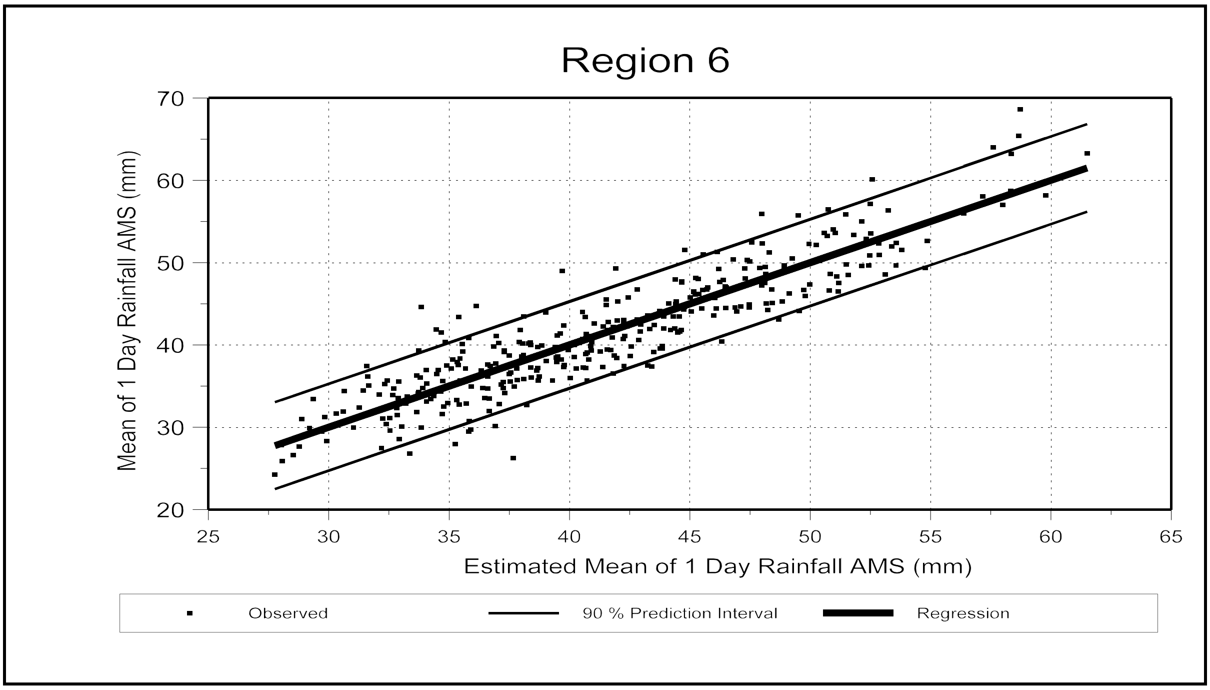


Figure 39 Estimated vs observed means of the 1 day AMS for Region 6, located as shown in Figure 33

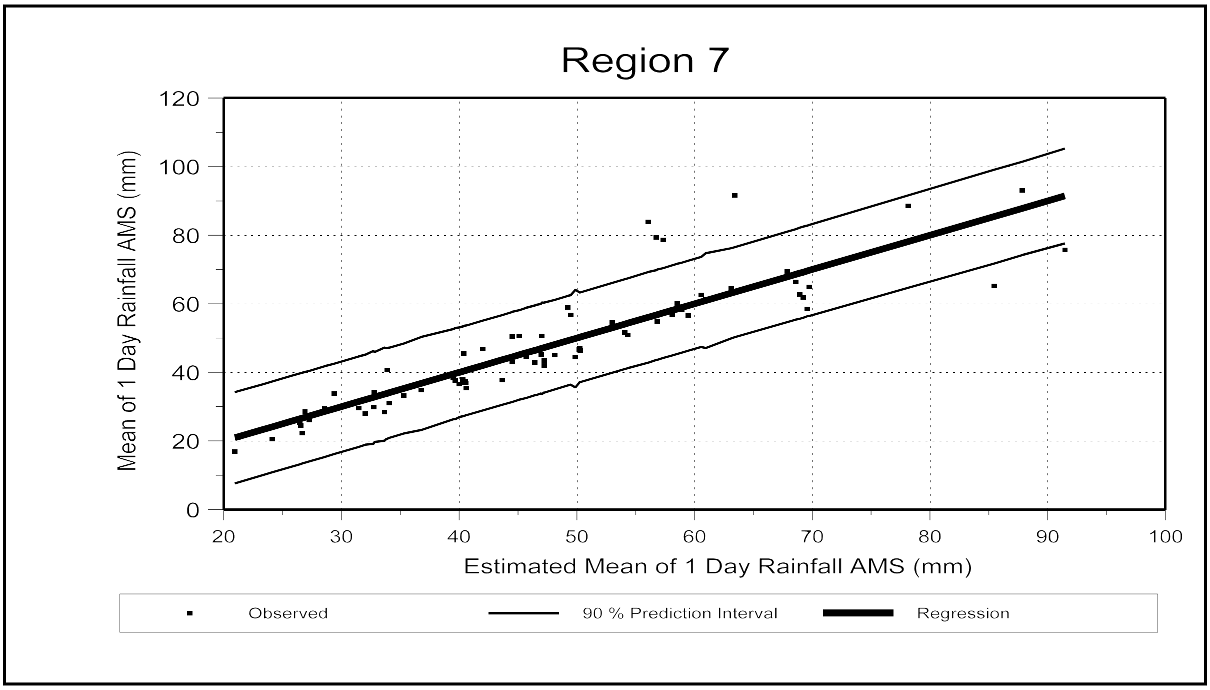


Figure 40 Estimated vs observed means of the 1 day AMS for Region 7, located as shown in Figure 33

4.1.4 Estimation of 1 day design rainfall at ungauged locations in South Africa

Using the derived relationships to estimate the mean of the 1 day AMS, as defined in the previous section, the mean of the 1 day AMS was estimated at each of 429 701 points forming a 1'x1' of a degree latitude and longitude grid in South Africa. The appropriate cluster membership for each 1'x1' grid point was determined as a function of the Euclidean distance of site characteristics to the closest station which were used to identify the 78 clusters. Thus, the appropriate regional growth curve and estimated means of the 1 day AMS at each 1'x1' grid point were used to estimate the 1 day design rainfall depths at each 1'x1' grid point located in South Africa.

The reliability of the design rainfall depths computed using the regional approach (i.e. estimated mean of the 1 day AMS multiplied by the appropriate regional growth curve) was assessed by a comparison with at-site design rainfall values estimated at 1 806 stations in South Africa which have at least 40 years of daily rainfall record. The at-site design values at the stations were estimated using regional growth curves and the mean of the 1 day AMS derived from the observed data at the station. As shown in Figure 41, the use of estimated means of the 1 day AMS to re-scale the regional growth curves results in differences in design rainfalls of less than 20% at approximately 95 % of the stations, all of which have at least 40 years of record. It is noted that the design values computed using the estimated means of the 1 day AMS values generally exceed the design values computed using means of the 1 day AMS calculated from the observed data with, on average for all return periods, 22% of the relative difference (*RD,* Equation 8) values less than -5% and 32% of the RD values greater than 5%.

$$RD = \frac{Regional - AtSite}{Regional} \times 100 \qquad ...8$$

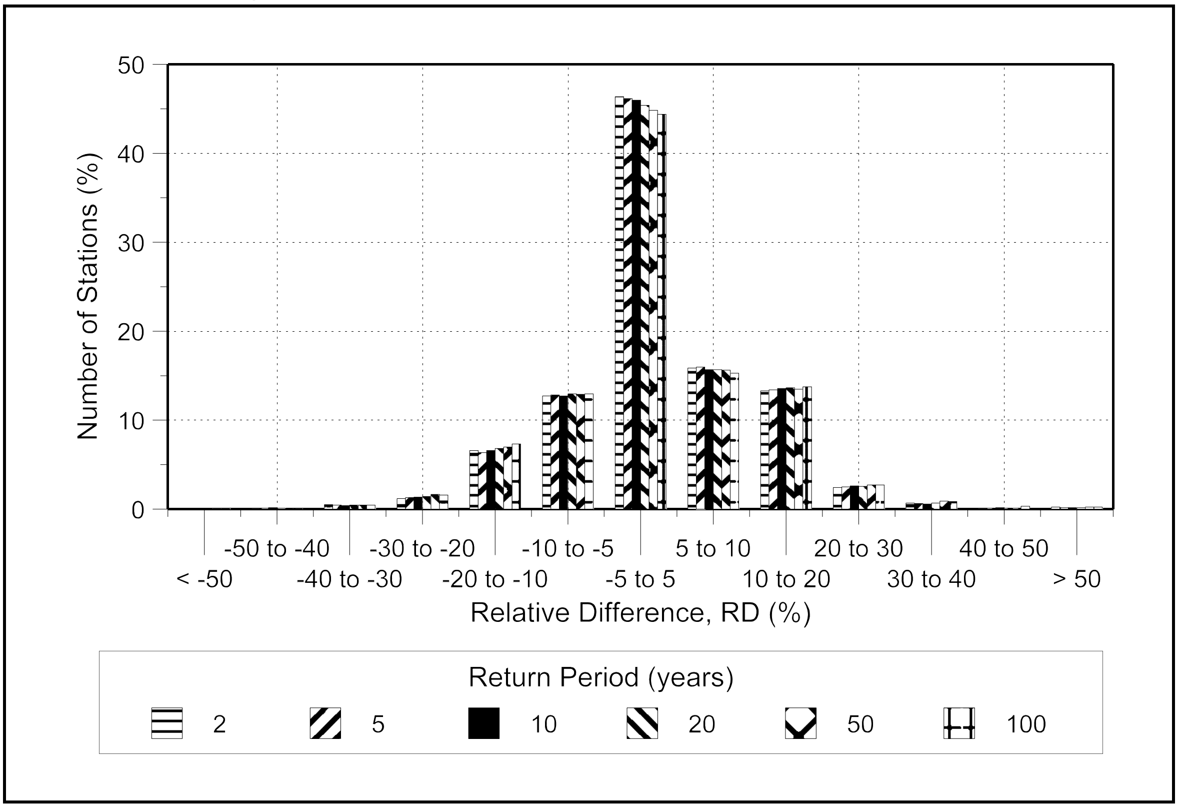


Figure 41 Relative differences in design rainfall depths computed using observed and estimated means of the 1 day AMS at 1 806 rainfall stations in South Africa which have at least 40 years of daily record

4.1.5 Corrections to estimated means of 1 day AMS using residual error surface

At each of 1 806 daily rainfall stations which have at least 40 years of record, the error (*ERR*) between the the mean of the 1 day AMS calculated from the observed data and estimated using the regionalised regression equations was computed, as shown in Equation 9.

$$ERR_i = \frac{\hat{L\_l}_{1d} - L\_l_{1d}}{L\_l_{1d}} \times 100 \qquad ...9$$

where

ERR_i = residual error (%) at station *i*,

L_l_{1d} = mean of 1 day AMS computed from observed data, and

$\hat{L\_1}_{1d}$ = mean of 1 day AMS estimated using regionalised regression equations.

An Inverse Distance Weighting technique was then employed to interpolate the irregularly spaced ERR_i values onto a rectangular 1'x1' latitude and longitude grid over South Africa. The gridded $ERR_{(i,j)}$ values were used to adjust the estimated means of the 1 day AMS at each grid point (Equation 10) and thus minimise the error between the estimated and observed means of the 1 day AMS at the 1 806 sites which have at least 40 years of record.

$$\hat{L\_1}_{adj} = \frac{\hat{L\_1}}{(1 + ERR_{(i)})} \qquad ...10$$

where

$\hat{L\_1}_{adj}$ = mean of AMS estimated using regionalised regression equations and adjusted using gridded residual error values,

$\hat{L\_1}$ = mean of AMS estimated using regionalised regression equations, and

$ERR_{(i)}$ = residual error in $\hat{L\_1}$ at station *i*.

The $\hat{L\_1}_{adj}$ values at each 1' x 1' gridded point in South Africa were then used to rescale the appropriate quantile growth curve and hence compute the design values for each gridded point. A similar approach to fitting a surface to observed point values was adopted by Dent *et al.* (1987) when mapping MAP values for South Africa.

A comparison of the errors in the estimated mean of the 1 day AMS of rainfall before and after adjustment using the residual error surface is shown in Figure 42 and errors in design rainfall using the adjusted mean of the AMS are illustrated in Figure 43. The use of the residual error surface to adjust the estimated mean of the 1 day annual maxima results in a significant decrease in the error in the estimated mean of the 1 day AMS. This results in improved estimates of design rainfall with less than 2% of the stations having relative errors greater than 20%.

A comparison between the design rainfall estimated using the adjusted mean of the 1 day AMS and the observed means at 2130 stations which have at least 20 years of record, but which were not used in the estimation of the residual error surface, is shown in Figure 44. At these sites the relative differences in design rainfalls are greater than 20% at less than 10% of the sites. However, at a number of sites, differences in excess of 40% were noted and investigated.

4.1.6 Station vs gridded 1 day design rainfall values

The residual errors in the means of the 1 day AMS from 1806 rainfall stations which have at least 40 years of record were interpolated onto a grid. As shown in the previous section, large errors were noted between the gridded and station design rainfall values at some stations which have between 20 and 40 years of record and which were not used in the generation of the gridded residual error surface. Both estimates utilised the regional growth curves with the station values re-scaled using at-site estimates of the mean of the 1 day AMS, while the gridded values were estimated using the regressions for the 7 regions as described in Section 4.1.2. A summary of the errors at the four sites which have the largest discrepancies and information from the closest surrounding stations are contained in Table 5. From these results it is evident that the mean of the AMS at the stations with the large discrepancies appear to be discordant with values computed from the data at nearby stations. Therefore, it is concluded that the gridded design rainfall depths generally provide a more consistent estimate of the true design rainfall depths.

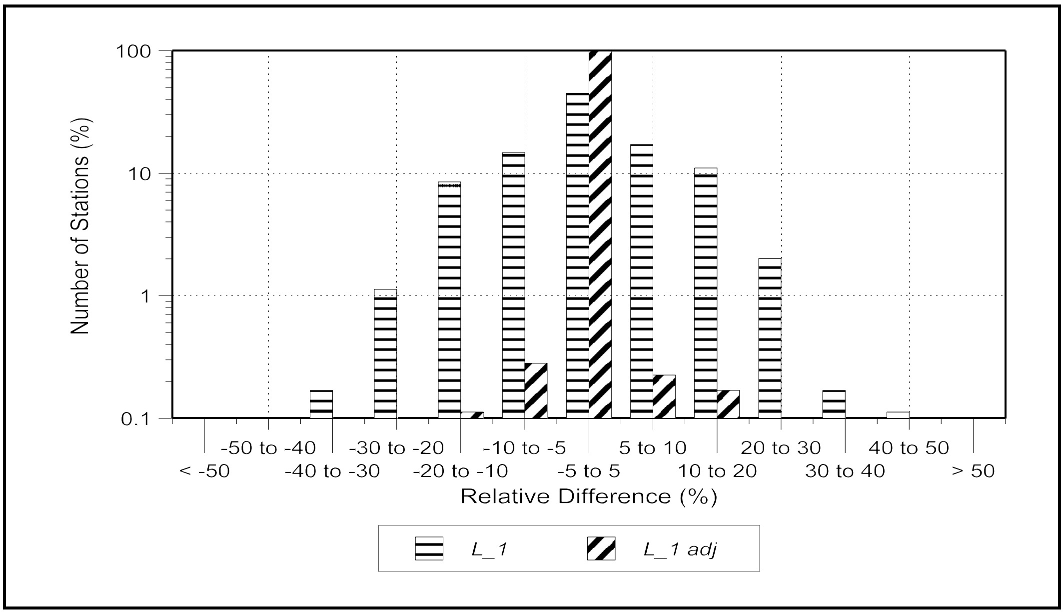


Figure 42 Relative differences in estimated means of the 1 day rainfall AMS before and after adjustment using the residual error surface

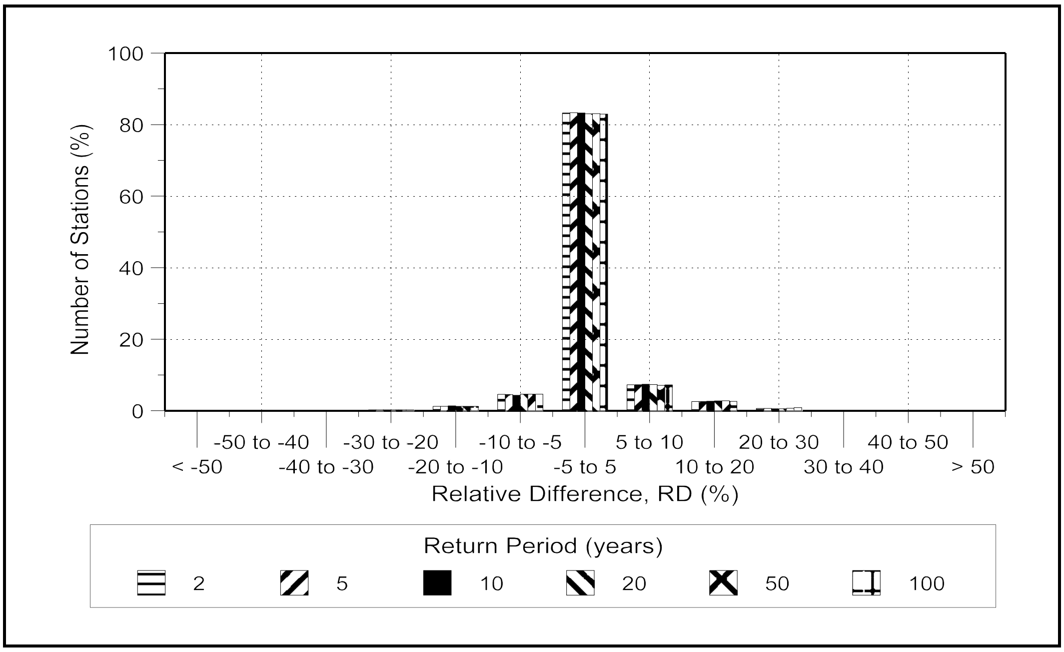


Figure 43 Relative differences in design rainfall depths computed using observed and estimated means of the 1 day AMS values, adjusted using the residual error surface, at 1 806 daily rainfall stations in South Africa which have at least 40 years of record

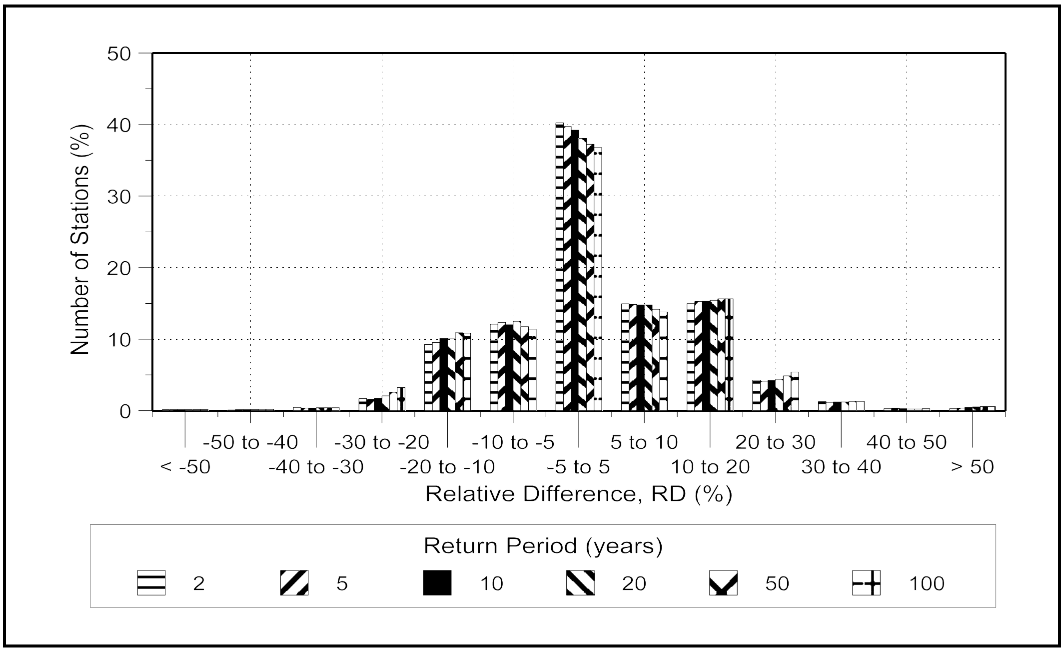


Figure 44 Relative differences in design rainfall depths computed using observed and estimated means of the 1 day AMS, adjusted using the residual error surface, at 2130 daily rainfall stations in South Africa which have at least 20 years of record and which were not used in the generation of the residual error surface

4.2 Estimation of the Mean of the AMS for 2 to 7 Day Durations

For each of the 78 clusters of relatively homogeneous extreme daily rainfall identified in South Africa, quantile growth curves which are scaled by the mean of the AMS have been developed for durations ranging from 1 to 7 days. In order to re-scale the growth curves it is necessary to estimate the mean of the *D* day AMS (L_1_D) for the required Duration (*D*). The mean of the *D* day AMS for durations > 1 day may be estimated as a function of site characteristics, as was developed for the 1 day duration. Another approach, which was adopted in this study, is to utilise the scaling characteristics of the AMS to estimate the mean of the *D* day AMS for durations greater than 1 day.

Table 5 Anomalies in the station and gridded design rainfall values at sites with large differences and information from surrounding stations

Station Number	Latitude		Longitude		Difference in 2 Year Return Period Design Rainfall Depths (%)	Mean of 1 day AMS (mm)	Record Length (Years)
	(°)	(')	(°)	(')			
0722693 A	23	3	29	54	113.9	33.2	21
0722571 W	23	1	29	50	-6.6	64.2	70
0722721 W	23	1	29	54	1	77.9	76
0722783 W	23	3	29	57	-2.7	76.6	23
0722700 W	23	10	29	54	0.9	58.7	57
0003020 W	34	50	20	0	51.2	33.2	27
0002885 W	34	45	20	0	4.7	53.1	56
0003192 W	34	43	20	6	9.6	42.8	41
0431548 W	26	38	24	19	-68.8	173.1	21
0431306 W	26	36	24	11	-21.6	61.9	21
0431465 W	26	45	24	15	7.7	49.5	25
0020719AW	33	58	18	24	-54.2	94.8	25
0020719CW	33	58	18	24	-0.2	75.7	30
0020689 W	33	58	18	23	0.3	65.2	61

4.2.1 Scaling characteristics of the AMS

As shown in Figure 45 for daily rainfall stations in various climatic regions of South Africa, a strong power law relationship exists between the mean of the *D* day AMS and duration. This relationship may be represented as

$$L\_1_D \cong D^{\gamma} \qquad ...11$$

where

L_1_D = mean of AMS for duration = *D* days, and
γ = scaling exponent.

Thus L_1_D for $D > 1$ can be estimated as

$$\log(L\_1_D) = \log(\hat{L\_1}_{1d}) + \gamma \times (\log(D) - \log(1))$$

where

$\hat{L\_1}_{1d}$ = L_1_{1d} estimated as a function of site characteristics, using regression constants from Table 4.

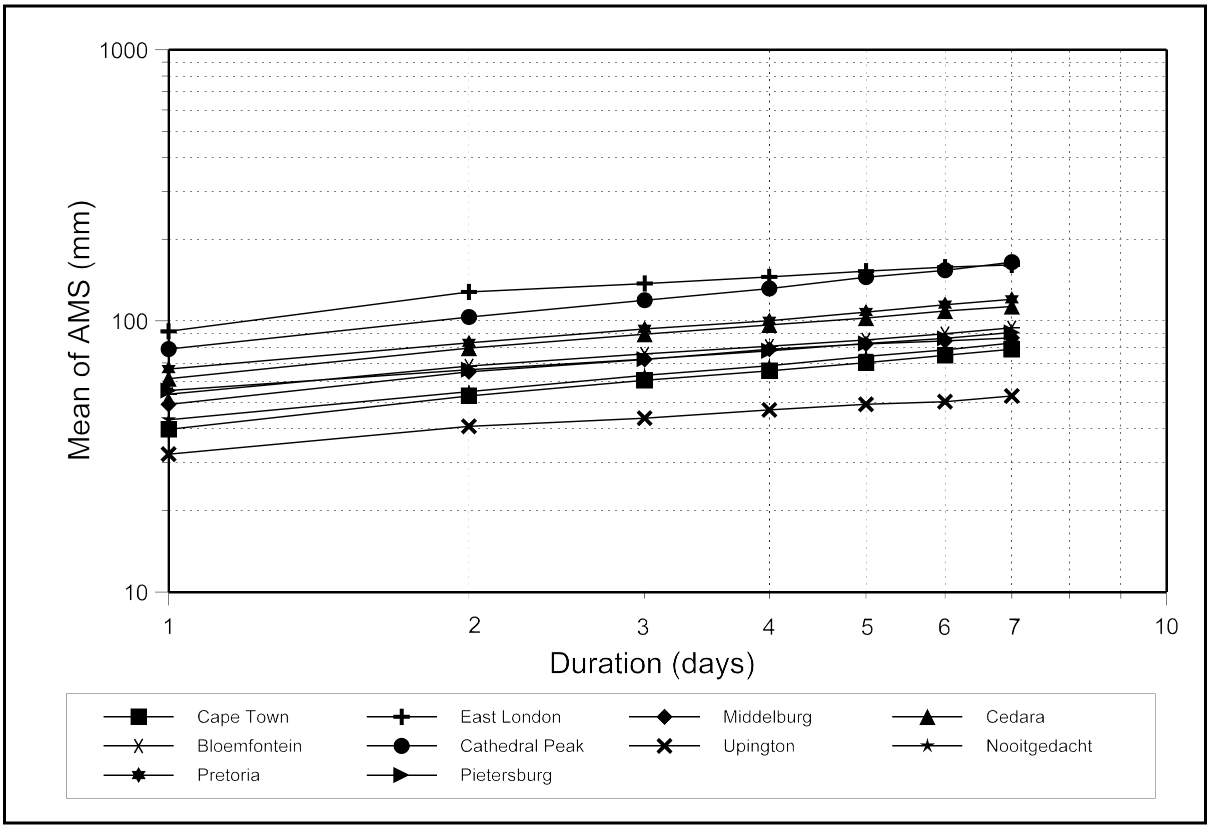


Figure 45 Mean of annual maximum series vs duration at selected raingauge sites in different climatic regions of South Africa

For each of the 7 regions used to estimate the mean of the 1 day AMS as a function of site characteristics, relationships between γ and site characteristics were developed. The same site characteristics as those used in the estimation of the mean of the 1 day AMS were selected, but the variation in γ was not well explained by the selected site characteristics, with R^2 ranging from 0.45 to a maximum of 0.67. Hence, an alternative method of estimating the mean of the AMS at ungauged sites was investigated.

4.2.2 *D* day : 1 day means of the AMS

A strong linear relationship was noted between the mean of the 1 day AMS and the mean of the AMS for durations longer than 1 day, as shown for 2 and 7 day durations in Figure 46 for stations which have at least 40 years of record. Included in Figure 46 are the fitted regressions, with regression coefficients derived on a regional basis as described below.

As evident by the linear relationships depicted in Figure 46, the mean of the AMS for durations of 2 to 7 days were estimated using Equation 12:

$$L\_1_D = \phi_D + \left(\alpha_D \times L\_1_{1\text{day}} \right) \qquad ...12$$

where

ϕ_D	=	regression constant for duration = *D* days, and
α_D	=	regression coefficient for duration = *D* days.

A power law relationship is evident between the slope (α_D) and duration for all regions, as shown in Figure 47. Now the regression constant and coefficient can be estimated from the following equations.

$$\alpha_D = \theta + \tau \times D^{\sigma} \qquad ...13$$

where

θ	=	regression constant ,
τ	=	regression coefficient, and
σ	=	transformation exponent for duration = *D* days.

The observed and fitted relationships are depicted in Figure 47.

Similarly, ϕ_D relationships of the form shown in Equation 14 were developed for each region and observed and estimated values are shown in Figure 48.

Thus, at an ungauged location the mean of the AMS for durations > 1 day can be estimated as:

$$\phi_D = \nu + \kappa \times D^{\rho} \qquad ...14$$

where

ν	=	regression constant,
κ	=	regression coefficient, and
ρ	=	transformation exponent for duration = *D* days.

Therefore, for a given duration (D), Equations 13 and 14 can be used to estimate the parameters for Equation 12 and hence L_1_D ($2 \leq D \leq 7$ days) can be estimated using Equation 12. The estimated parameters of the regression relationships, Standard Errors (SE) and coefficients of determination are summarised in Table 6.

Table 6 Regression parameters and statistics for the estimation of 2 to 7 day means of the AMS of rainfall in South Africa

Variable	Regression Statistics	Region (Number of stations)						
		1 (596)	2 (173)	3 (62)	4 (264)	5 (234)	6 (401)	7 (75)
α_D	θ	0.60	3.37	5.10	0.15	2.20	-0.02	-0.86
	τ	0.39	-2.31	-4.04	0.90	-1.16	1.02	1.87
	σ	0.68	-0.19	-0.12	0.42	-0.41	0.35	0.27
	SE(τ)	0.00	0.03	0.02	0.00	0.01	0.01	0.00
	SE(α_D)	0.01	0.00	0.00	0.00	0.00	0.01	0.00
	R^2	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ϕ_D	κ	-2.16	47.11	23.60	-11.53	0.49	-9.68	-17.78
	ν	6.09	-46.38	-22.54	11.01	-3.48	11.92	18.96
	ρ	1.21	-0.14	-0.36	0.56	1.68	0.54	0.33
	SE (κ)	0.08	1.05	0.68	0.23	0.01	0.32	0.29
	SE(ϕ)	0.57	0.13	0.16	0.28	0.19	0.37	0.15
	R^2	0.99	1.00	1.00	1.00	1.00	1.00	1.00

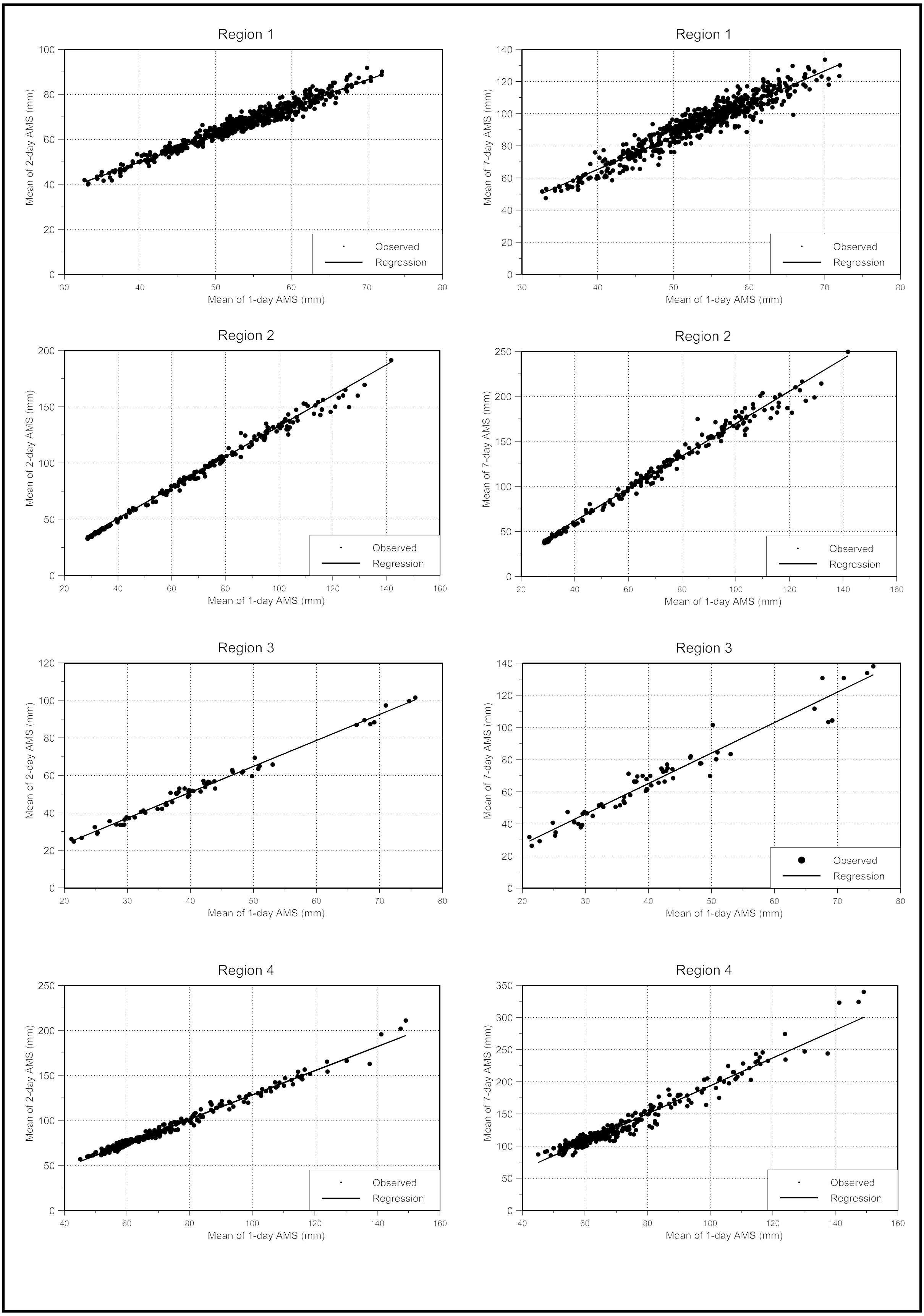


Figure 46 *D* day (2 and 7) vs 1 day means of the AMS at rainfall stations in South Africa which have at least 40 years of daily record

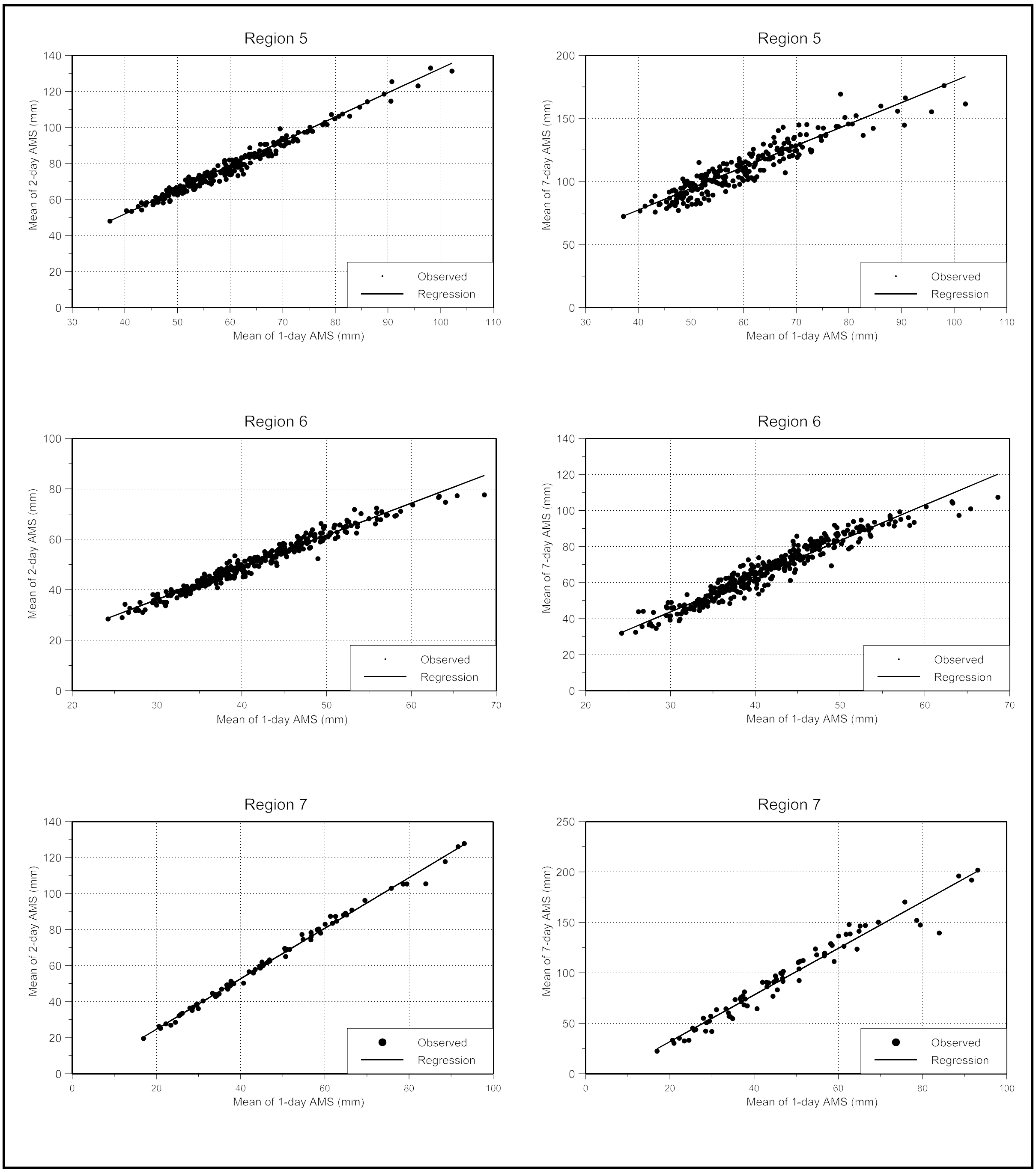


Figure 46 (continued) *D* day (2 and 7) vs 1 day means of the AMS at rainfall stations in South Africa which have at least 40 years of daily record

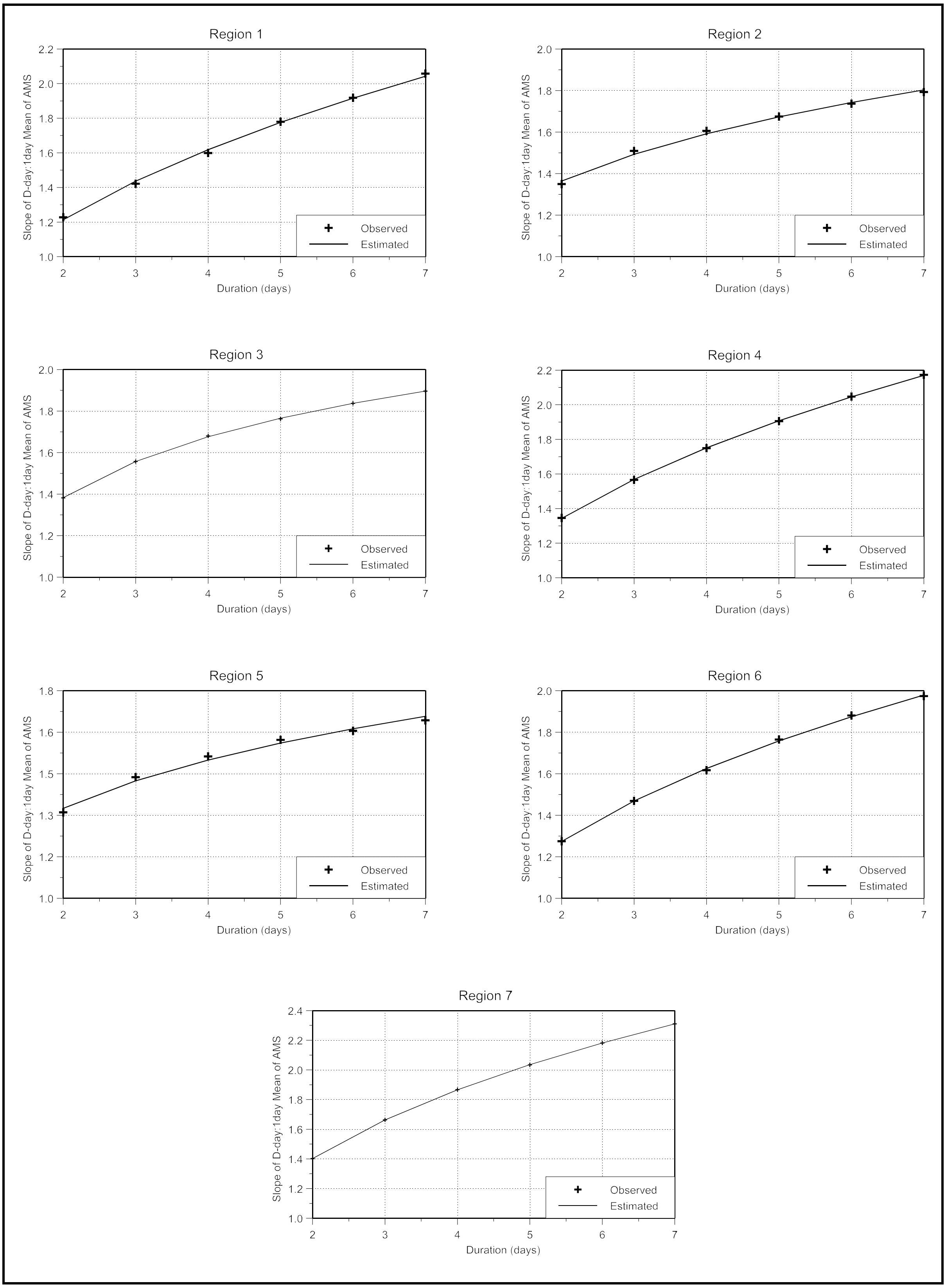


Figure 47 Observed and estimated slopes (α) of D day to 1 day mean of AMS

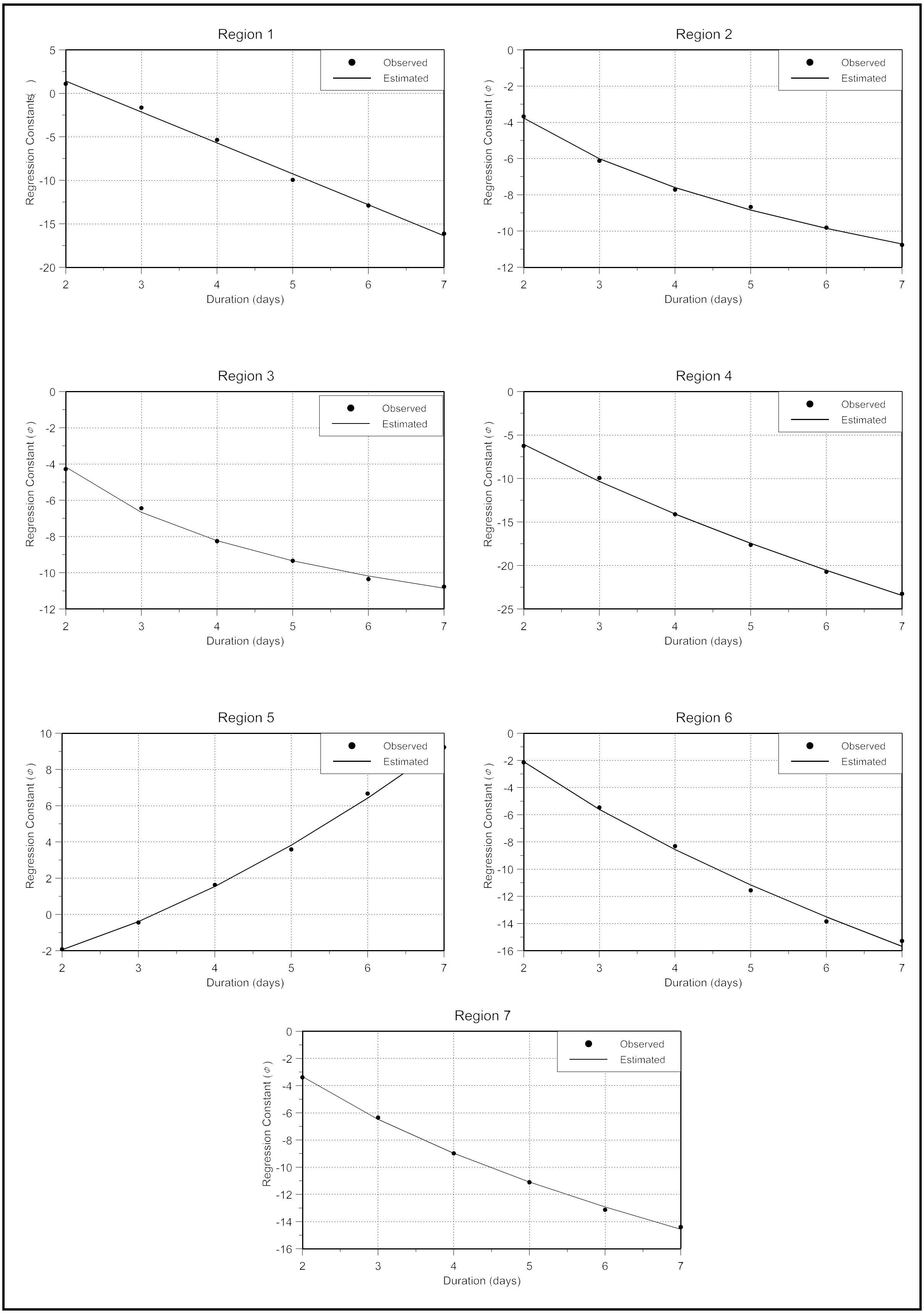


Figure 48 Observed and estimated regression constants (ϕ) for six regions in South Africa

4.3 Estimation of the Mean of AMS for Durations < 24 h

Smithers and Schulze (2000a) developed regional regression relationships to estimate the mean of the 24 h AMS as a function of site characteristics (latitude, longitude, altitude, MAP, rainfall seasonality, an index of rainfall concentration based on monthly rainfall and distance from sea). The results using this approach were satisfactory in 13 of the 15 clusters. Some of the problems with this approach were the limited number of stations in some clusters, and hence insufficient degrees of freedom, inter-dependence between the site characteristics and poor relationships in certain clusters, notably in Clusters 10 and 11.

Smithers and Schulze (2001b) presented the results of using a simpler approach to estimate the mean of the AMS. As shown in Figure 49, there is a relatively strong relationship between the mean of the 24 h AMS and MAP. It was noted that the relationship between the median of the 24 h AMS and MAP was slightly weaker than the relationship between the mean of the 24 h AMS and MAP. Therefore the mean, as implemented in the RLMA, was used as the index storm. Some deviations to the general trend are noted in Figure 49, with some anomalies in Cluster 7 and particularly in Cluster 8, both of which are located on the coastal belt of KwaZulu-Natal, and at Newlands (Cape Town) in Cluster 6. Using data from all the 172 stations, Equation 15 ($R^2 = 0.70$) was developed to estimate the mean of the 24 h AMS in South Africa. Probable explanations of the anomalies in Figure 49 were attributed by Smithers and Schulze (2001b) to inconsistencies in the MAP values used and different meteorological conditions which occur on the East coast of South Africa.

$$L\_I_{24} = 16.28 + 0.063 \times \text{MAP} \qquad ...15$$

where

L_I_{24} = Mean of 24 h AMS (mm), and

MAP = Mean Annual Precipitation (mm).

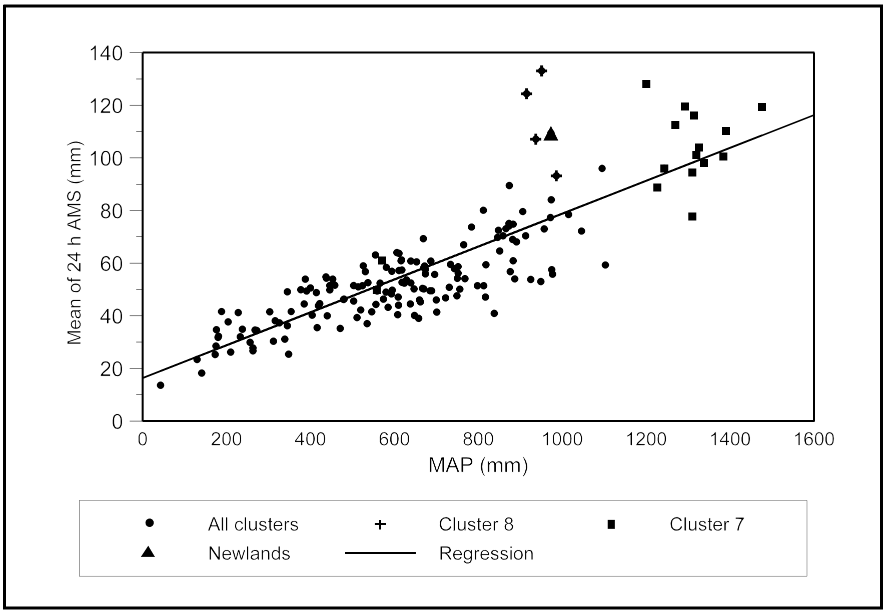


Figure 49 Mean of 24 h AMS vs MAP using data from 172 stations which have digitised rainfall data

In this study, the relationship between the *D* h and 24 h mean of the AMS was investigated to improve the estimates of the mean of the AMS for durations shorter than 24 h.

4.3.1 *D* hour : 24 hour relationships

The relationship between the *D* h and 24 h mean of AMS in the 15 short duration rainfall clusters are shown in Figure 50. As evident from Figure 50 there are strong relationships between the *D* h and 24 h mean of the AMS for durations ranging to as short as 5 minutes. These relationships were found to apply in all 15 clusters. The regression coefficients for the relationship shown in Equation 16 are contained in Table 7 for all 15 short duration clusters.

$$L\_1_D = Const + Xcoeff \times L\_1_{24} \qquad ...16$$

where

L_1_D = mean of D h AMS.

Table 7 Regression parameters and statistics for 15 clusters to estimate the mean of the AMS for durations < 24 h as a function of the 24 h value

Cluster	Duration (min)	R^2	*Xcoeff*	*Const*	SE(*Xcoeff*)	SE(*Const*)	Cluster	Duration (min)	R^2	*Xcoeff*	*Const*	SE(*Xcoeff*)	SE(*Const*)
1	5	0.57	0.0923	3.8797	0.0319	1.7000	2	5	0	-0.0150	10.5849	0.0344	2.3003
1	10	0.61	0.1463	5.0415	0.0458	2.4461	2	10	0.08	0.0139	13.8042	0.0587	3.9272
1	15	0.63	0.1764	7.0258	0.0527	2.8113	2	15	0.21	0.0391	16.0588	0.0632	4.2304
1	30	0.51	0.1718	14.1536	0.0706	3.7642	2	30	0.16	0.0462	24.3809	0.1014	6.7853
1	45	0.47	0.1862	16.9113	0.0840	4.4841	2	45	0.29	0.0923	25.7435	0.1073	7.1810
1	60	0.57	0.2330	16.4947	0.0823	4.3904	2	60	0.55	0.1974	21.8449	0.1074	7.1828
1	90	0.62	0.2908	15.9214	0.0901	4.8087	2	90	0.74	0.3229	17.3012	0.1046	6.9961
1	120	0.68	0.3604	14.0952	0.0950	5.0697	2	120	0.82	0.4249	13.5000	0.1046	6.9965
1	240	0.83	0.5041	11.7955	0.0808	4.3109	2	240	0.94	0.6272	7.0738	0.0773	5.1737
1	360	0.89	0.5769	10.9397	0.0721	3.8447	2	360	0.96	0.7310	3.9253	0.0744	4.9746
1	480	0.92	0.6441	9.6918	0.0675	3.6020	2	480	0.98	0.8503	-0.3842	0.0650	4.3470
1	600	0.94	0.7130	7.5810	0.0615	3.2828	2	600	0.98	0.8495	1.3596	0.0605	4.0499
1	720	0.95	0.7553	6.4667	0.0573	3.0567	2	720	0.98	0.8821	0.7691	0.0591	3.9559
1	960	0.98	0.8468	3.9779	0.0462	2.4632	2	960	1.00	0.9205	0.5318	0.0243	1.6234
1	1200	0.99	0.9464	0.7498	0.0346	1.8447	2	1200	1.00	0.9678	-0.3519	0.0239	1.6007
3	5	0.6	0.1483	2.3719	0.0362	2.3449	4	5	0.91	0.1143	2.5965	0.0259	0.8677
3	10	0.46	0.1267	8.2786	0.0444	2.8734	4	10	0.84	0.2097	2.4553	0.0674	2.2606
3	15	0.37	0.1041	13.3526	0.0473	3.0627	4	15	0.78	0.2584	3.1253	0.1036	3.4745
3	30	0.23	0.0793	22.0109	0.0623	4.0314	4	30	0.73	0.3403	4.2770	0.1608	5.3924
3	45	0.42	0.1645	20.5722	0.0656	4.2451	4	45	0.73	0.4054	4.0300	0.1910	6.4076
3	60	0.57	0.2532	17.4304	0.0668	4.3215	4	60	0.74	0.4470	4.0338	0.2058	6.9024
3	90	0.67	0.3478	14.5765	0.0700	4.5349	4	90	0.79	0.4966	3.7201	0.1936	6.4948
3	120	0.71	0.3860	14.1375	0.0707	4.5781	4	120	0.86	0.5501	2.8506	0.1668	5.5931
3	240	0.79	0.4859	12.9281	0.0697	4.5106	4	240	0.92	0.5875	4.2623	0.1262	4.2337
3	360	0.87	0.5578	11.4020	0.0567	3.6711	4	360	0.93	0.6640	3.3691	0.1336	4.4814
3	480	0.92	0.6152	9.8269	0.0474	3.0693	4	480	0.93	0.7214	2.7333	0.1401	4.6984
3	600	0.95	0.6513	9.4183	0.0376	2.4374	4	600	0.94	0.7725	2.2127	0.1375	4.6125

Cluster	Duration (min)	R^2	*Xcoeff*	*Const*	SE(*Xcoeff*)	SE(*Const*)	Cluster	Duration (min)	R^2	*Xcoeff*	*Const*	SE(*Xcoeff*)	SE(*Const*)
3	720	0.97	0.6901	8.5148	0.0308	1.9918	4	720	0.96	0.8188	1.6941	0.1134	3.8035
3	960	0.98	0.7794	5.6472	0.0267	1.7271	4	960	0.99	0.9299	-0.4875	0.0736	2.4688
3	1200	0.99	0.8865	2.4208	0.0237	1.5336	4	1200	1.00	0.9300	0.9739	0.0332	1.1130
5	5	0	0.0024	8.7465	0.0345	1.8099	6	5	0.88	0.0396	3.3994	0.0074	0.4293
5	10	0.24	0.0254	11.5868	0.0420	2.2014	6	10	0.87	0.0422	5.4591	0.0085	0.4952
5	15	0.60	0.0869	11.9385	0.0479	2.5120	6	15	0.88	0.0472	6.7972	0.0090	0.5219
5	30	0.77	0.2075	12.8711	0.0712	3.7356	6	30	0.89	0.0749	8.6806	0.0136	0.7896
5	45	0.85	0.2973	12.4460	0.0743	3.8935	6	45	0.92	0.1076	9.2315	0.0166	0.9646
5	60	0.84	0.3845	10.6553	0.0996	5.2211	6	60	0.93	0.1321	9.7558	0.0190	1.1032
5	90	0.77	0.4204	12.4383	0.1406	7.3711	6	90	0.93	0.1896	9.8328	0.0260	1.5040
5	120	0.75	0.4507	13.0382	0.1622	8.5056	6	120	0.94	0.2401	9.6347	0.0305	1.7700
5	240	0.85	0.6587	6.9769	0.1698	8.9053	6	240	0.98	0.3832	8.8665	0.0287	1.6602
5	360	0.89	0.7597	4.0615	0.1574	8.2515	6	360	0.99	0.5093	7.0885	0.0268	1.5544
5	480	0.92	0.8613	0.4021	0.1535	8.0462	6	480	0.99	0.5807	6.5744	0.0209	1.2105
5	600	0.94	0.9577	-3.3262	0.1426	7.4772	6	600	1.00	0.6495	5.4221	0.0162	0.9376
5	720	0.96	0.9687	-2.7026	0.1194	6.2607	6	720	1.00	0.7152	4.3546	0.0144	0.8322
5	960	0.97	0.9737	-1.3786	0.0927	4.8596	6	960	1.00	0.8340	2.1099	0.0076	0.4375
5	1200	0.99	1.0094	-1.9000	0.0415	2.1770	6	1200	1.00	0.9219	0.7993	0.0083	0.4794
7	5	0.38	0.0519	6.3133	0.0348	3.6817	8	5	0.93	0.0517	4.5662	0.0146	1.7014
7	10	0.38	0.0565	10.0239	0.0379	4.0072	8	10	0.97	0.0834	6.9401	0.0143	1.6691
7	15	0.42	0.0681	12.5861	0.0407	4.3065	8	15	0.98	0.1169	7.7585	0.0155	1.8163
7	30	0.44	0.0821	19.0440	0.0469	4.9641	8	30	0.93	0.1326	15.0990	0.0376	4.3907
7	45	0.48	0.1037	22.0067	0.0525	5.5505	8	45	0.86	0.1224	21.9088	0.0514	5.9994
7	60	0.47	0.1109	25.1194	0.0585	6.1828	8	60	0.92	0.1547	22.9352	0.0476	5.5650
7	90	0.54	0.1521	26.7598	0.0654	6.9204	8	90	0.93	0.2163	22.4071	0.0581	6.7817
7	120	0.65	0.2024	26.4768	0.0653	6.9053	8	120	0.98	0.2593	22.9463	0.0354	4.1342
7	240	0.87	0.3626	22.0900	0.0570	6.0268	8	240	0.98	0.3449	26.5535	0.0500	5.8411
7	360	0.94	0.5117	15.8893	0.0504	5.3310	8	360	0.97	0.4139	27.5278	0.0779	9.1020
7	480	0.95	0.6301	9.8498	0.0551	5.8321	8	480	0.99	0.4899	25.3092	0.0557	6.5019
7	600	0.97	0.7139	7.0232	0.0502	5.3072	8	600	0.97	0.5535	24.6865	0.0985	11.5071
7	720	0.98	0.7672	6.1739	0.0436	4.6158	8	720	0.98	0.6103	23.8021	0.0906	10.5827
7	960	0.99	0.8655	3.7845	0.0301	3.1845	8	960	0.99	0.8220	7.9328	0.0657	7.6751
7	1200	1.00	0.9348	1.5801	0.0178	1.8832	8	1200	1.00	0.9665	-1.6203	0.0544	6.3494
9	5	0	-0.0072	5.9777	0.0173	0.9419	10	5	0.18	0.0084	6.1800	0.0211	0.8067
9	10	0.08	0.0045	7.5117	0.0239	1.3018	10	10	0.08	0.0068	9.1578	0.0391	1.4991
9	15	0.22	0.0159	8.6239	0.0288	1.5665	10	15	0	-0.0069	11.8186	0.0546	2.0903
9	30	0.21	0.0241	11.7661	0.0449	2.4455	10	30	0.16	0.0273	14.2721	0.0745	2.8550
9	45	0.33	0.0488	12.7010	0.0575	3.1301	10	45	0.36	0.0595	14.7732	0.0687	2.6325
9	60	0.54	0.0941	12.0246	0.0597	3.2550	10	60	0.57	0.0950	14.6028	0.0613	2.3497
9	90	0.70	0.1445	12.0904	0.0606	3.3015	10	90	0.88	0.1445	14.4951	0.0344	1.3169
9	120	0.85	0.1968	12.1137	0.0498	2.7145	10	120	0.91	0.1927	14.0599	0.0382	1.4624
9	240	0.99	0.3867	9.5118	0.0249	1.3577	10	240	0.97	0.3616	10.8995	0.0422	1.6157

Cluster	Duration (min)	R^2	*Xcoeff*	*Const*	SE(*Xcoeff*)	SE(*Const*)	Cluster	Duration (min)	R^2	*Xcoeff*	*Const*	SE(*Xcoeff*)	SE(*Const*)
9	360	0.99	0.5117	7.9027	0.0340	1.8547	10	360	0.99	0.4650	9.3312	0.0353	1.3537
9	480	0.99	0.6023	6.6963	0.0337	1.8340	10	480	0.97	0.5456	7.9258	0.0636	2.4340
9	600	1.00	0.6942	4.7192	0.0249	1.3544	10	600	0.96	0.6514	5.3833	0.0844	3.2324
9	720	1.00	0.7520	3.8480	0.0188	1.0218	10	720	0.97	0.7107	4.9766	0.0734	2.8093
9	960	1.00	0.8479	2.7507	0.0204	1.1129	10	960	0.98	0.8068	3.4508	0.0760	2.9112
9	1200	1.00	0.9280	1.3828	0.0122	0.6621	10	1200	1.00	0.9473	0.0995	0.0398	1.5235
11	5	0.46	0.0669	5.0539	0.0301	1.6037	12	5	0.79	0.1295	1.9085	0.0357	1.5719
11	10	0.51	0.1200	6.3158	0.0482	2.5657	12	10	0.81	0.1611	3.7402	0.0415	1.8306
11	15	0.31	0.0855	11.3601	0.0608	3.2362	12	15	0.81	0.1940	4.8688	0.0492	2.1700
11	30	0.22	0.0811	17.4901	0.0865	4.6055	12	30	0.86	0.2707	5.7881	0.0580	2.5573
11	45	0.27	0.1226	18.5496	0.1011	5.3823	12	45	0.86	0.3439	4.6457	0.0711	3.1322
11	60	0.31	0.1424	19.6956	0.1029	5.4785	12	60	0.88	0.3992	3.6599	0.0746	3.2885
11	90	0.44	0.2301	17.6776	0.1094	5.8236	12	90	0.89	0.4440	3.5675	0.0802	3.5332
11	120	0.54	0.2719	17.5168	0.1007	5.3630	12	120	0.90	0.4707	4.0248	0.0783	3.4485
11	240	0.68	0.4109	14.9130	0.1046	5.5678	12	240	0.90	0.5777	3.7441	0.0980	4.3168
11	360	0.77	0.4967	13.2305	0.0976	5.1964	12	360	0.89	0.6113	5.1719	0.1090	4.8041
11	480	0.83	0.6113	9.3418	0.0962	5.1247	12	480	0.91	0.7178	2.5954	0.1179	5.1978
11	600	0.89	0.6829	7.5003	0.0822	4.3755	12	600	0.92	0.7383	3.1730	0.1074	4.7338
11	720	0.93	0.7676	4.6418	0.0712	3.7914	12	720	0.95	0.7625	3.5743	0.0859	3.7856
11	960	0.97	0.8707	1.9546	0.0523	2.7866	12	960	0.97	0.8091	3.9721	0.0676	2.9772
11	1200	0.99	0.9697	-0.7085	0.0376	2.0019	12	1200	0.99	0.8781	3.0684	0.0356	1.5702
13	5	0.17	-0.0226	9.1244	0.0222	1.2674	14	5	0.35	0.0483	5.6177	0.0574	2.7875
13	10	0	-0.0037	11.6905	0.0217	1.2370	14	10	0.50	0.0894	7.1337	0.0689	3.3480
13	15	0	-0.0054	14.8076	0.0262	1.4944	14	15	0.47	0.1095	9.4261	0.0928	4.5099
13	30	0.22	0.0169	18.4250	0.0332	1.8914	14	30	0.67	0.2516	7.8713	0.1235	5.9980
13	45	0.55	0.0552	18.6612	0.0371	2.1137	14	45	0.80	0.3765	4.5577	0.1279	6.2147
13	60	0.78	0.0919	18.2126	0.0327	1.8656	14	60	0.83	0.4444	2.8843	0.1322	6.4224
13	90	0.93	0.1582	16.6326	0.0282	1.6061	14	90	0.92	0.5433	0.6221	0.1044	5.0742
13	120	0.98	0.2257	14.7643	0.0222	1.2622	14	120	0.96	0.5944	0.0660	0.0804	3.9042
13	240	0.99	0.3930	11.1940	0.0232	1.3198	14	240	0.98	0.7330	-1.6145	0.0644	3.1301
13	360	1.00	0.5268	8.0679	0.0221	1.2612	14	360	0.99	0.8171	-2.7460	0.0408	1.9824
13	480	1.00	0.6180	5.9437	0.0227	1.2934	14	480	0.99	0.8654	-2.8754	0.0402	1.9553
13	600	1.00	0.7121	3.1372	0.0259	1.4746	14	600	1.00	0.9558	-5.5491	0.0402	1.9538
13	720	1.00	0.7772	1.8094	0.0234	1.3318	14	720	0.99	0.9367	-3.3439	0.0430	2.0874
13	960	1.00	0.8753	0.0716	0.0164	0.9356	14	960	0.98	0.9003	0.6960	0.0782	3.7985
13	1200	1.00	0.9626	-0.9622	0.0192	1.0968	14	1200	0.99	0.9970	-2.1296	0.0592	2.8747
15	5	0.98	0.1634	-0.2312	0.0155	0.3948	15	240	0.98	0.7110	-1.2663	0.0622	1.5859
15	10	0.98	0.2447	-0.6720	0.0223	0.5682	15	360	0.99	0.7895	-1.4310	0.0557	1.4219
15	15	0.97	0.3055	-0.9936	0.0319	0.8129	15	480	0.99	0.8236	-1.0729	0.0464	1.1824
15	30	0.96	0.4126	-1.4910	0.0523	1.3334	15	600	0.99	0.8529	-0.8552	0.0453	1.1566
15	45	0.97	0.4872	-1.9825	0.0544	1.3871	15	720	1.00	0.8906	-0.8888	0.0338	0.8634
15	60	0.98	0.5158	-1.7239	0.0512	1.3066	15	960	1.00	0.9153	-0.0197	0.0256	0.6522
15	90	0.97	0.5851	-1.8885	0.0626	1.5970	15	1200	1.00	0.9532	0.3203	0.0144	0.3675
15	120	0.97	0.6286	-1.8933	0.0702	1.7896							

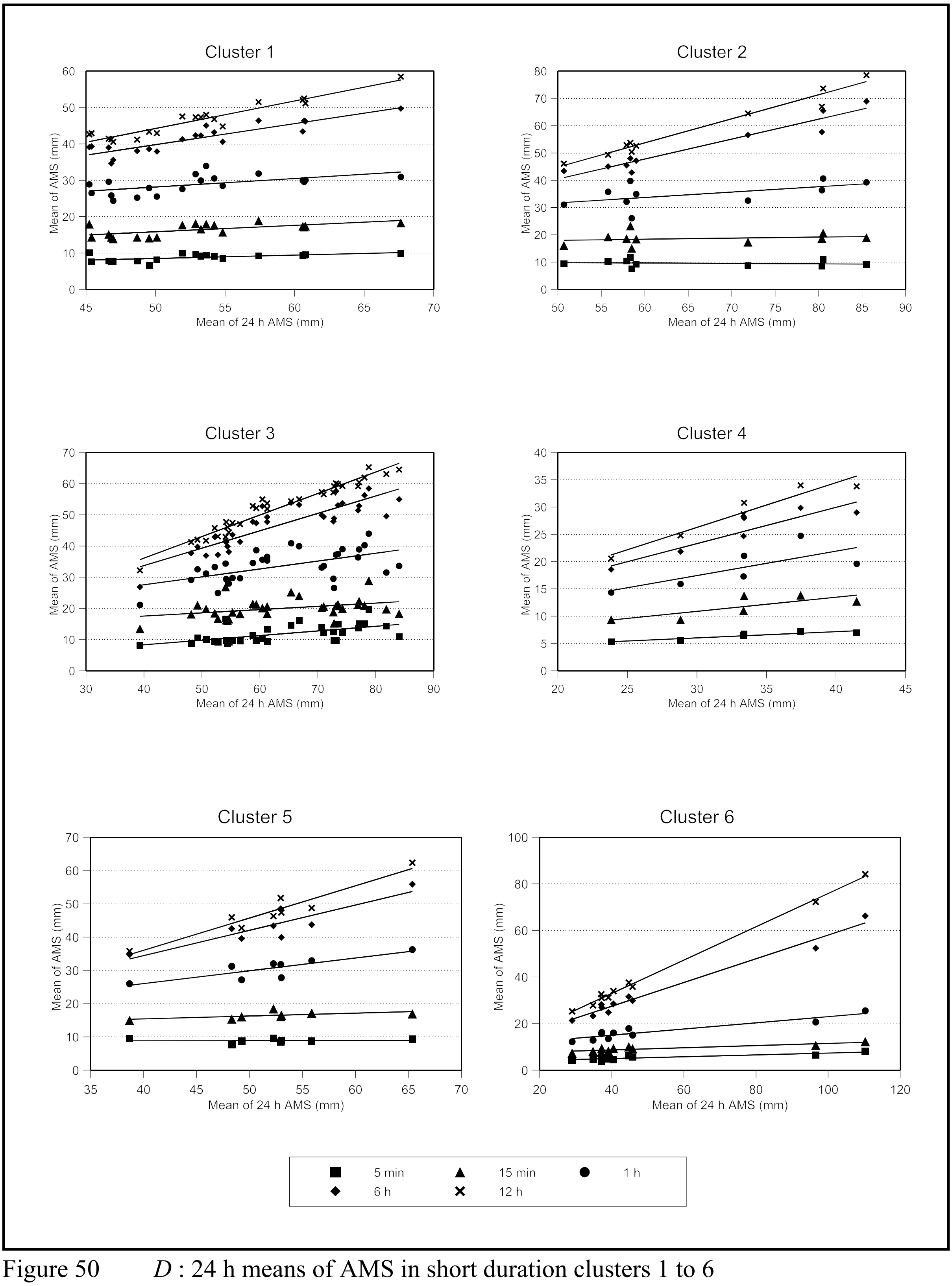


Figure 50 *D* : 24 h means of AMS in short duration clusters 1 to 6

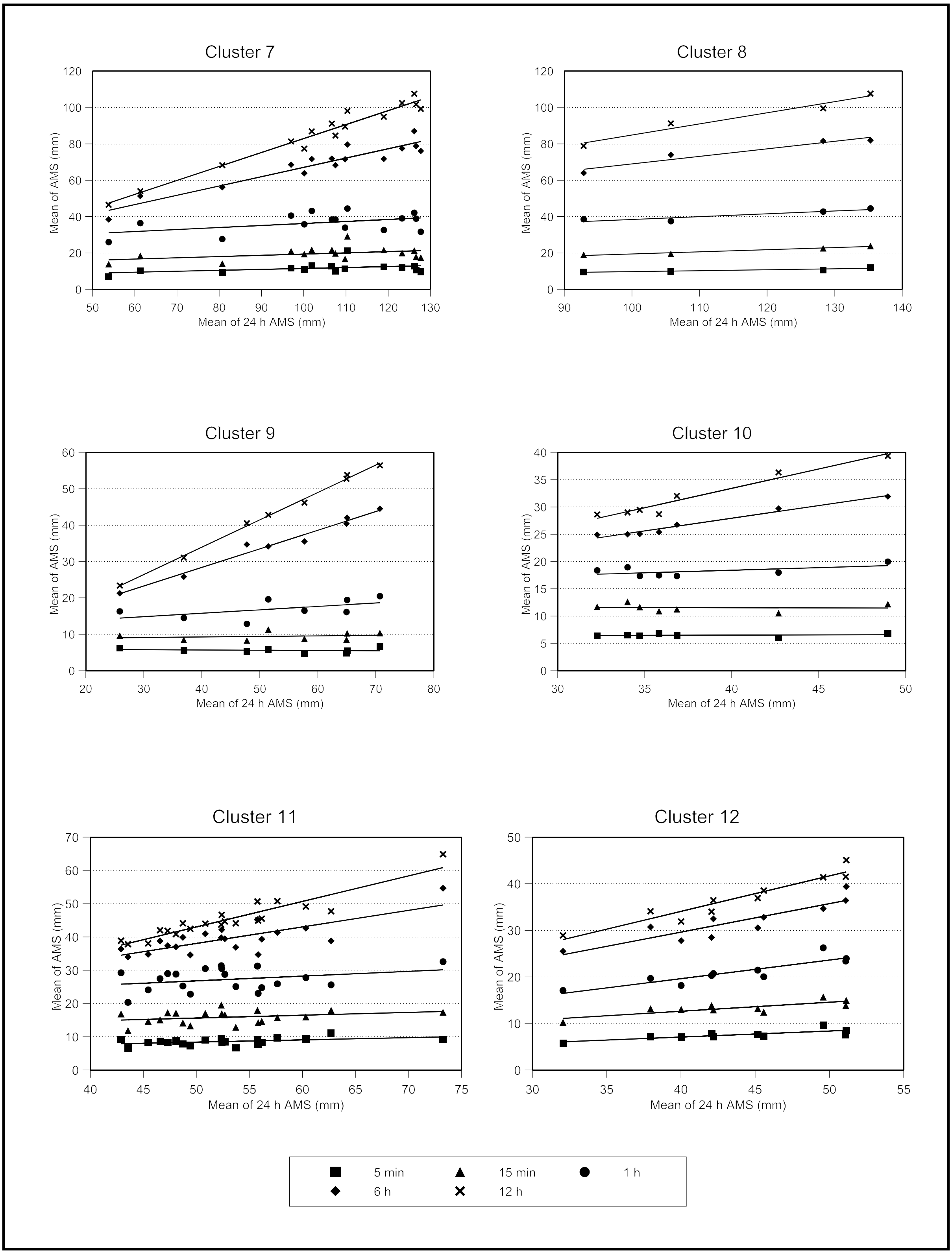


Figure 50 (continued) *D* : 24 h means of AMS in short duration clusters 7 to 12

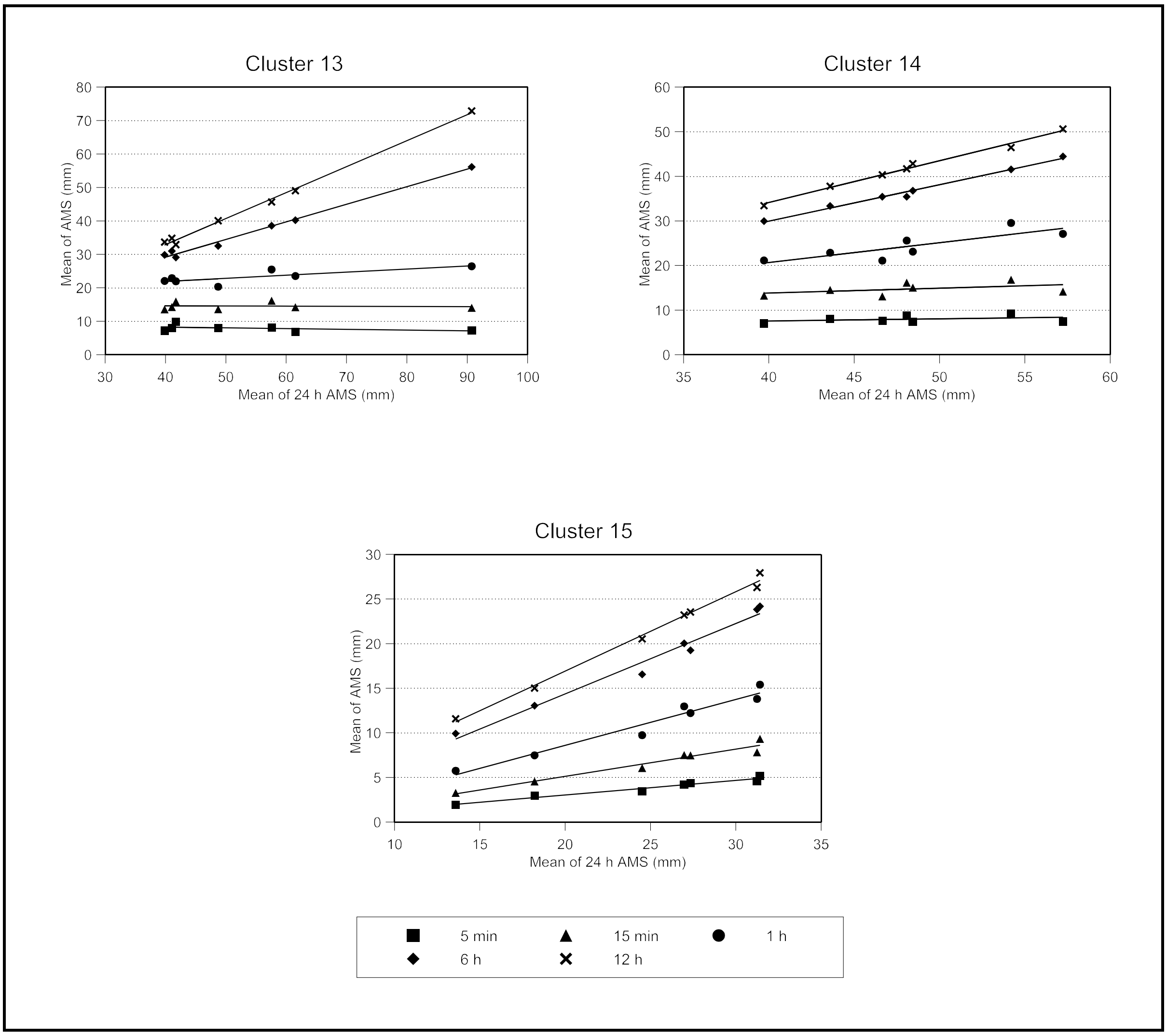


Figure 50 (continued) *D* : 24 h means of AMS in short duration clusters 13 to 15

Equation 16 was utilised to estimate the mean of the AMS for durations ranging from 5 minutes to 12 h. A comparison, reported in Section 4.3.3, was performed between the mean of the AMS estimated using this approach and that used by Smithers and Schulze (2000a). The estimation of the mean of the 24 h AMS from the 1 day value is discussed in the following section.

4.3.2 Converting the mean of the 1 day AMS into 24 hour values

Using data from the 172 stations which comprise the 15 short duration clusters, Smithers and Schulze (2000a) sampled the data using a sliding 24 h window, to extract the true maximum, and a fixed 24 h window, as would be derived from daily rainfall data, and computed the mean ratio for each cluster of the 24 h : 1 day values. This study also computed the median ratio for each cluster and the results are included in Table 8. Thus, the median ratios from Table 8 are used to convert the estimated mean of the 1 day AMS into a 24 h value, as would be derived from continuously recorded rainfall data.

Table 8 Ratios of 24 h : 1 day means of AMS

Cluster	Average	Median	Std Error	Cluster	Average	Median	Std Error
1	1.20	1.20	0.049	9	1.26	1.27	0.111
2	1.21	1.21	0.063	10	1.19	1.18	0.090
3	1.19	1.18	0.072	11	1.20	1.15	0.087
4	1.21	1.22	0.090	12	1.19	1.18	0.044
5	1.20	1.17	0.097	13	1.28	1.30	0.139
6	1.17	1.16	0.055	14	1.24	1.24	0.056
7	1.15	1.14	0.051	15	1.25	1.26	0.096
8	1.20	1.20	0.032				

4.3.3 Comparison of techniques for estimating short duration mean of AMS

As detailed in Section 4.3.1, this study has developed relationships to estimate the mean of the AMS for durations shorter than 24 h as a function of the 24 h value. Smithers and Schulze (2000a) developed regional regressions to estimate the slope between the mean of the AMS and duration as a function of site characteristics. For both techniques which were developed for estimating the mean of the AMS for durations shorter than 24 h, the errors between the estimated values, expressed as a percentage of the mean of the AMS calculated from the observed data, were computed and the results are summarised in Figure 51. As evident in Figure 51, there is little difference in the performance of the two techniques for longer durations. However, for shorter durations, the mean of the AMS is generally estimated better in all 15 clusters using the *D*:24 h regression relationships developed in this study and detailed in Table 7.

The digitised rainfall database was shown by Smithers and Schulze (2000a) to contain many inconsistencies, particularly in the case of SAWB stations, and hence they computed regional sliding to fixed scale ratios to account for the differences in the 24 h extreme values extracted from the digitised and daily rainfall databases. These ratios were then used to adjust the 1 day AMS into 24 h values and Smithers and Schulze (2000a) recommend that the mean of the AMS for durations < 24 h should be estimated from the adjusted 1 day values using the scaling characteristics of extreme rainfall. Thus, for durations < 24 h, the mean of the AMS can be estimated using Equation 16 and the mean of the 24 h AMS computed from the 1 day value. The following section details the procedure for estimating confidence intervals for the estimated means of the AMS.

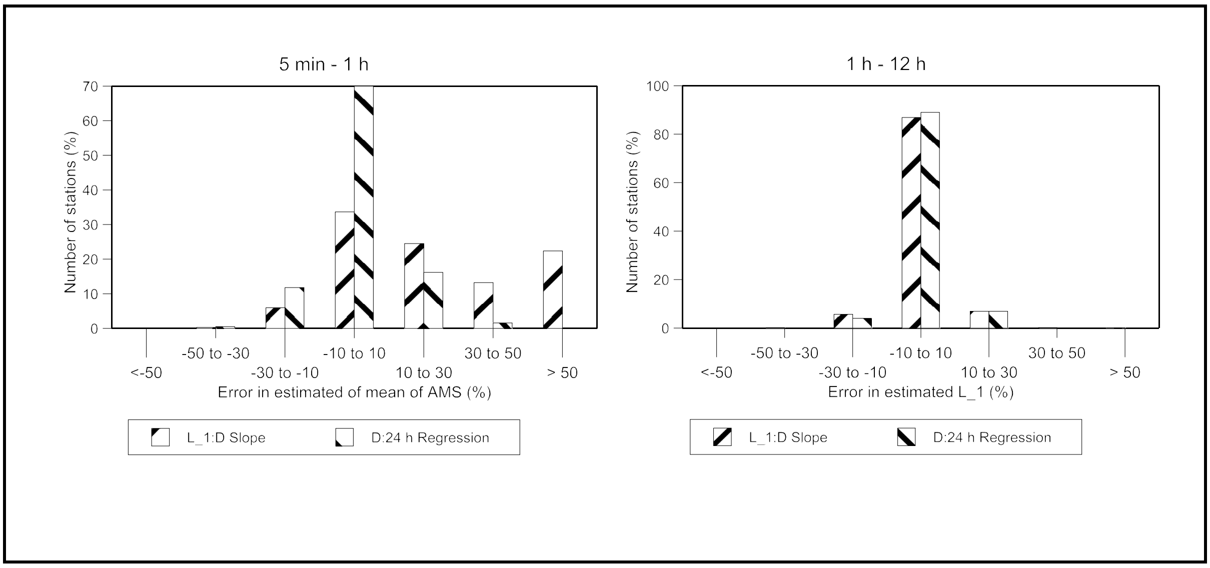


Figure 51 Comparison of techniques for estimating the mean of the AMS for durations shorter than 24 h. "L_1 : D Slope" is the technique used by Smithers and Schulze (2000a) and "D : 24 h Regression" is the technique developed in this study

4.4 Estimation of Prediction Intervals for the Mean of the AMS

Equation 7 (page 54), which incorporates both parameter uncertainty and unexplained variability of the dependent variables, was used in conjunction with the relevant regression equation for the different clusters and durations to estimate the 90% prediction interval for each estimate of the mean of the AMS. This was performed using SAS (1989) software for all durations considered, which range from 5 minutes to 7 days, and at a 1'x1' latitude/longitude grid resolution in South Africa. As evident in Equation 7, the prediction interval is symmetrical about the mean and the prediction interval was therefore expressed as a percentage of the mean. Thus, at any location in South Africa, and for all durations considered, the percentage value can be applied to the estimated mean of the AMS to compute 90% prediction intervals for the mean. The application of this procedure is detailed in Chapter 5.

4.5 Chapter Conclusions

It was necessary to develop regional relationships to estimate the mean of the 1 day AMS. A cluster analysis of the average site characteristics was performed to identify 6 regions, one of which was subsequently further sub-divided to result in a total of 7 regions. The independent variables used in the multiple linear regression are MAP, latitude and altitude. These relationships enable the mean of the 1 day AMS to be estimated at any location in South Africa. Gridded residual errors at stations which had at least 40 years of data were used to correct the estimated values at these sites and ensure that the estimated value were the same as the observed values at these sites. This approach was shown to result in reliable and consist estimates of the 1 day AMS.

For durations longer than 1 day, the mean of the *D* day ($2 \leq D \leq 7$) duration AMS were noted to scale linearly as a function of the 1 day values. The parameters of the regression were found to scale (power law) with duration, and three parameters were derived to describe the relationship between both the constant and X-coefficient with duration. Thus, 6 parameters were derived for each of the 7 regions and which enable the estimation of the mean of the AMS for durations ranging from 2 to 7 days at any location in South Africa.

For durations shorter than 1 day, the mean of the *H* ($H \leq 1440$ minutes) duration values were found to scale linearly as a function of the 24 h values. Thus, for each of the 15 short duration clusters and for 15 durations ranging from 5 to 1200 minutes, linear regression coefficients were derived.

The approach adopted to estimate the mean of the AMS for any duration is a two step process. First, the mean of the 1 day AMS is estimated at the required location using the regionalised regressions. Secondly, the means of the AMS for durations longer than 1 day are scaled directly from the 1 day value. For durations shorter than 1 day, the values are scaled from the 24 h value, which in turn is estimated directly from the 1 day value for the location. Thus, the daily rainfall database, with many more stations and with longer records lengths that those contained in the digitised rainfall database, is utilised in the estimation of the mean of the AMS for all durations. Inconsistencies in the digitised rainfall database are therefore, to some extent compensated for by scaling from the daily values.

A summary of the procedures to estimate design rainfalls in South Africa is contained in Chapter 5. The estimation of error bounds, i.e. confidence intervals, for the design values is also detailed in Chapter 5.

CHAPTER 5

ESTIMATION OF DESIGN RAINFALL IN SOUTH AFRICA USING A REGIONALISED APPROACH AND SCALE INVARIANCE PROPERTIES OF RAINFALL

5.1 Assumptions and Methodology

An index storm approach, based on L-moments, has been developed for design rainfall estimation in South Africa. Growth curves which relate design rainfall, scaled by the mean of the annual maximum series (AMS), to duration are utilised in conjunction with an estimate of the mean of the AMS at the required location to compute the rainfall depth for the specified duration and return period. In Chapter 3 it is concluded that the growth curves should be scale invariant and that the most reliable estimate of the growth curves are those derived from the daily rainfall database for the 1 day duration. Thus, the growth curves for the 1 day duration are applied to all durations ranging from 5 minutes to 7 days. Also illustrated in Chapter 3 are 90% error bounds for the growth curves, which are used in conjunction with the 90% prediction intervals for the mean of the AMS, to estimate 90% error bounds for the design rainfall.

The mean of the 1 day AMS is estimated using the regression equations for the 7 regions, and corrected using a residual error surface, as detailed in Section 4.1. The mean for the 24 h AMS, as would be computed from continuously recorded rainfall data, is estimated as shown in Equation 17 from the 1 day mean of the AMS and the 24 h :1 day ratios contained in Table 8 (page 79).

$$L\_1_{24\mathrm{h}} = L\_1_{1\mathrm{day}} \times Ratio_{24\mathrm{h}\,:\,1\mathrm{d}} \qquad ...17$$

where

$L\_1_{24\mathrm{h}}$	=	mean of the 24 h AMS, extracted from digitised rainfall data,
$L\_1_{1\mathrm{day}}$	=	mean of the 1 day AMS, extracted from daily rainfall data, and
$Ratio_{24\mathrm{h}\,:\,1\mathrm{d}}$	=	ratio to convert the mean of the 1 day AMS to 24 h AMS.

In order to estimate the means of the AMS for durations of 2 to 7 days, Equation 18 is used:

$$L\_1_D = \phi_D + \left(\alpha_D \times L\_1_{1\mathrm{day}}\right) \qquad ...18$$

where

L_1_D	=	mean of the AMS for duration = *D* days,
ϕ_D	=	regression constant for duration = *D* days, and
α_D	=	regression coefficient for duration = *D* days.

Now, the regression constant and coefficient can be estimated from the following equations:

$$\alpha_D = \theta + \tau \times D^{\sigma} \qquad ...19$$

where

θ = regression constant,
τ = regression coefficient, and
σ = transformation exponent for duration = D days,

and

$$\phi_D = \nu + \kappa \times D^{\rho} \qquad ...20$$

where

ν = regression constant,
κ = regression coefficient, and
ρ = transformation exponent for duration = D days.

Thus, for a given duration (D), Equations 19 and 20 can be used to estimate the parameters for Equation 18 and hence L_1_D ($2 \le D \le 7$ days) can be estimated using Equation 18.

However, the regressions for different durations may intersect when $L\_1_{1\ day}$ values are used which are outside of the range of values used in the regression analysis. Therefore, it is necessary to estimate the slope of the relationship between the mean of the AMS (L_1) and duration. This is achieved by using L_1 values for durations of 1, 3 and 7 days derived from Equation 18 as shown in Equations 21, 22, 23 and 24.

For durations (D): 1 day < $D \le$ 3 day

$$Slope_{(1day-3day)} = \frac{\log(L\_1_{3day}) - \log(L\_1_{1day})}{\log(3) - \log(1)} \qquad ...21$$

$$L\_1_D = 10^{\left[\log(L\_1_{1day}) + Slope_{(1day-3day)}\right) \times \left[\log(D) - \log(1)\right]\right]} \qquad ...22$$

For durations (D): 3 day < $D \le$ 7d day

$$Slope_{(3day-7day)} = \frac{\log(L\_1_{7day}) - \log(L\_1_{3day})}{\log(3) - \log(1)} \qquad ...23$$

$$L\_1_D = 10^{\left[\log(L\_1_{3day}) + Slope_{(3day-7day)} \times \left[\log(D) - \log(3)\right]\right]} \qquad ...24$$

To estimate the mean of the AMS for durations < 24 h Equation 25 is used:

$$L\_1_k = (L\_1_{24h} \times XCOEFF_{i,k}) + CONST_{i,k} \quad ...25$$

where

L_1_k = mean of AMS for duration = *k,* minutes

$XCOEFF_{i,k}$ = regression coefficient for cluster = *i* and duration = *k* minutes in Table 7 (page 73), and

$CONST_{i,k}$ = regression intercept for cluster = *i* and duration = *k* minutes in Table 7 (page 73).

Thus L_1_k could be estimated for any available duration = *k* minutes. However, the regressions for different durations may intersect when $L\_1_{24\,h}$ values are used which are outside of the range of values used in the regression analysis. Thus, it is necessary to estimate the slope of the relationship between *L_1* and duration. This is achieved by using *L_1* values for durations of 5, 15 and 120 minutes derived from Equation 25 and the 24 h value calculated using Equation 17.

For durations (*D* minutes): 120 < *D* < 1440

$$Slope_{(1440-120)} = \frac{\log(L\_1_{1440}) - \log(L\_1_{120})}{\log(1440) - \log(120)} \quad ...26$$

$$L\_1_D = 10^{\left[\log(L\_1_{24h}) - Slope_{(1440-120)} \times \left[\log(1440) - \log(D)\right]\right]} \quad ...27$$

For durations (*D* minutes): 15 < *D* < 120

$$Slope_{(120-15)} = \frac{\log(L\_1_{120}) - \log(L\_1_{15})}{\log(120) - \log(15)} \quad ...28$$

$$L\_1_D = 10^{\left[\log(L\_1_{120}) - Slope_{(120-15)} \times \left[\log(120) - \log(D)\right]\right]} \quad ...29$$

For durations (*D* minutes): 5 < *D* < 15

$$Slope_{(15-5)} = \frac{\log(L\_1_{15}) - \log(L\_1_{5})}{\log(15) - \log(5)} \quad ...30$$

$$L\_1_D = 10^{\left[\log(L\_1_{15}) - Slope_{(15-5)} \times \left[\log(15) - \log(D)\right]\right]} \quad ...31$$

Design rainfall depths are calculated using Equation 32.

$$DRE_{i,j} = GC_{i,j} \times L\_1_i \quad ...32$$

where

$DRE_{i,j}$ = design rainfall estimate for duration = *i* and return period = *j*,

$GC_{i,j}$ = growth curve for duration = *i* and return period = *j*, and

L_1_i = mean of AMS for duration = *i* estimated using the above procedures.

However, as shown in Chapter 3, the best estimate of the growth curve for all durations are the values derived from the daily rainfall database for the 1 day duration. Hence Equation 32 may be re-written as:

$$DRE_{i,j} = GC_{1\ day,j} \times L\_1_i \qquad ...33$$

The 90 % prediction interval for $DRE_{i,j}$ is estimated by:

$$U_{90}DRE_{i,j} = U_{90}GC_{1day,j} \times U_{90}L\_1_i$$

...34

$$L_{90}DRE_{i,j} = L_{90}GC_{1day,j} \times L_{90}\ L\_1_i$$

where

$U_{90}DRE_{i,j}$	=	upper 90% error bound of design rainfall estimated for duration = *i* and return period = *j*,
$U_{90}GC_{i,j}$	=	upper 90% error bound of the growth curve for duration = *i* and return period = *j*,
$U_{90}L\_1_i$	=	upper 90% error bound of the estimated mean of annual maximum series for duration=*i*,
$L_{90}DRE_{i,j}$	=	lower 90% error bound of design rainfall estimated for duration = *i* and return period = *j*,
$L_{90}GC_{i,j}$	=	lower 90% error bound of the growth curve for duration = *i* and return period = *j*, and
$L_{90}L\_1_i$	=	lower 90% error bound of the estimated mean of annual maximum series for duration=*i*.

As shown in Equation 7 (page 54), the prediction interval for the mean of the AMS is symmetrical about the estimated value and hence may be represented as

$$\mathrm{PI}(L\_1_i) = L\_1_i \times (1 \pm \frac{P_i}{100}) \qquad ...35$$

where

$\mathrm{PI}(L\_1_i)$	=	prediction interval for the mean of the annual maximum series for duration = *i*, and

$$P_i = \frac{U_{90}L\_1_i - L\_1_i}{L\_1_i} \times 100 \qquad ...36$$

Therefore

$$
\begin{aligned}
U_{90}DRE_{i,j} &= U_{90}GC_{1day,j} \times L\_1_i \times (1 + \frac{P_i}{100}) \\
L_{90}DRE_{i,j} &= L_{90}GC_{1day,j} \times L\_1_i \times (1 - \frac{P_i}{100})
\end{aligned}
\qquad ...37
$$

The above procedures, which are based on the Regional L-Moment Algorithm (RLMA) and the Scale Invariance (SI) properties of extreme rainfall, have been termed the RLMA&SI procedures. The performance of the RLMA&SI procedures is assessed in the following sections.

5.2 Comparisons of Estimates of Daily Design Rainfall

5.2.1 Comparisons at hidden sites

In order to assess the performance of the RLMA&SI, 10 daily rainfall stations which cover a range of climatic regions in South Africa were excluded from the regionalisation. Each of these stations was allocated to the cluster with the closest Euclidean distance between the site characteristics of the station and the mean of the site characteristics of all sites within a cluster. The locations of the hidden stations are shown in Figure 52 and cluster numbers determined for each of the hidden stations are listed in Table 9.

Table 9 Hidden stations and cluster numbers

Station	Name	Cluster
0021055 W	Cape Town Maitland	51
0059572 A	East London	4
0144899 W	Middelburg	6
0239482 A	Cedara	15
0261368 W	Bloemfontein	23
0299357 W	Cathedral Peak Hotel	17
0317447AW	Upington	35
0442811 W	Nooitegedacht	24
0513404 W	Pretoria	16
0677834 W	Pietersburg	28

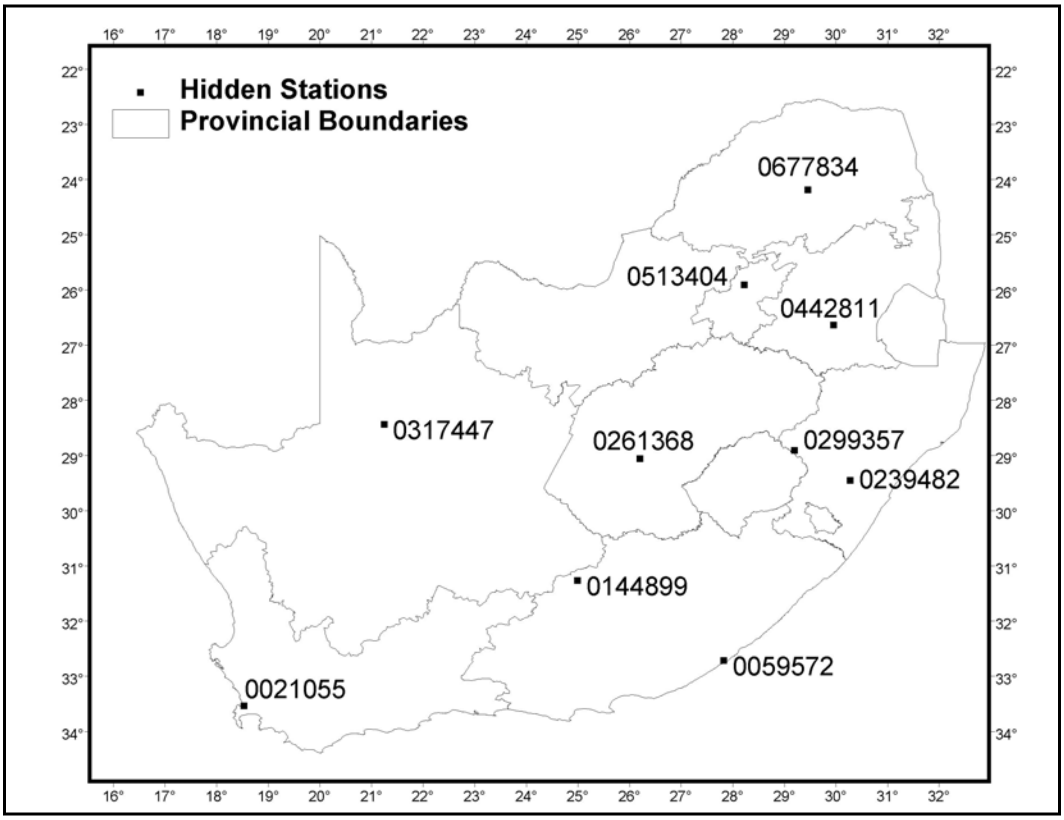


Figure 52 Locations of the 10 hidden daily rainfall stations in South Africa

A comparison between the design rainfall estimated using the at-site data and values estimated from the regional quantile curve is shown in Figure 53 for the 10 hidden stations which were not used in the regionalisation procedure. Included in Figure 53 are the 90% error bounds of the design values estimated from the error bounds of the quantile growth curve and estimated mean of the AMS.

As shown in Figure 53, the 1 day design rainfall depths estimated from the observed data and from the regional growth curve are similar for return periods up to 20 years and, with the exception of three stations (Cape Town - 0021055 W, Cedara - 0239482 A and Pretoria - 0513404 W), where the values estimated using the RLMA&SI procedures generally exceed the values estimated from the at-site data for return periods greater than 20 years. The regional growth curve, used in the RLMA&SI procedures, pools information from stations within a relatively homogeneous region and is thus considered to result in more reliable estimates of design rainfall than values estimated directly from the at-site data. Hence, the recommended design values estimated using the regional approach are generally more conservative (overestimate) for longer return periods than those estimated directly from the at-site data.

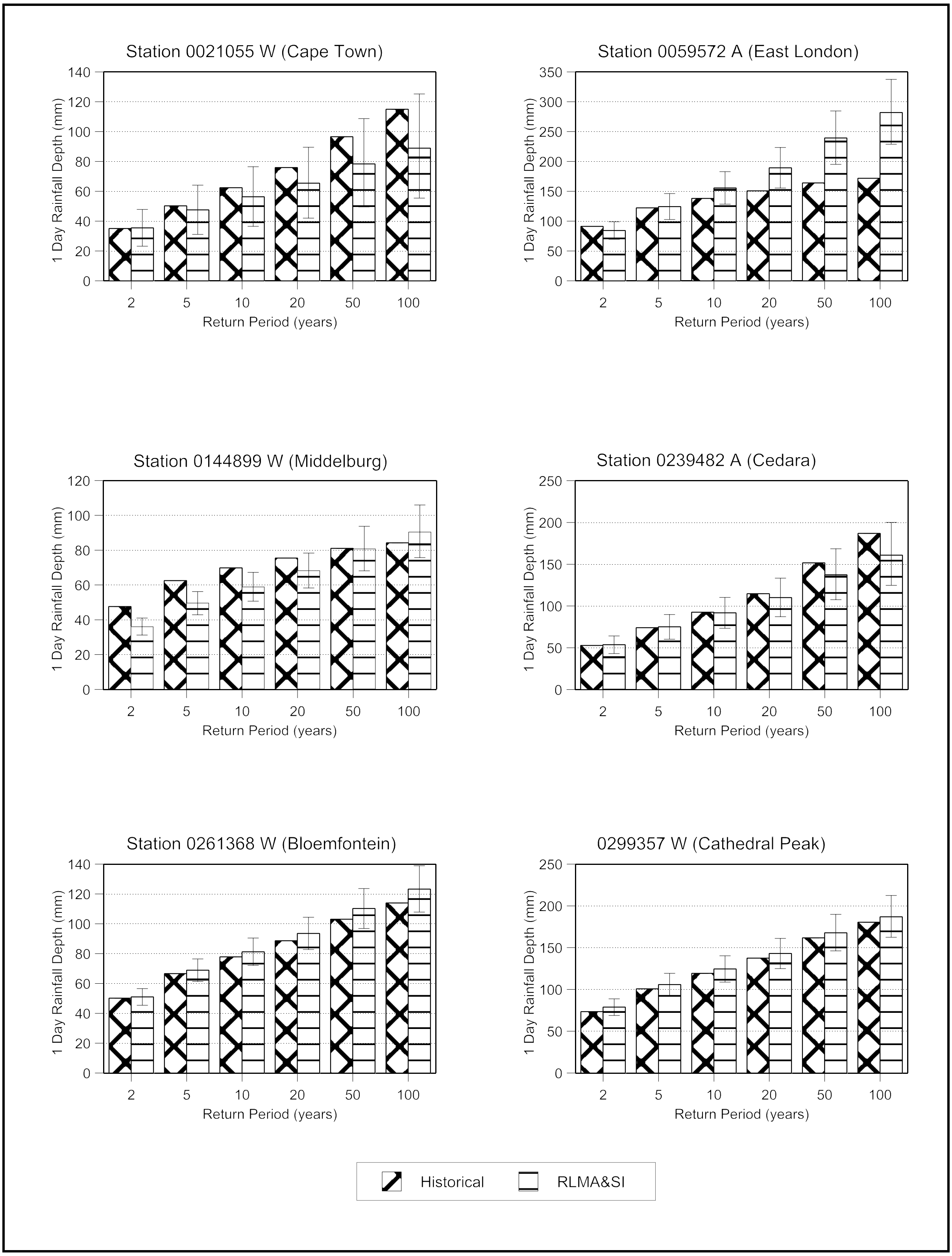


Figure 53 Comparison of design rainfall depths computed from at-site data and from regional growth curves at 10 stations not used in the regionalisation process (I-beams indicate 90% error bounds)

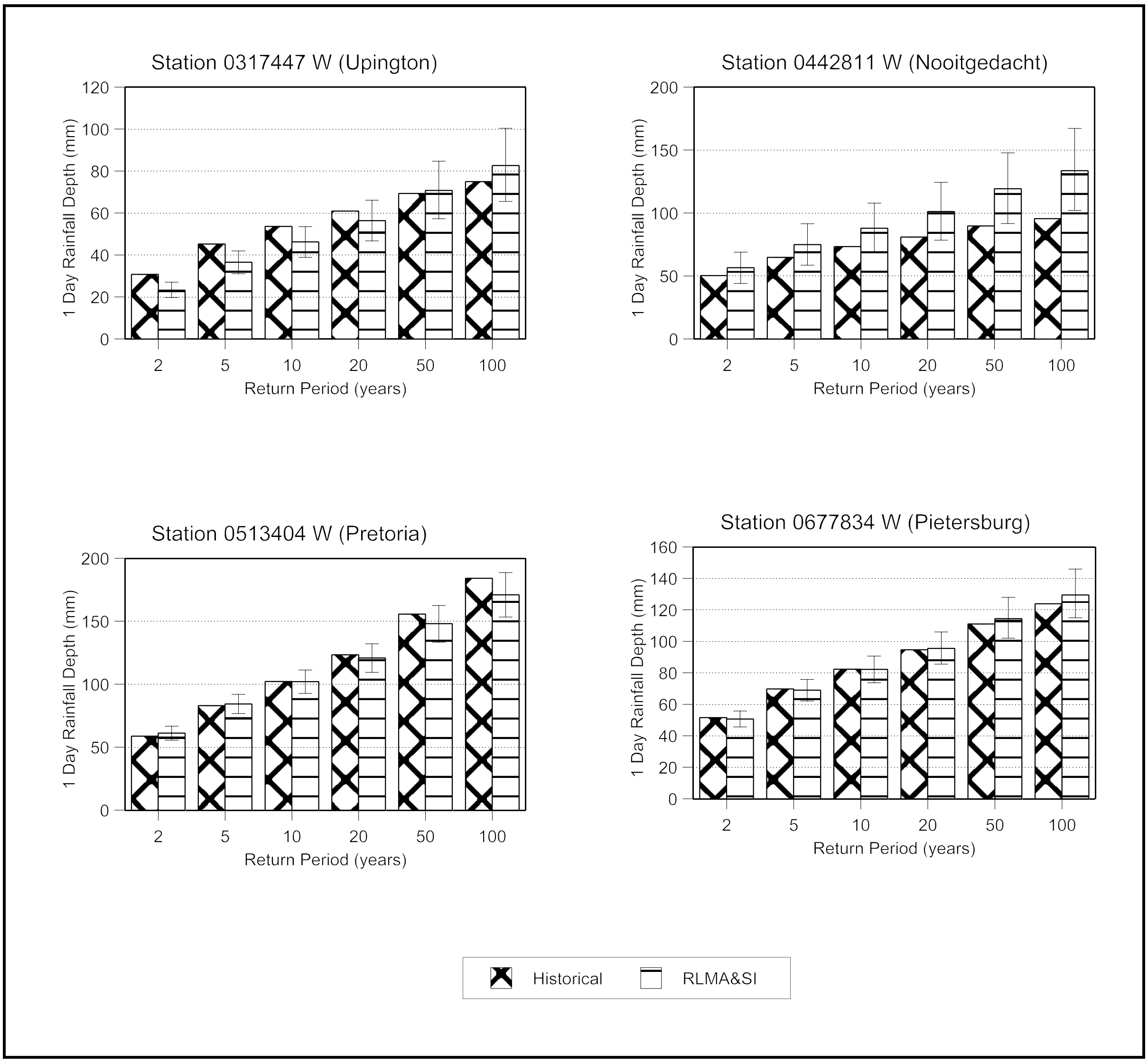


Figure 53 (cont) Comparison of design rainfall depths computed from at-site data and from regional growth curves at 10 stations not used in the regionalisation process (I-beams indicate 90% error bounds)

5.2.2 Comparisons at sites with at least 40 years of data

A comparison was performed between the 1 day design rainfall estimated in this study using the RLMA&SI procedures and those estimated directly from at-site data using the GEV distribution fitted to the AMS by L-moments. The Relative Difference (*RD*) was computed for return periods of 2 to 100 years, as shown in Equation 38, between 1 day design rainfall estimated in this study and those estimated from the at-site data at 1 789 stations in South Africa used by Smithers and Schulze (2000b) in the regionalisation process.

$$RD_T = \frac{P_{RLMA\&SI,T} - P_{GEV/LM,T}}{P_{GEV/LM,T}} \qquad ...38$$

where

RD_T	=	Relative Difference for return period = *T* years,
$P_{RLMA\&SI,T}$	=	*T* year return period design rainfall estimated using the RLMA&SI procedures developed in this study, and
$P_{GEV/LM,T}$	=	*T* year return period design rainfall estimated by fitting a GEV distribution to the at-site AMS using L-moments.

The results of frequencies analyses of RD_T for 1 and 3 day durations at 1 779 stations which have at least 40 years of record are contained in Figure 54. Similar results were obtained for all durations ranging from 1 to 7 days. It is evident from Figure 54 that the RLMA&SI procedures tend to slightly overestimate the at-site values. Using the 1 day, 10 year return period as an example, differences of less than 20% occur at 99.4% of the stations, of which 60.7% consist of positive differences and 38.7% of these differences are negative, i.e. the values estimated using the regional scale invariance approach tend to exceed the values computed directly from the at-site data.

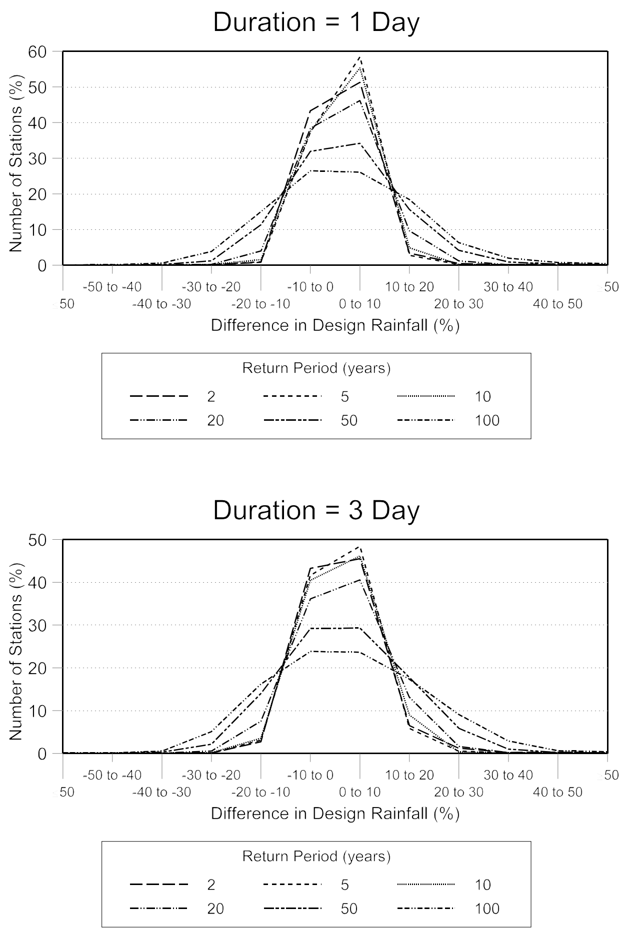


Figure 54 Frequency analyses of the differences in design rainfall estimated using the RLMA&SI procedures and those from the observed data at 1 789 daily rainfall stations which have at least 40 years of record

5.2.3 Comparison with Adamson's (TR102) values

A comparison was performed between the 1 day design rainfall estimated using the RLMA&SI procedures developed in this study and those estimated by Adamson (1981) in the widely cited DWAF Technical Report TR102. The Relative Difference (*RD*) was computed, as shown in Equation 39, between 1 day design rainfall estimated in this study and those estimated by Adamson (1981) at 2 184 stations in South Africa and for return periods of 2 to 200 years.

$$RD_T = \frac{P_{RLMA\&SI,T} - P_{ADAM,T}}{P_{RLMA,T}} \qquad ...39$$

where

- RD_T = Relative Difference for return period = *T* years,
- $P_{RLMA,T}$ = *T* year return period design rainfall estimated using the RLMA&SI procedures and GEV distribution in this study,
- $P_{ADAM,T}$ = *T* year return period design rainfall estimated by Adamson (1981), who used a single site approach and a censored LN distribution.

A frequency analysis was performed for the RD_T values computed at the 2 184 stations used by Adamson (1981). The results are summarised in Figure 55. From Figure 55 it is evident that for return periods less than 50 years the differences between the design rainfall estimated in this study and by Adamson (1981) are less than 20 % at the majority of the stations. As expected, the differences are bigger for longer return periods and for return periods $\geq$50 years there is a definite trend with the Adamson design values exceeding the values computed in this study. The differences in the design rainfall values estimated in the two studies may be attributed to the following factors:

- The different approaches to design rainfall estimation used in the two studies:
  - Adamson (1981) used a single site approach with a censored LN distribution;
  - the regional approach used in the RLMA&SI procedures adopted the GEV distribution;
- The longer record lengths used in the regional approach;
- The stringent data quality control procedures used in this regional approach; and
- L-moments used in this study to fit the GEV distribution are less influenced by outliers in the data.

As shown in Figure 53 and generalised in Figure 54, design rainfall depths computed using the regional approach generally exceed the values computed directly from the at-site data. In addition, the regional approach has been shown in many international studies (e.g. Potter, 1987; Cunnane, 1989; Hosking and Wallis, 1997) to result in more reliable and robust estimates compared to design values computed using only single at-site data. Thus, it is postulated that the design values computed in this study may be used with confidence.

The biggest apparent discrepancy where the RLMA&SI value is larger than Adamson's 1 day design rainfall occurs at Station 0022038 (Vrugbaar). In this instance, the location specified by Adamson for this station is incorrect. Table 10 contains 1 day design rainfall values at the location specified by Adamson, the values estimated by the RLMA&SI procedures at this location and the values estimated by the RLMA&SI procedures at the correct location, which correspond closely to the values given by Adamson for Station 0022038.

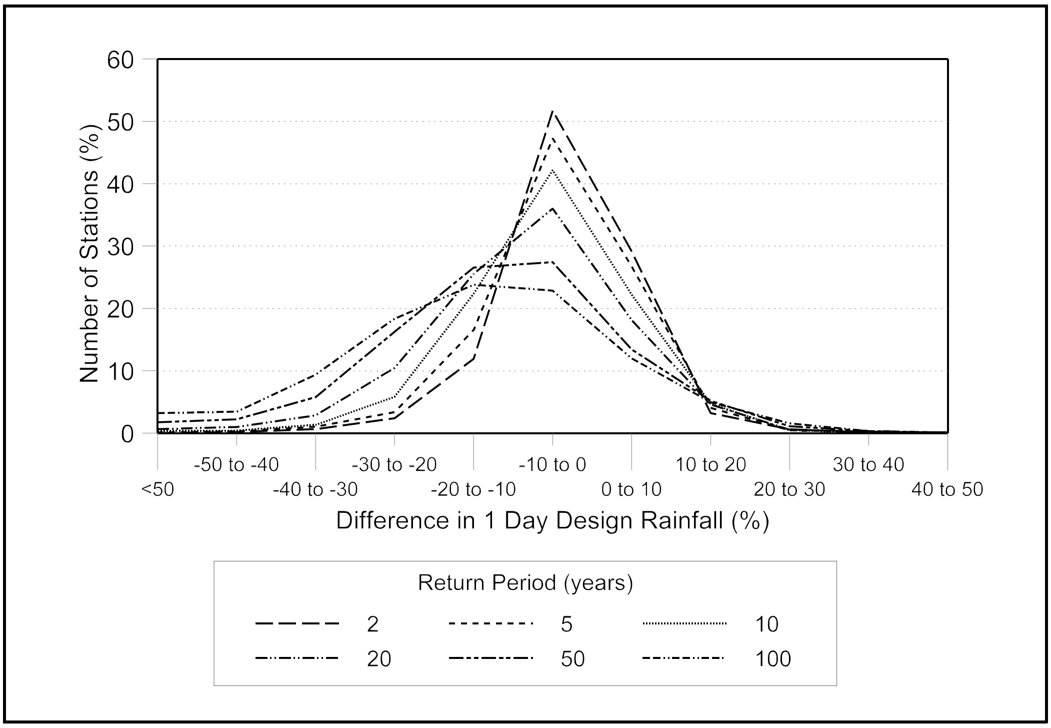


Figure 55 Comparison between 1 day design rainfall estimated in this study and values estimated by Adamson (1981)

Table 10 Comparison between 1 day design rainfall depths (mm) estimated by Adamson and RLMA&SI procedures

Station No.	Name	Latitude		Longitude		Source	1 Day Rainfall (mm) for Return Period (Years)					
		(°)	(')	(°)	(')		2	5	10	20	50	100
22038	Vrugbaar	33	48	19	2	Adamson	49	64	76	88	105	119
		33	48	19	2	RLMA&SI	95	125	145	164	188	206
22038	Vrugbaar	33	37	19	2	RLMA&SI	49	61	70	79	91	100
		33	37	19	2	GEV/LM	47	61	70	81	96	108
762372	Essexvale	22	42	28	13	Adamson	75	115	147	183	238	287
		22	42	28	13	RLMA&SI	51	72	87	103	124	141
		22	42	28	13	GEV/LM	71	106	130	153	184	208
762532	Droevlei	22	52	28	18	Adamson	52	76	95	115	146	173
		22	42	28	13	RLMA&SI	55	78	95	100	134	153
		22	42	28	13	GEV/LM	55	72	81	88	96	103

Similarly, the largest apparent discrepancy where the RLMA&SI value is less than Adamson's 1 day design rainfall is also contained in Table 10 (Station 0762372, Essexvale). The design values estimated using the RLMA&SI procedures are also contained in Table 10, as are design values for the closest station (Station 0762532, Droëvlei) used by Adamson to Station 0762372. From these results it is apparent that Adamson's values for Station 0762372 are inconsistent with the values from Station 0762532, whereas the value at both sites estimated using the RLMA&SI procedures are similar.

5.3 Comparisons of Estimates of Short Duration Design Rainfall

Alexander (2001) presents comparisons between his new and old (Alexander, 1990) relationships to estimate short duration design rainfall at 8 representative sites in South Africa. The log-Pearson Type 3 (LP3) distribution fitted by the Method of Moments (LP3/MM) is used by Alexander (2001) for design rainfall estimation in South Africa. Hence in Figures 56 to 71 for the depth:return period plots for 1 and 4 h durations, both the GEV/LM and LP3/MM are plotted and overlain on the AMS plotted using the Cunnane plotting position. From these figures it is evident that the differences in the GEV/LM and LP3/MM values are insignificant.

Also included in Figure 56 to 71 are design rainfalls estimated by the RLMA&SI procedures, the equation developed by Alexander (2001) and the equations developed by Adamson (1981) in Report TR102 and by Midgley and Pitman (1978) in Report HRU2/78. The HRU2/78 values were estimated using the equations developed by Op Ten Noort (1983) from the Midgley and Pitman (1978) data. The algorithm developed by Adamson (1981) is only valid for durations < 2 h and hence the TR102 values in Figures 56 to 71 for durations > 2 h should be viewed for illustrative purposes only.

The inconsistency between the digitised and daily rainfall data is again evident in Figures 56 to 71 where the 1 day design value, computed from the daily rainfall data, exceeds the 24 h value, computed from the digitised rainfall, at all the stations considered. Generally the 1 day value estimated using the RLMA&SI procedures compares favourably with the 1 day value estimated from the at-site data using the GEV distribution fitted using L-moments. At most stations the 1 to 7 day design rainfall values computed directly from the at-site data fall within the 90% error interval estimated using the RLMA&SI procedures. It is noted that there is generally some agreement between the 1 to 7 day design values estimated using the at-site data and the values from Adamson's TR102 report. In instances where the at-site values or the TR102 values are inconsistent for 1 to 7 day durations (e.g. Pietersburg 50 year return period or Durban 50 year return period) the RLMA&SI procedures result in consistent estimates for these durations.

Discontinuities in the Alexander estimates are evident where the 24 h values are less than the 1 day TR102 value (e.g. Port Elizabeth, East London), on which the algorithm is based. Similarly, at some sites the Alexander 24 h estimates greatly exceed the TR102 value (e.g. Bloemfontein). Alexander (2001) attributes these inconsistencies to the "relationships reflecting the average conditions" and therefore accepts the equation values for durations up to 4 h and thereafter recommends linear interpolation between 4 hour and the daily TR102 value. Thus, there is no distinction between his 1 day (fixed 24 h window as extracted from daily rainfall data) and 24 h value (sliding 24 h window as extracted from continuously recorded data). This again is inconsistent with his equation which includes a factor of 1.13 which is a “clock time correction” factor.

At all the sites contained in Figures 56 to 71, the design rainfall values estimated using both the Alexander and TR102 algorithms for 1 and 4 h periods exceed both the at-site data and the values estimated using the RLMA&SI procedures, and also generally exceed the upper 90% error bound of the RLMA&SI estimate. Generally the design rainfalls estimated using the RLMA&SI and HRU2/78 procedures are similar and, where no obvious anomalies are evident in the data, follow the trends in the observed data. The overestimation of design rainfalls for durations < 24 h by the Alexander equation is illustrated in Figure 72 for three stations in the Western Cape which are considered to have reliable digitised data. These results are generalised and expressed as the percentage difference between the value estimated using Alexander's equation and the value computed directly from the observed data in Figure 73. Included in Figure 73 are results from Raingauge N23 in the Ntabamhlope research catchments near Escourt, CP6 in Cathedral Peak research catchments, SAL10 from the La Mercy research catchments and Moko3a from the Mokobulaan research catchments. The data from these stations are also considered to be reliable (Smithers and Schulze, 2000a). Similar results, but using the RLMA&SI procedures to estimate the design rainfall, are contained in Figure 74. From these figures it is evident that the Alexander equations tends to overestimate design rainfalls for durations greater than 10 minutes, with the degree of overestimation decreasing with duration from the 1 to 24 h. The differences between design rainfall estimated using the RLMA&SI procedures and the observed data generally fall into a smaller range compared to those estimated using Alexander's equation and do not display significant trends with duration.

A frequency analysis of the differences in the design rainfalls estimated directly from the at-site data, the Alexander equation and the RLMA&SI procedures was performed. The locations used in the analyses were the same 85 sites that Alexander (2001) used in the derivation of his equation. Figure 75 contains the results for a duration of 1 h. The results for longer durations displayed similar trends. It is evident from Figure 75 for the 2 year return period that the design rainfall determined using the Alexander equation are not biased compared to the values derived from the at-site data. However, the 2 year, 1 h values derived using the RLMA&SI procedures generally exceed the at-site derived values and hence the RLMA&SI values are generally larger than the values estimated using the Alexander equation. The reason for the RLMA&SI values exceeding the at-site values is attributed to the scaling performed to compensate for the inadequacies contained in the digitised rainfall data. This trend is reversed for longer return periods, with the values estimated using the Alexander equation generally exceeding the RLMA&SI values.

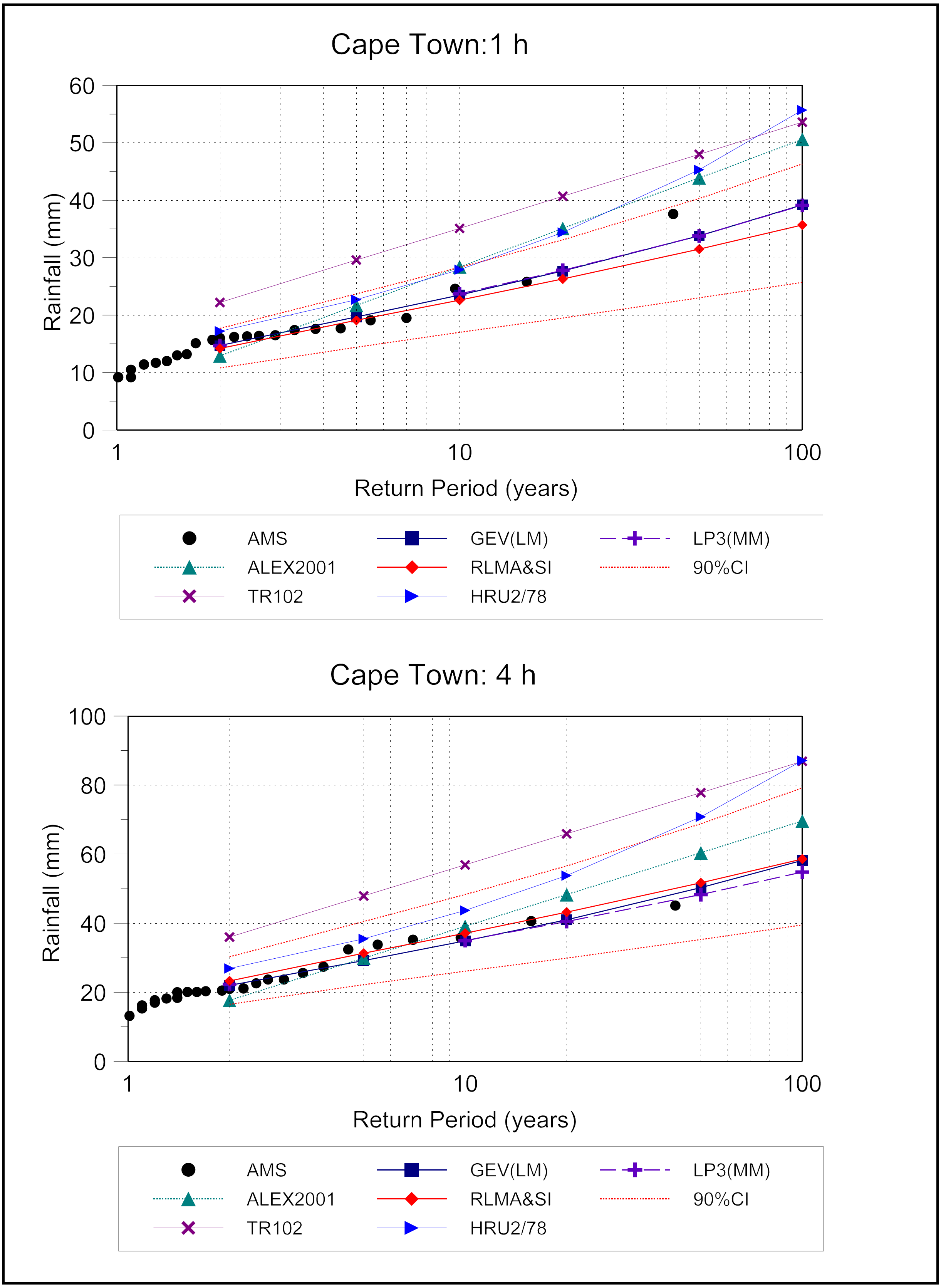


Figure 56 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Cape Town using various approaches

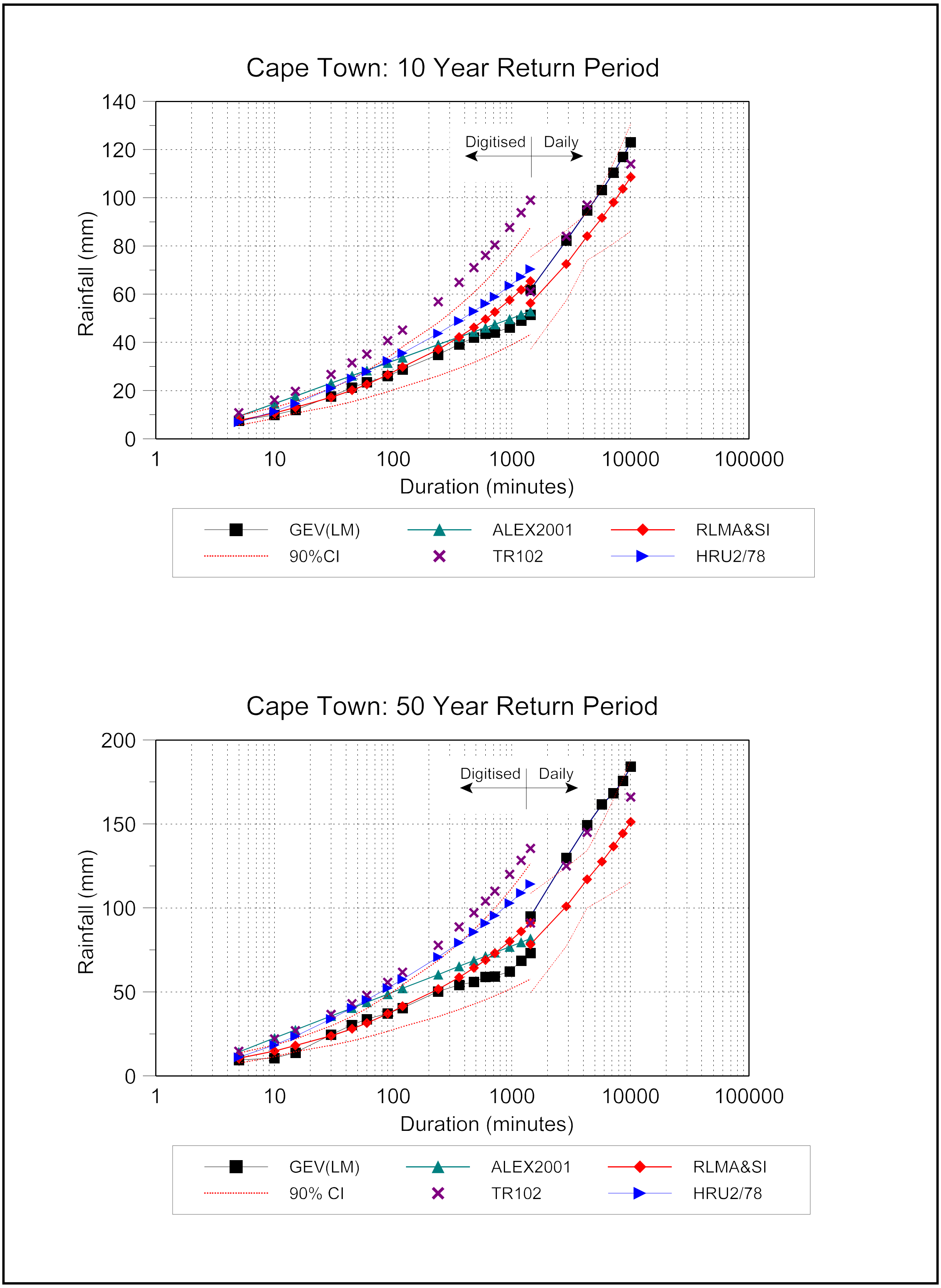


Figure 57 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Cape Town using various approaches

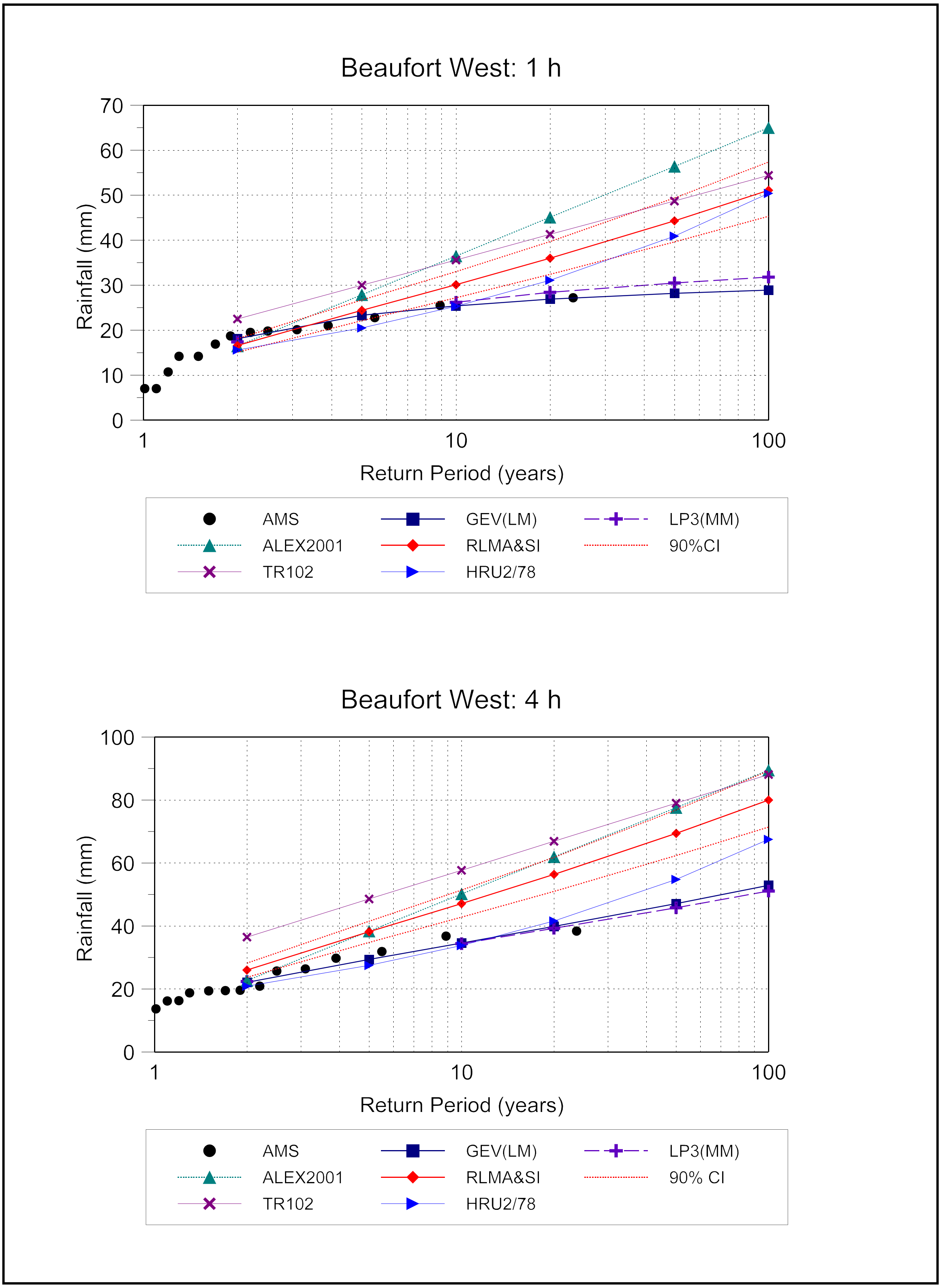


Figure 58 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Beaufort West using various approaches

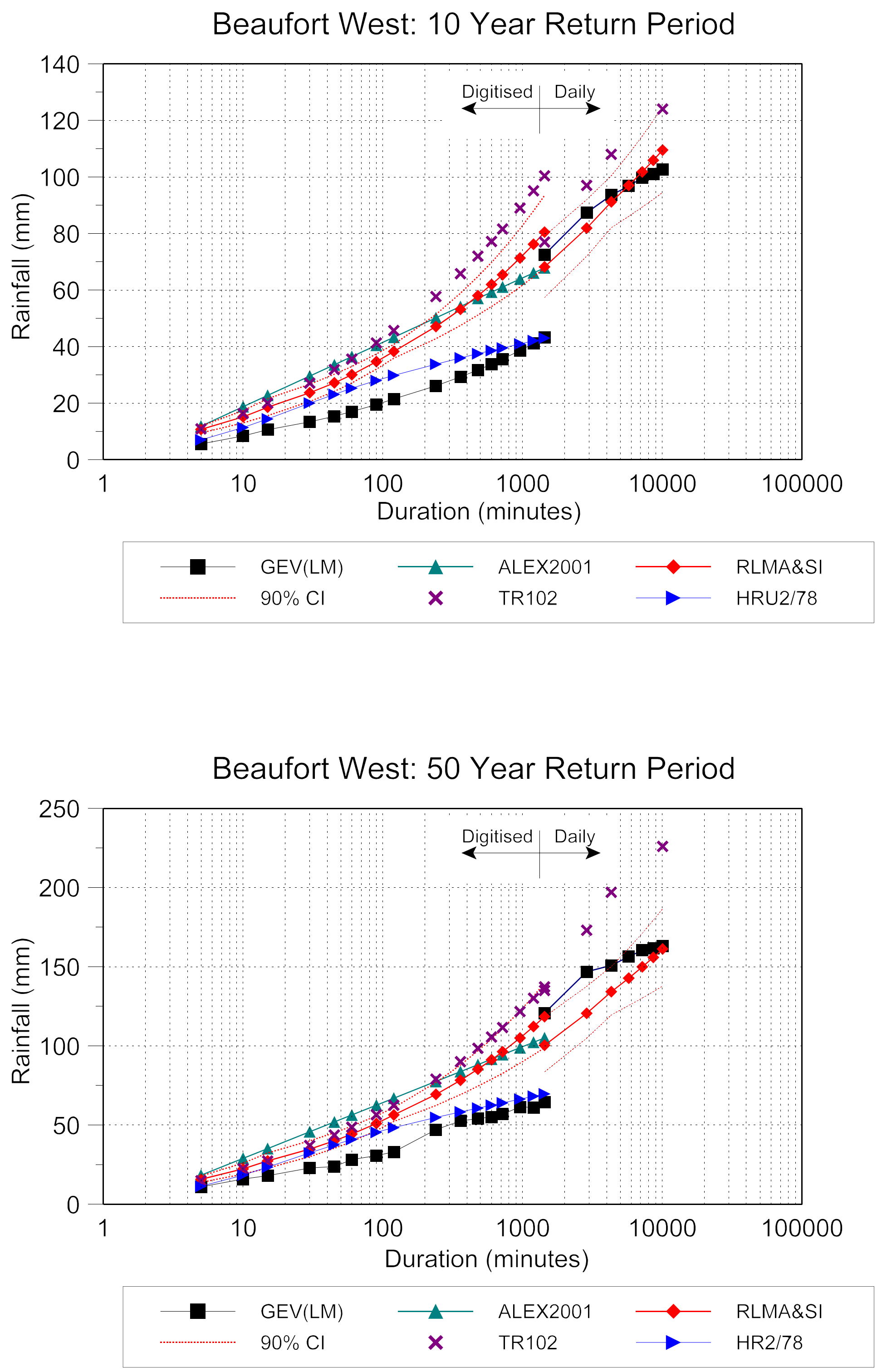


Figure 59 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Beaufort West using various approaches

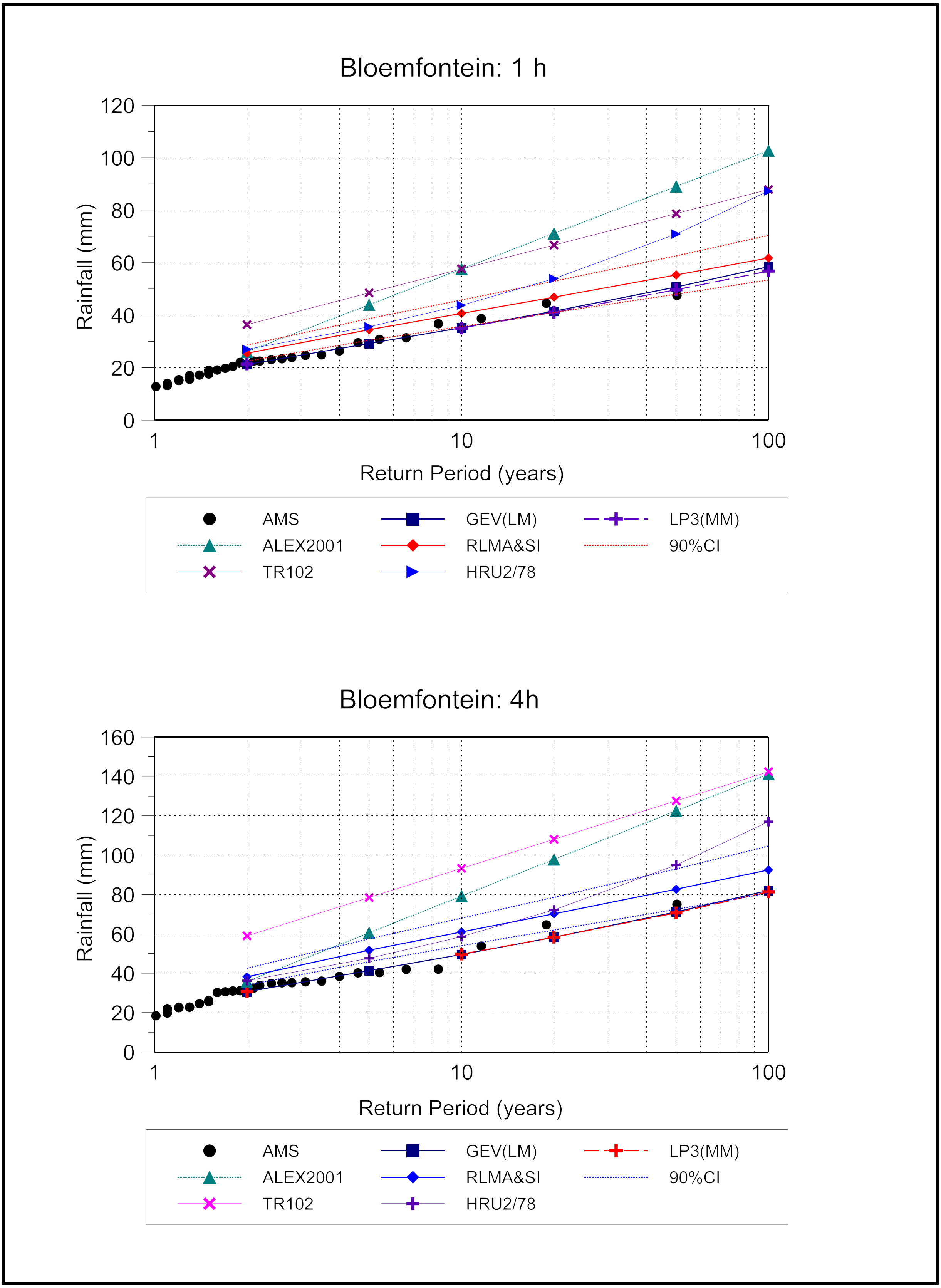


Figure 60 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Bloemfontein using various approaches

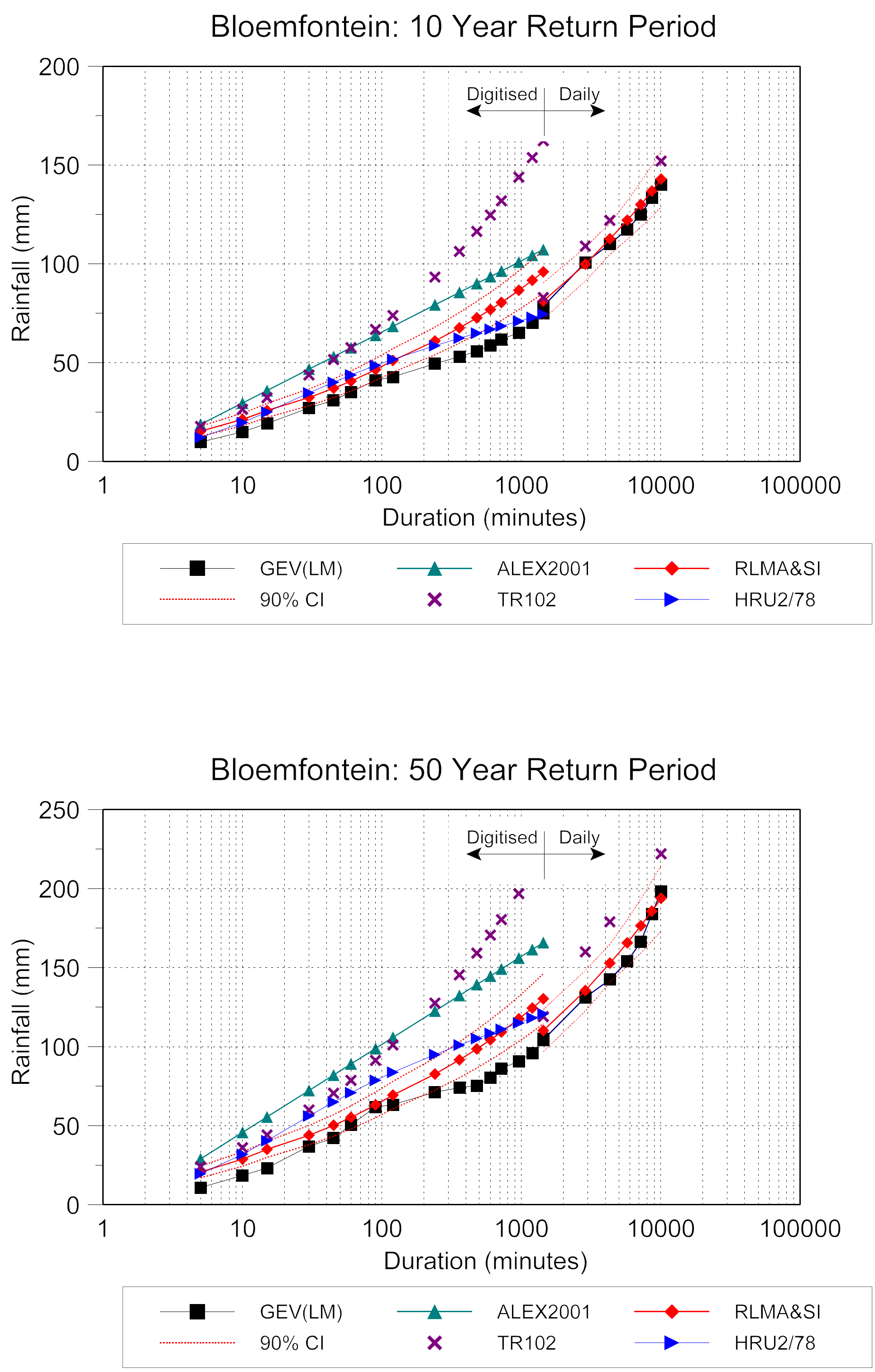


Figure 61 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Bloemfontein using various approaches

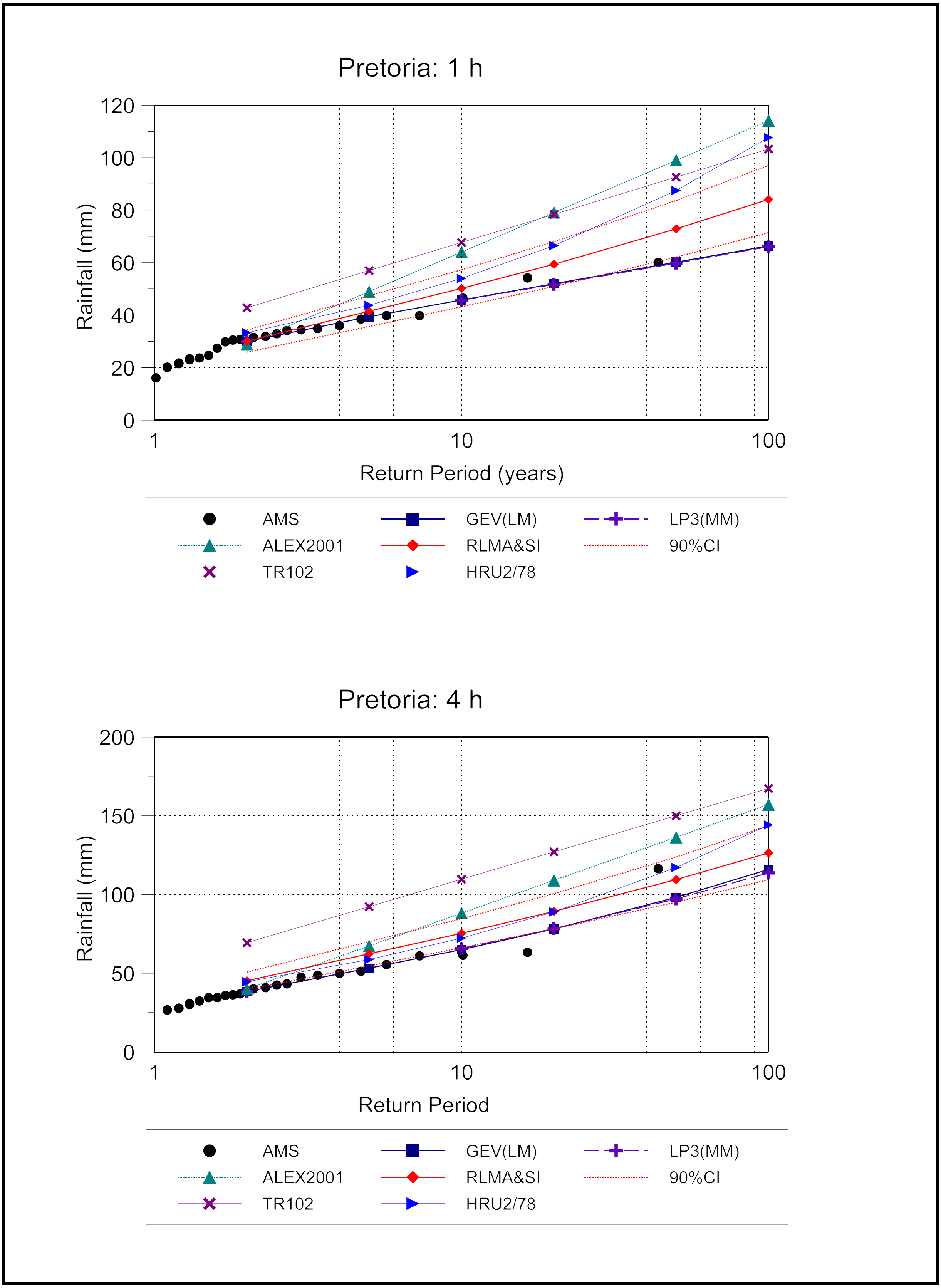
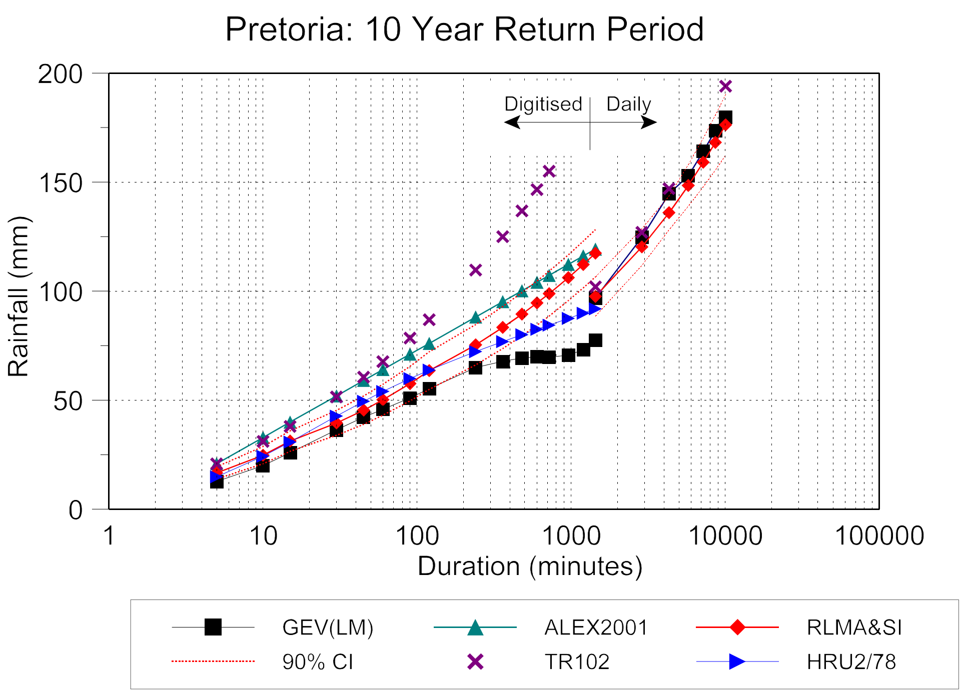


Figure 62 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Pretoria using various approaches



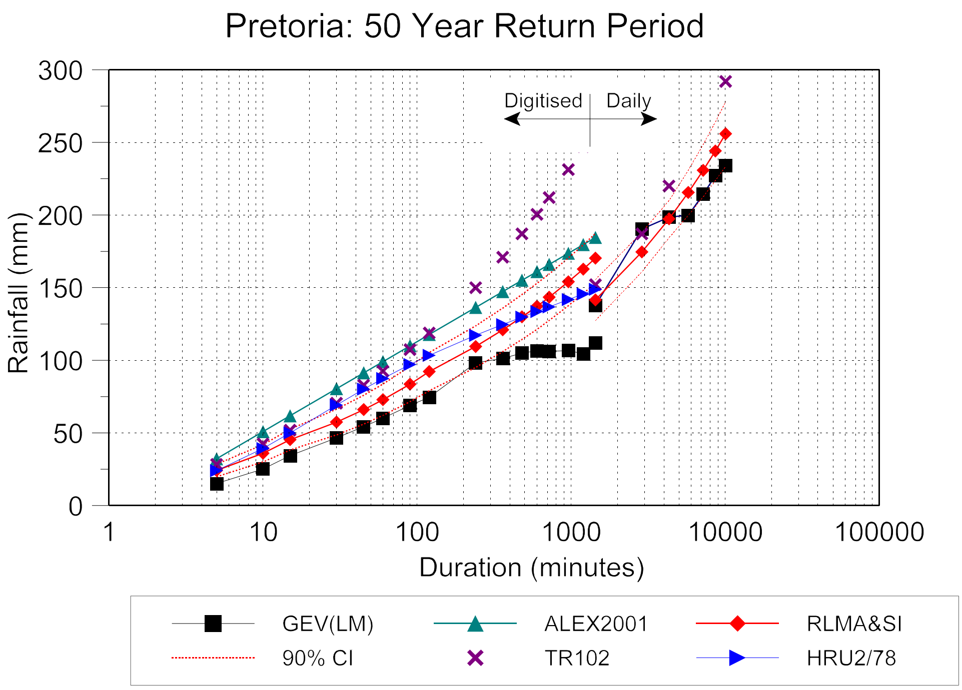


Figure 63 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Pretoria using various approaches

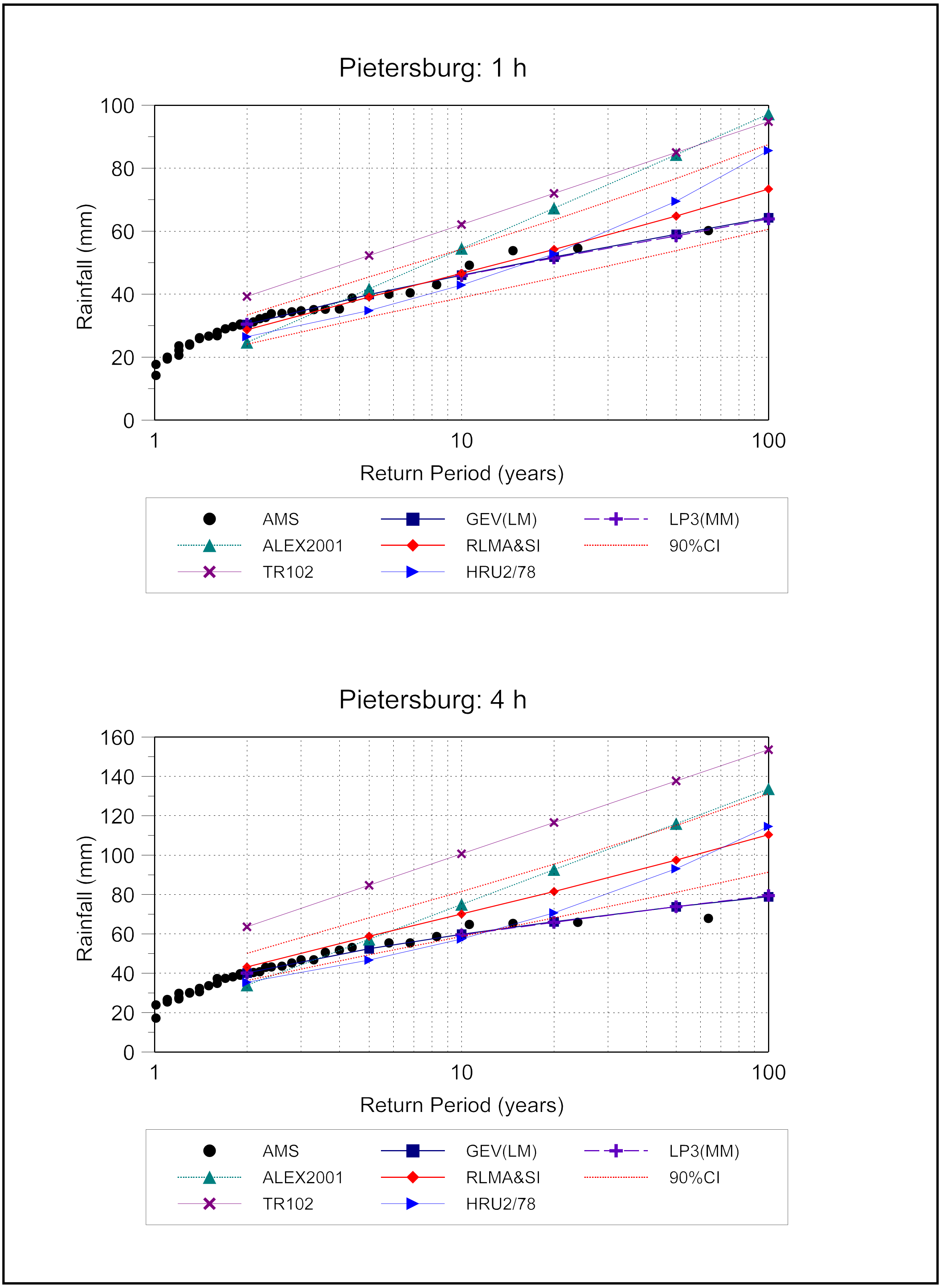


Figure 64 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Pietersburg using various approaches

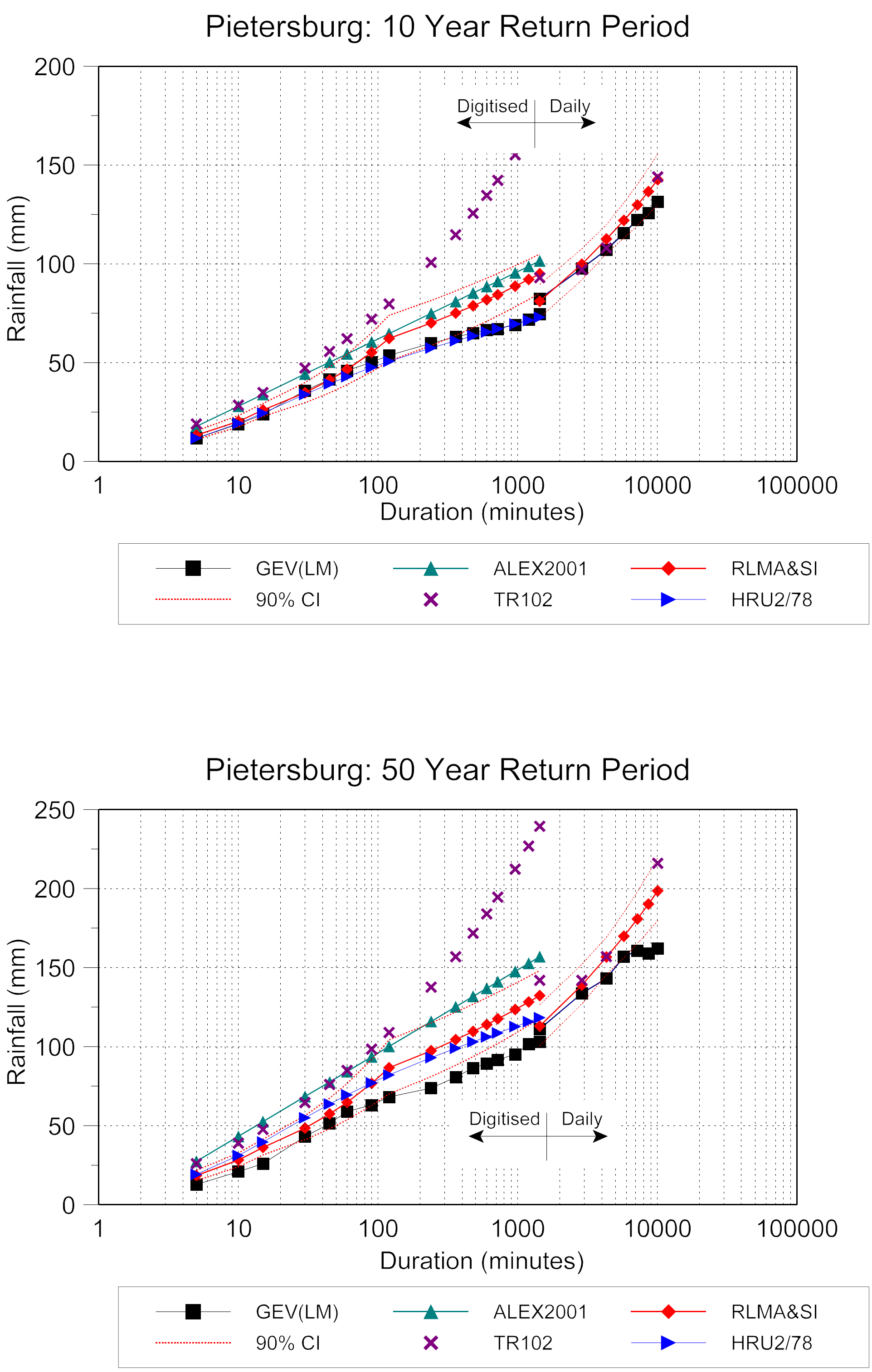


Figure 65 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Pietersburg using various approaches

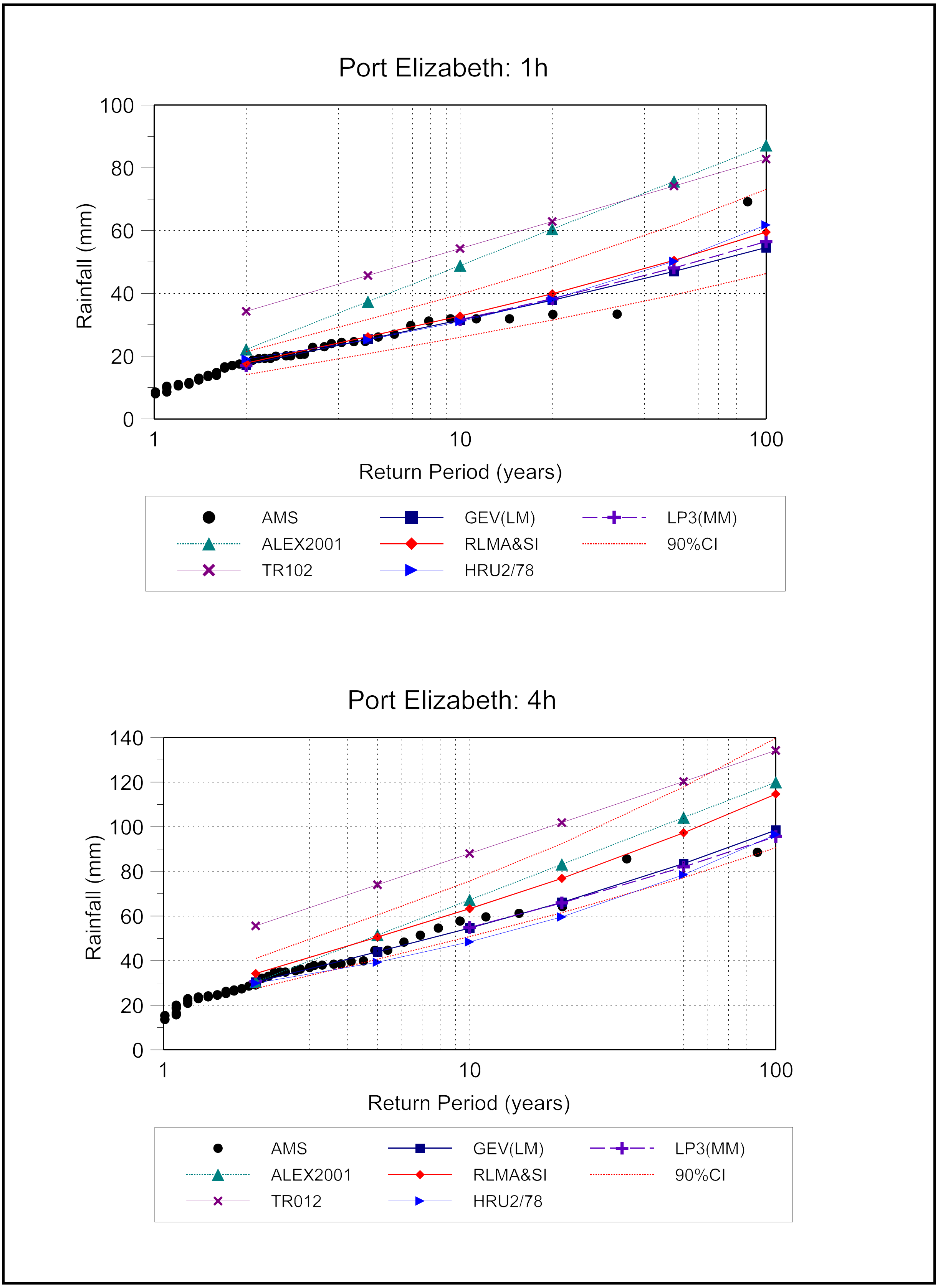


Figure 66 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Port Elizabeth using various approaches

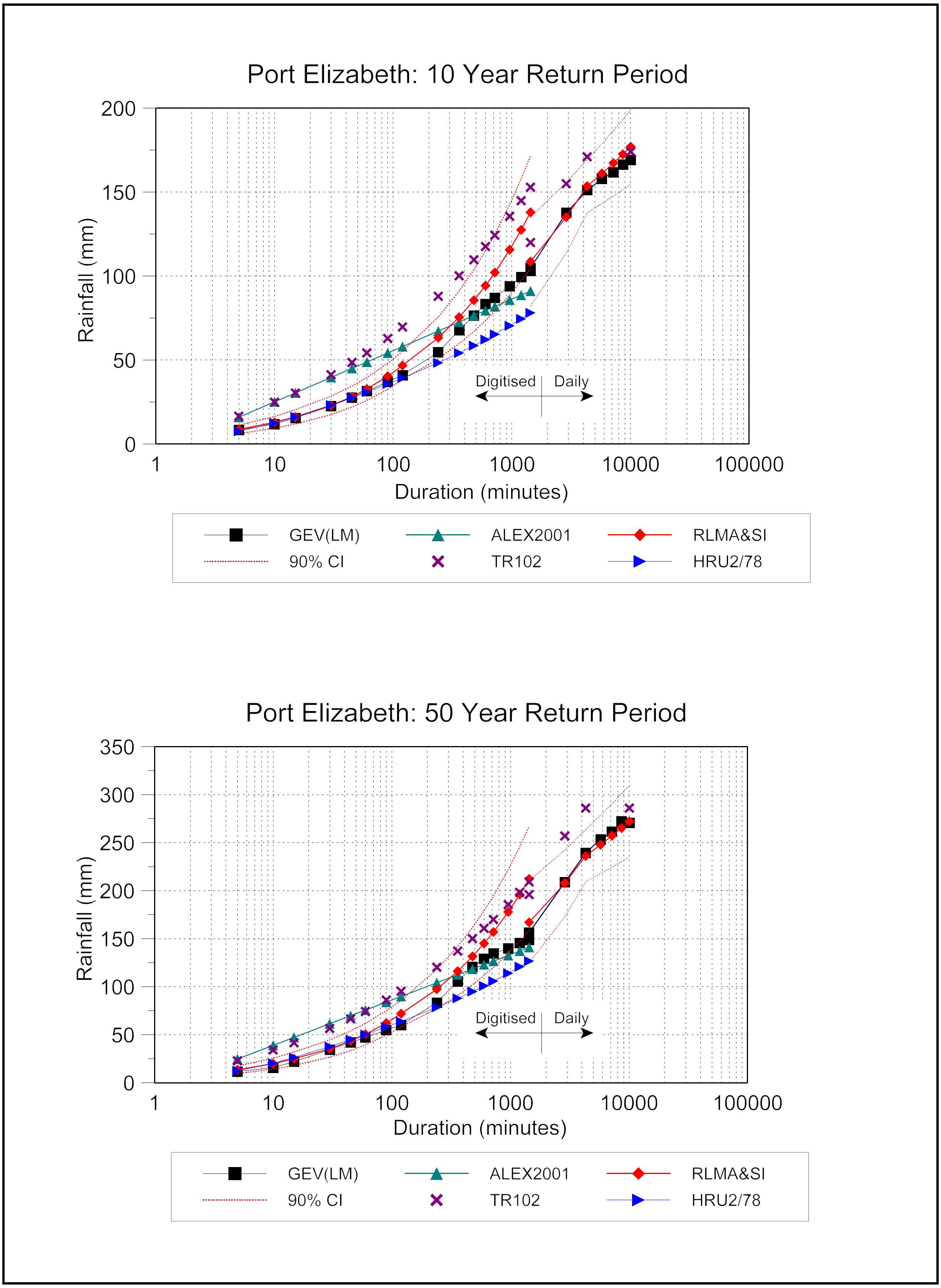
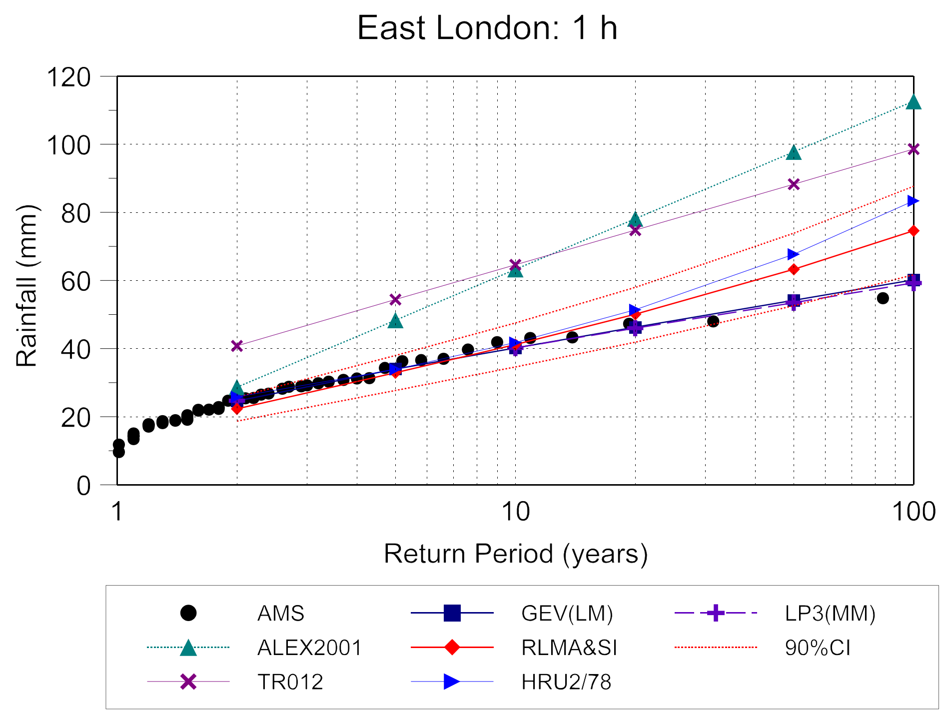


Figure 67 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Port Elizabeth using various approaches



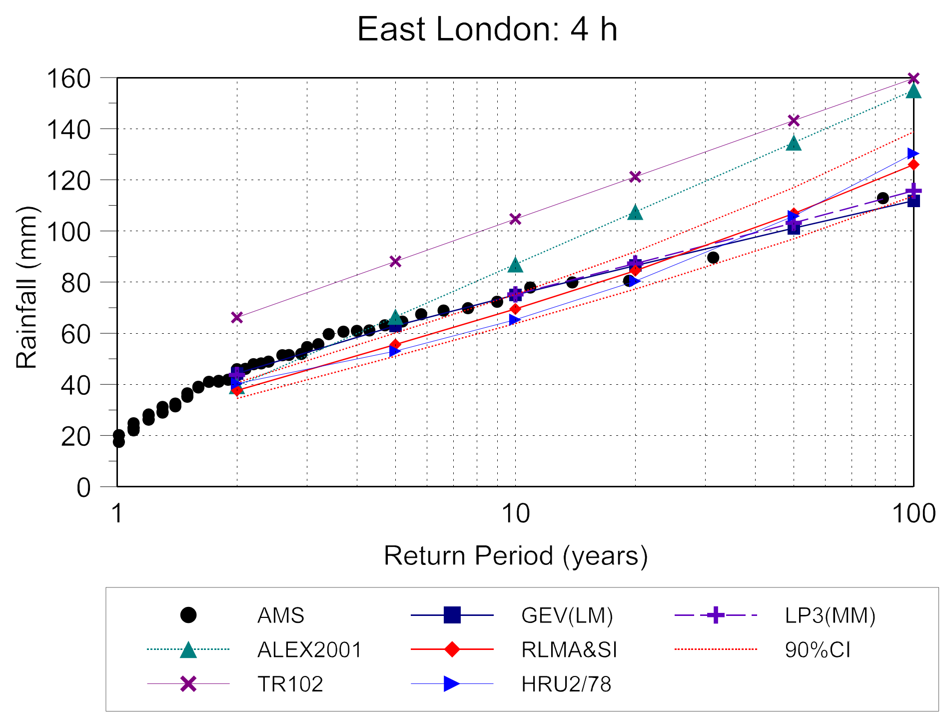


Figure 68 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at East London using various approaches

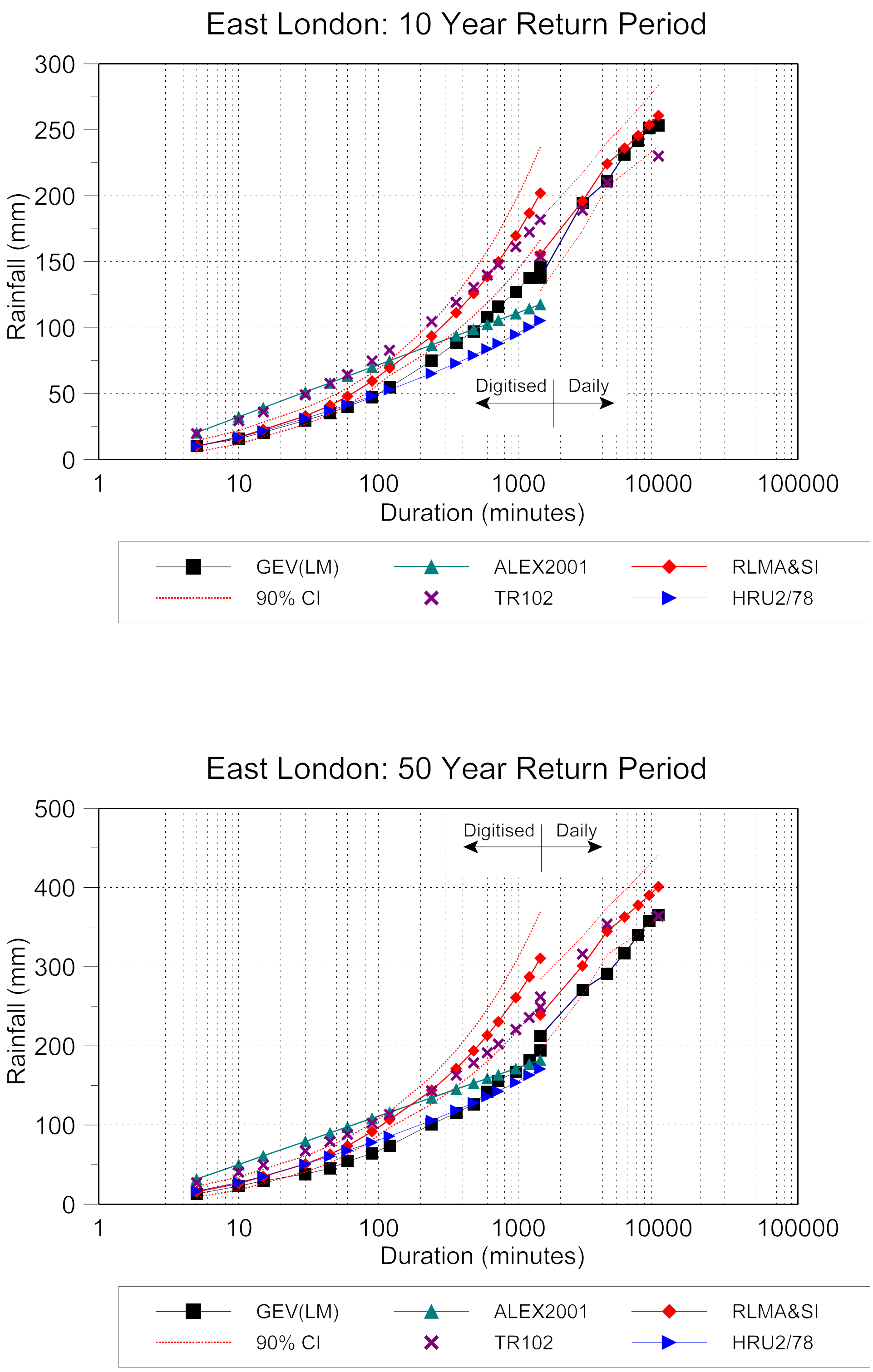


Figure 69 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at East London using various approaches

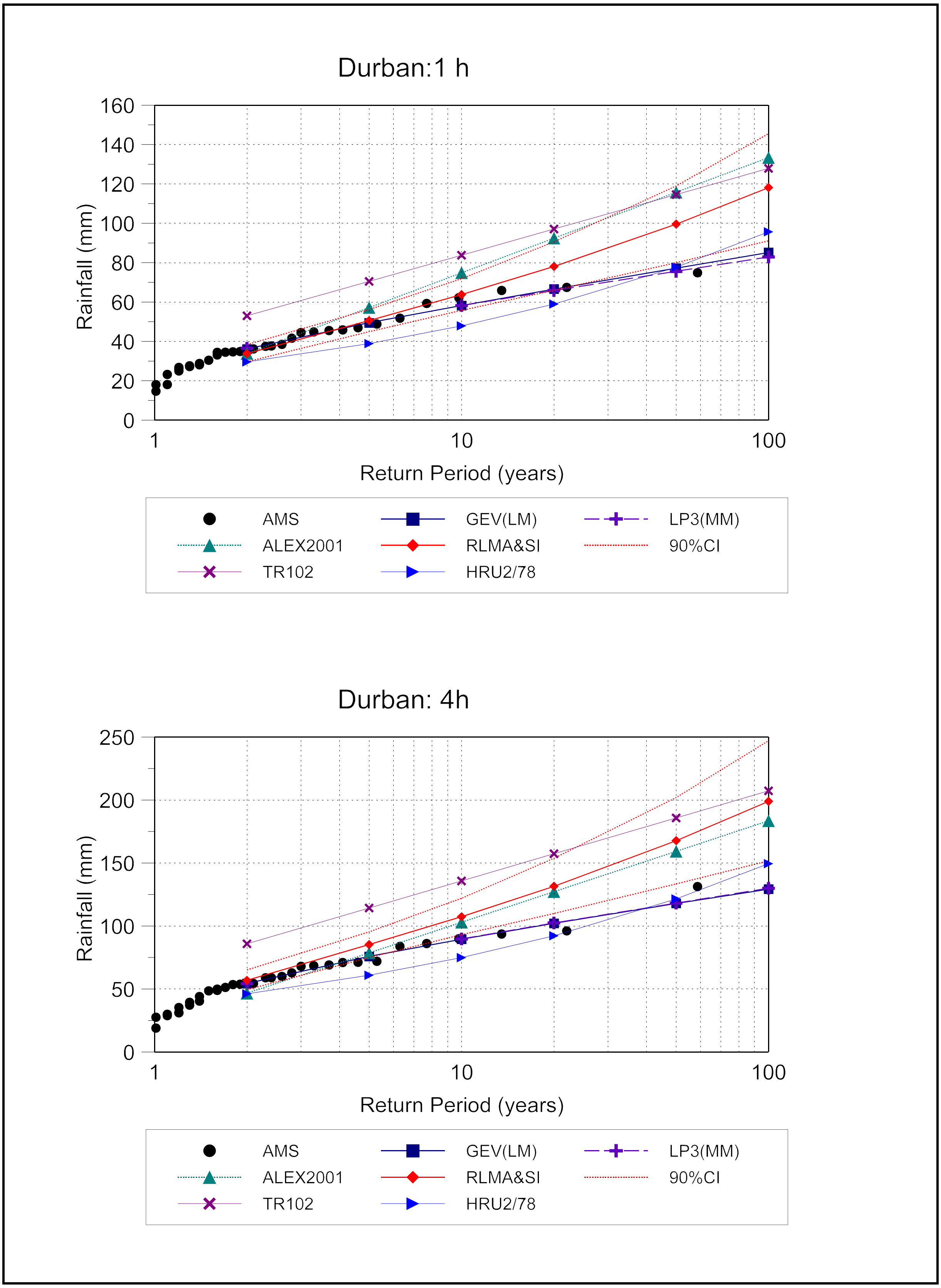


Figure 70 Comparison of 1 and 4 h rainfall depth:frequency relationships estimated at Durban using various approaches

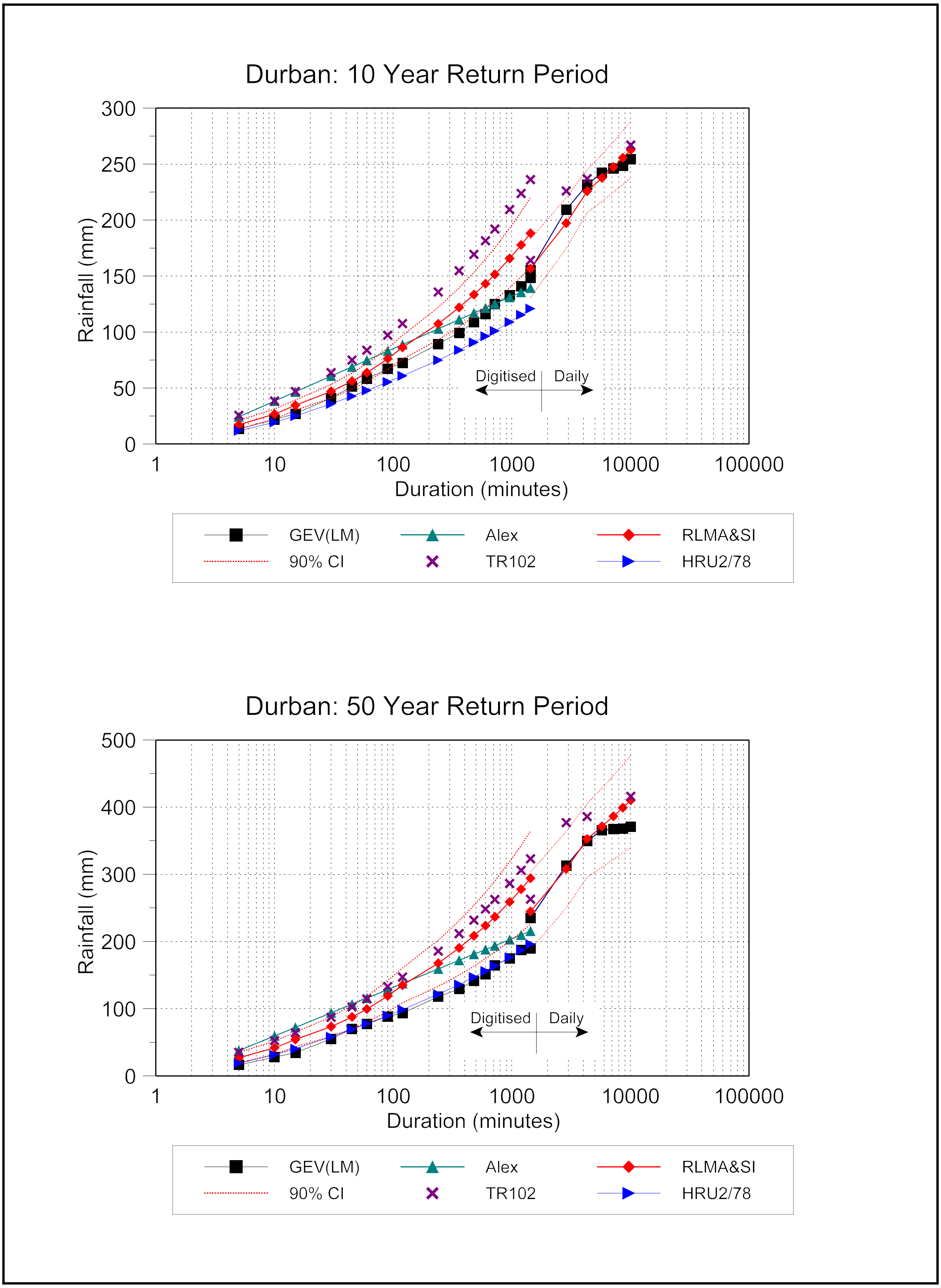


Figure 71 Comparison of 10 and 50 year return period rainfall depth:duration relationships estimated at Durban using various approaches

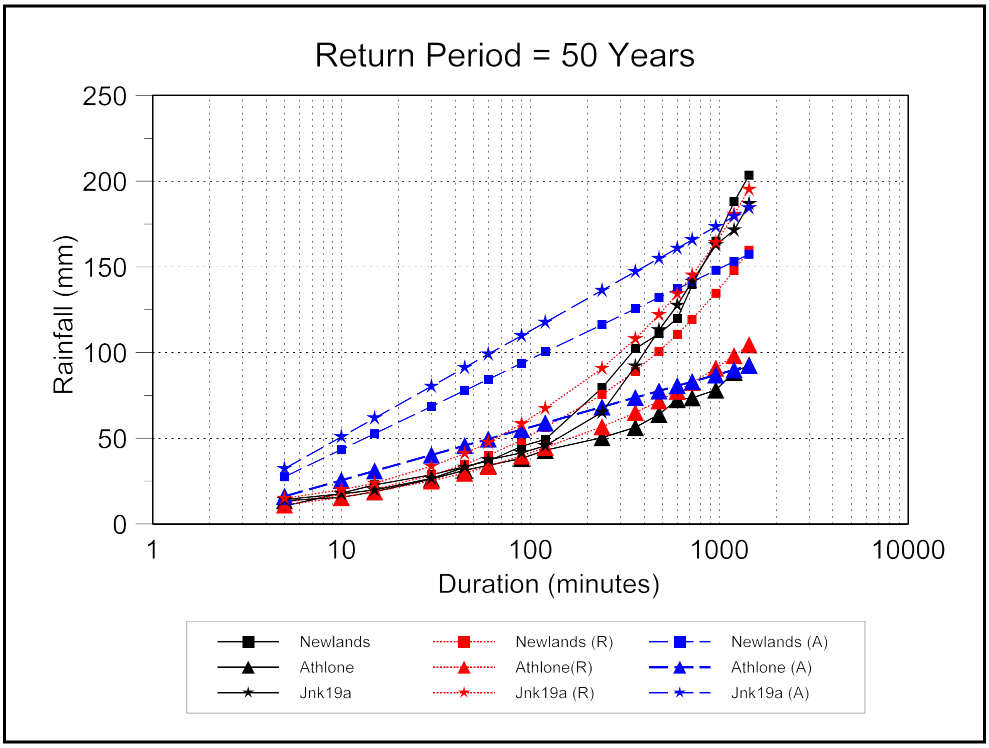


Figure 72 Comparisons between 50 year return period rainfalls estimated from at-site data (black, solid line), RLMA&SI procedures (R) (red, dotted line) and Alexander's 2001 equation (A) (blue, dashed line) for 3 stations in the Western Cape which are considered to have reliable digitised rainfall data

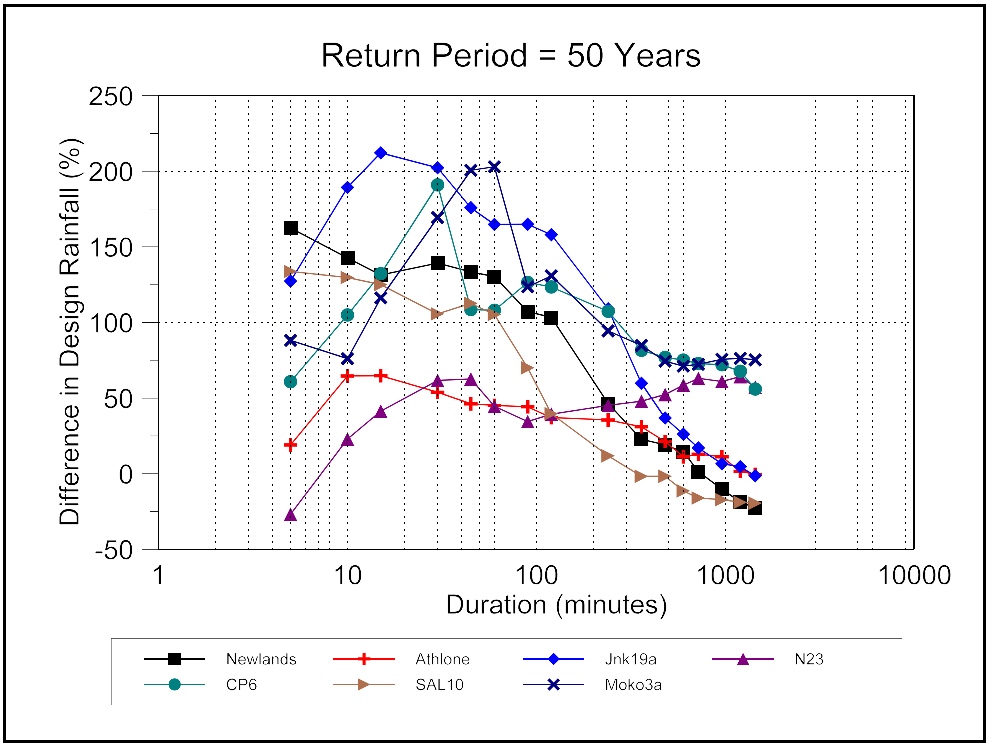


Figure 73 Differences in the 50 year return period design rainfall estimated using at-site data and the Alexander 2001 equation

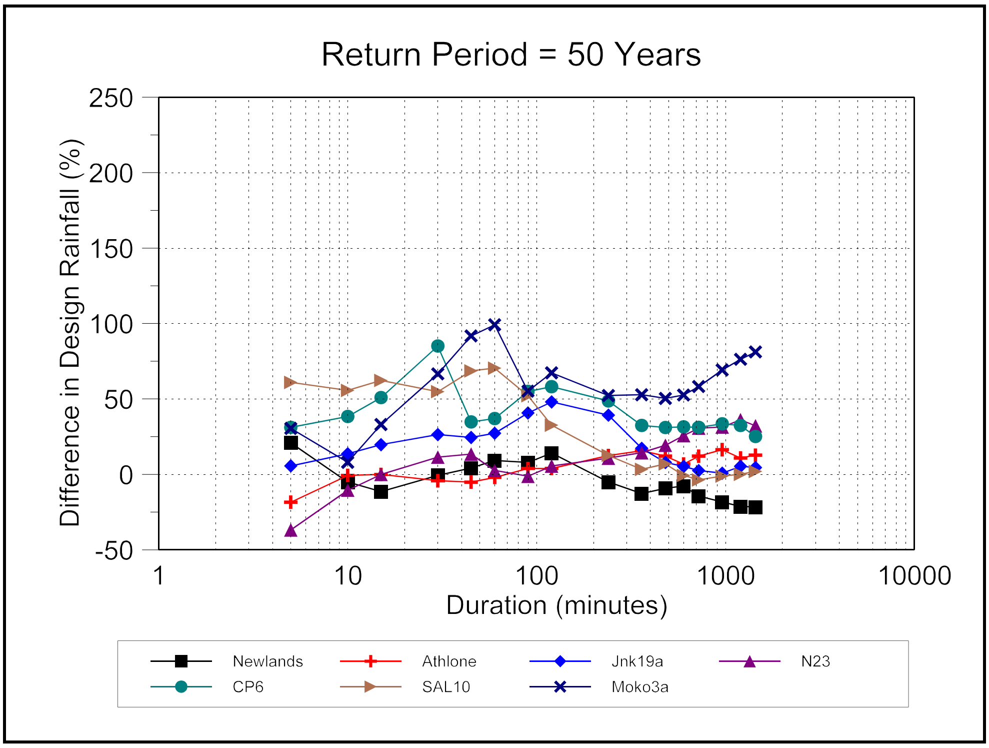


Figure 74 Differences in the 50 year return period design rainfall estimated using at-site data and the RLMA&SI procedures

5.4 Chapter Conclusions

The comparisons performed in this study and reported in this chapter indicate that, compared to the observed data and other techniques for estimating design rainfalls, the RLMA&SI procedures developed in this project generally result in reasonable estimates of design rainfall and which are frequently more consistent than other estimates. This is evident for the 1 to 7 day durations where RLMA&SI values are generally similar to the values computed directly from the observed data and display a consistent trend for these durations, whereas inconsistencies in both the TR102 and observed data are evident. The RLMA&SI values are consistent over the entire range of durations, whereas, the other techniques considered are frequently inconsistent with discontinuities between values for durations shorter than 24 h and the 24 h value. It is evident that the Alexander (2001) equation generally overestimates design rainfalls for durations ranging from 10 minutes to 24 h, with the maximum overestimation occurring at durations of approximately 1 h. The functional relationship of the Alexander equation does not seem to accommodate the curvilinear relationship between design rainfall depth and log transformed duration, which is evident from the data at most stations investigated.

The RLMA&SI procedures utilise the more reliable and longer records of the daily rainfall database to estimate design rainfalls for shorter durations, thus compensating for deficiencies in the digitised rainfall database. An additional advantage of the RLMA&SI procedures is the spatial resolution at which the method can be applied. A user is able to estimate design rainfall depths at a spatial resolution of 1' x 1' latitude/longitude in South Africa and hence spatial trends, and any anomalies, may be determined from estimates at surrounding points.

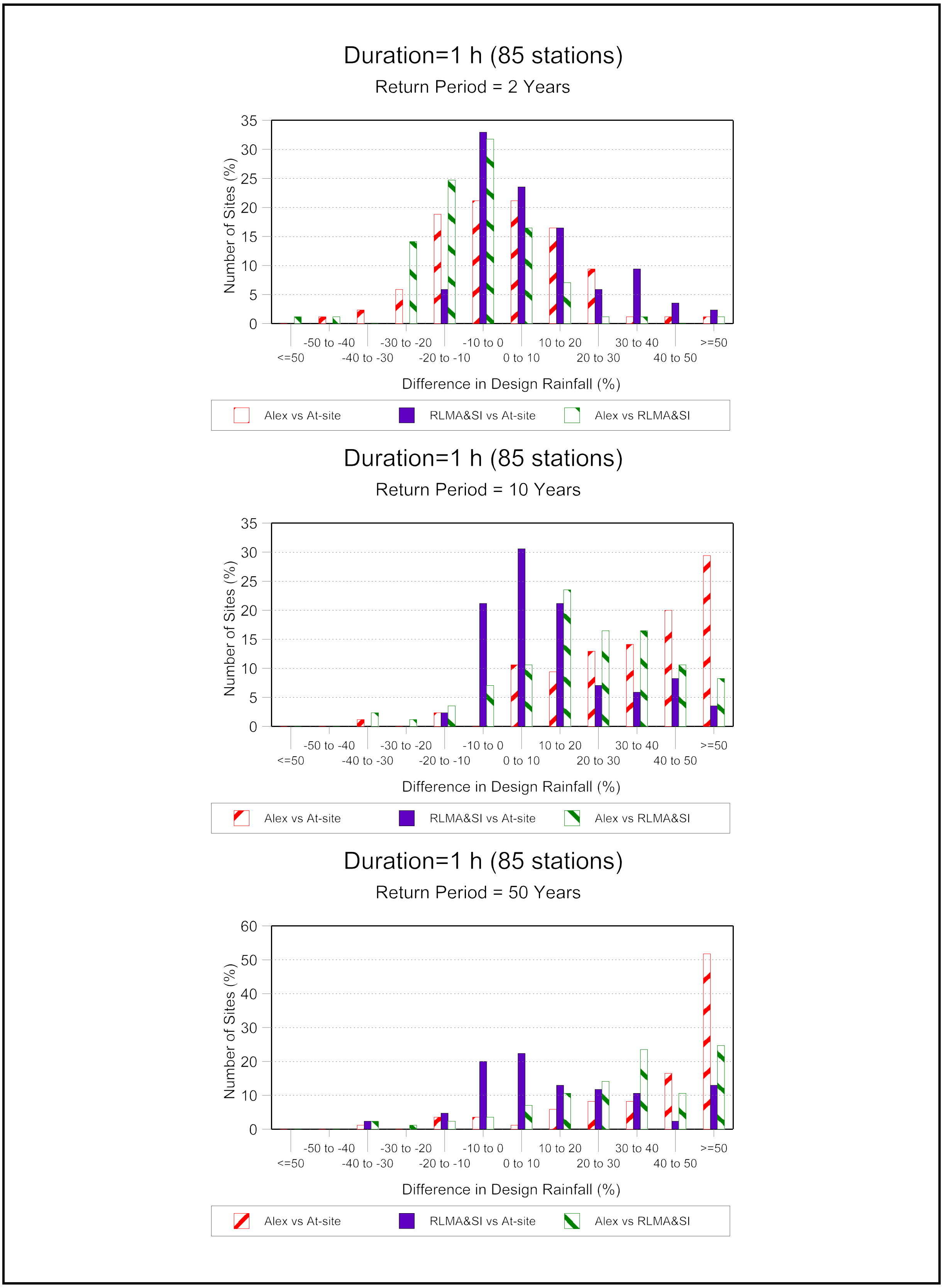


Figure 75 Comparison of design rainfall estimated from at-site data, Alexander's 2001 equation and RLMA&SI procedures for 1 h duration and return periods of 2, 10 and 50 years

PART B

ESTIMATION OF DESIGN FLOODS

CHAPTER 6

A REVIEW OF DESIGN FLOOD ESTIMATION METHODS WITH REFERENCE TO PRACTICES IN SOUTH AFRICA

6.1 Introduction

The estimation of design flood events are necessary for the planning and design of engineering projects (Rahman *et al.*, 1998). Flood frequency analysis remains a subject of great importance owing to its economical and environmental impact (Pilgrim and Cordery, 1993; Bobee and Rasmussen, 1995). However, reliable estimates of flood frequency in terms of peak flows and volumes remain a current challenge in hydrology (Cameron *et al.*, 1999). Cordery and Pilgrim (2000) express the opinion that the demands for improved estimates of floods have not been met with any increased understanding of the fundamental hydrological processes. The urgency for new approaches to design flood estimation in South Africa is highlighted by Alexander (2002).

Standard techniques for flood estimation have been developed for most countries. These generally include statistical analyses of observed peak discharges and event modelling using rainfall-runoff techniques. Observed streamflow data are often not available at the site of interest and rainfall event-based methods have to be used. Recent reviews of approaches to design flood estimation are contained in Cordery and Pilgrim (2000) and Smithers and Schulze (2001c).

The objective of this chapter may be summarised as follows:

- To present a brief overview of methodologies currently used to estimate design floods both in South Africa and internationally;
- To present perceived deficiencies in the techniques currently used to estimate design floods in South Africa;
- To identify and discuss research needed to improve the estimation of design floods in South Africa; and
- To illustrate the use of continuous simulation modelling for design flood estimation, which is finding increasing support internationally.

6.2 Approaches to Design Flood Estimation

The categorisation of approaches to design flood estimation has been attempted by numerous authors. According to HRU (1972), design floods may be estimated using either a statistical approach, which is an ordering and transposition of past experience, or a deterministic approach, in which rainfall is translated into a flood. Pegram (1994) divides the methods into deterministic, empirical and statistical and presents a decision tree for the selection of method for design flood estimation in South Africa. In addition to these approaches, the ASCE (1997) summarises the use of simplified methods such as formulae, regression equations and envelope curves, and also includes rainfall-runoff analysis for a period of record where a historical sequence of rainfall is input to the model to generate the variable of interest, which can then be subjected to frequency analyses, i.e. continuous simulation modelling.

Cordery and Pilgrim (2000) make a similar distinction between statistical analyses, applied either at a single location or across a region, and either deterministically or probabilistically based rainfall-runoff modelling for flood estimation. Beven (2000) distinguishes between statistical estimation based on samples of observed floods at a site, regionalisation methods for catchments with no data, and methods based on rainfall-runoff modelling.

Alexander (1990; 2001) classifies the methods for design flood estimation in South Africa as direct statistical analysis, regional statistical analysis, deterministic and empirical methods. The SANRA (1986) identifies empirical, statistical, as well as the Rational, SCS, run-hydrograph and synthetic unit hydrograph approaches as appropriate and promising methods for estimating design floods in South Africa.

The recently published Flood Estimation Handbook (FEH) for the UK provides two main approaches to flood frequency estimation (Reed, 1999). The first is an index flood approach which utilises growth curves and is the first choice when there is a long record of gauged flow at or close to the site of interest, and which may be used for catchments with areas larger than 0.5 km^2. The second approach is the Flood Studies Report (FSR) rainfall-runoff method which may be used for catchments with areas up to 1000 km^2. The methods used for design flood estimation are categorised and summarised in Figure 76.

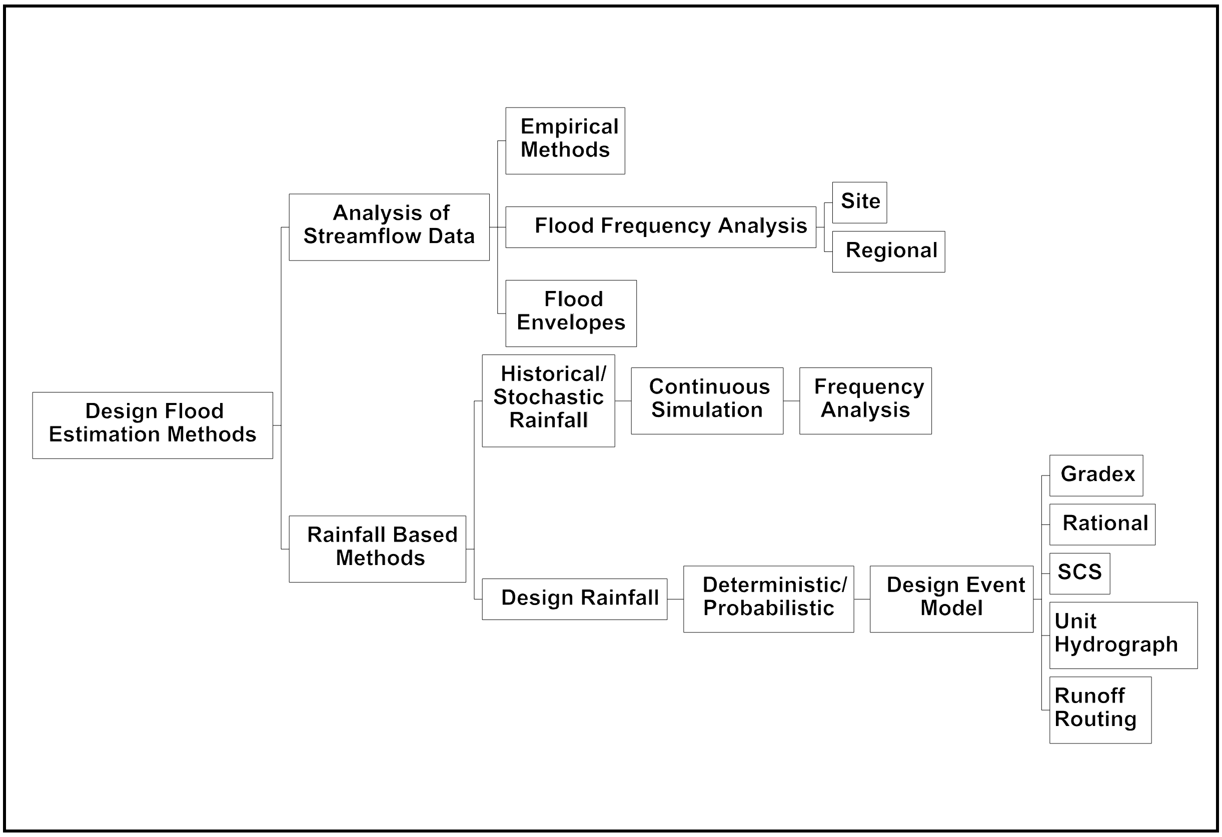


Figure 76 Methods for estimating design floods (after Smithers and Schulze, 2001)

6.3 Flood Frequency Analysis

Where long records of streamflow are available at a site, a frequency analysis of observed data may be performed. However, many studies have shown that a regional approach to frequency analysis results in more reliable design estimates. At-site and regional approaches are reviewed in the following sections.

6.3.1 At-site analysis

The procedures for direct frequency analysis of observed peak discharge often involves selecting and fitting an appropriate theoretical probability distribution to the data. These procedures are referenced in standard hydrology texts (e.g. Chow *et al.*, 1988; Stedinger *et al.*, 1993). As shown by Schulze (1989) and Smithers and Schulze (2000a), the question of selecting an appropriate distribution has received considerable attention in the literature, with diverging opinions expressed by various authors. Schulze (1989) questions whether a suitable probability distribution can be selected, given that the best distribution varies with, *inter alia*, the season, storm type and duration and regional differences.

Smithers and Schulze (2000a) summarise approaches available for estimating the parameters of a selected distribution as Method of Moments (MM), Maximum Likelihood Procedure (MLP), Probability Weighted Moments (PWM), L-Moments (LM), Bayesian Inference and non-parametric methods. The use of L-moments to fit distributions has received extensive coverage in the recent literature (e.g. Wallis, 1989; Hosking, 1990; Pearson *et al.*, 1991; Gingras and Adamowski, 1992; Guttman, 1992; Pilon and Adamowski, 1992; Guttman, 1993; Guttman *et al.*, 1993; Lin and Vogel, 1993; Vogel and Fennessy, 1993; Vogel *et al.*, 1993a; Vogel *et al.*, 1993b; Wallis, 1993; Gingras and Adamowski, 1994; Zrinji and Burn, 1994; Hosking, 1995; Hosking and Wallis, 1995; Karim and Chowdhury, 1995; Hosking and Wallis, 1997). L-moments are reported to have less bias when compared to other techniques.

Bobee and Rasmussen (1995) describe the use of L-moments for distribution fitting as an "eye-catching" development for flood frequency analysis while Cordery and Pilgrim (2000) "welcome" the developments of L-moments. However, Bobee and Rasmussen (1995) caution that L-moments may be too robust and outliers may be given too little significance, while Cordery and Pilgrim (2000) emphasise that the use of L-moments does not entirely overcome the fundamental problem of selecting an appropriate distribution for a sample from a population with an unknown distribution.

Schulze (1989) highlights the problem of short data sets and extrapolation beyond the record length. He also illustrates typical measurement errors as well as inconsistency, non-homogeneity and non-stationarity of data, all of which violate the assumptions made when fitting a distribution to the data.

Beven (2000) identifies the following limitations of a direct statistical approach:

- The correct distribution of the flood peaks is unknown and different probability distributions may give acceptable fits to the available data, but result in significantly different estimates of design floods when extrapolated.

- The records of gauged runoff are generally short and the calibration of the gauging structures may not be very robust. Hence the sample only represents a small distribution of the floods at the site and the fitted distribution may be further biased by gauging errors.
- The frequency of flood-producing rainfalls and land use characteristics may have changed during the period of historical measurement.
- The fitted distribution does not explicitly take into account any changes in the runoff generation processes for higher magnitude events.

6.3.2 Regional analysis

Given that the data at a site of interest will seldom be sufficient, or available, for frequency analysis, it is necessary to use data from similar and nearby locations (Stedinger *et al.*, 1993). This approach is known as regional frequency analysis and utilises data from several sites to estimate the frequency distribution of observed data at each site (Hosking and Wallis, 1987; Hosking and Wallis, 1997). Regional frequency analysis assumes that the standardised variate has the same distribution at every site in the selected region and that data from a region can thus be combined to produce a single regional flood, or rainfall, frequency curve that is applicable anywhere in the region with appropriate site-specific scaling (Cunnane, 1989; Gabriele and Arnell, 1991; Hosking and Wallis, 1997). Regionalisation enables a frequency analysis of short records of annual floods to be performed by assisting with the identification of the shape of the parent distribution and leaving the measure of scale to be estimated from the at-site data (Bobee and Rasmussen, 1995).

In the context of flood frequency analysis, regionalisation refers to the identification of homogeneous flood response regions and the selection of an appropriate frequency distribution for the selected regions (Kachroo *et al.*, 2000). Within a homogeneous region, historical data can be pooled to obtain efficient estimates of the parameters of the distribution and hence robust quantile estimates (Kachroo *et al.*, 2000) with smaller standard errors (Mkhandi *et al.*, 2000). Thus, the concept of regional analysis is to supplement the time limited sampling record by the incorporation of spatial randomness using data from different sites in a region (Schaefer, 1990; Nandakumar, 1995).

Regional approaches can also be used to estimate events where no information exists (ungauged) at a site (Pilon and Adamowski, 1992). However, care must be exercised to ensure that such an approach is not applied outside of the region where the method was developed, nor outside of the range of observations used to develop the method (Cordery and Pilgrim, 2000).

In nearly all practical situations a regional method will be more efficient than the application of an at-site analysis (Potter, 1987). This view is also shared by both Lettenmaier (1985; cited by Cunnane, 1989) who expressed the opinion that "regionalisation is the most viable way of improving flood quantile estimation" and by Hosking and Wallis (1997) who, after a review of literature up to 1996, advocate the use of regional frequency analysis based on the belief that a "well conducted regional frequency analysis will yield quantile estimates accurate enough to be useful in many realistic applications". This opinion is also expressed by Cordery and Pilgrim (2000), who conclude that regional approaches are "the only sure basis for improved flood prediction". According to Alexander (1990), regional statistical analyses provide a basis for improving the estimates of the parameters of the distribution at both gauged sites with short records and at ungauged sites. The advantages of regionalisation are thus accepted by numerous respected researchers.

The index flood-based procedure developed by Hosking and Wallis (1993; 1997) and which utilises L-moments appears to be a robust procedure and has been applied in a number of studies. For example, the methodology has been successfully applied by Smithers and Schulze (2000a; 2000b) to estimate both short and long duration design rainfalls in South Africa. A cluster analysis of site characteristics is used to identify potential homogeneous regions, which allows for independent testing of the at-site data for homogeneity. Methods based on L-moments are used for frequency estimation, screening for discordant data and testing clusters for homogeneity (Hosking and Wallis, 1993; Hosking and Wallis, 1997).

Much research in recent years has focussed on the identification of homogeneous regions, as geographical proximity does not imply hydrological similarity (Bobee and Rasmussen, 1995). Kachroo *et al*. (2000) reviewed recent literature and concluded that no objective methods of regionalisation are universally accepted. A significant development in the identification of homogeneous regions is the region of influence approach developed by Burn (1990b; 1990a) and Zrinji and Burn (1990b; 1990a) and which has been adopted by the FEH (Reed, 1999).

The recommended distribution for flood frequency analyses in the USA is the log-Pearson Type 3 (LP3), fitted using the at-site mean and standard deviation and a regionalised estimate of the coefficient of skewness (Stedinger *et al.*, 1993). Details are contained in USWRC (1976) and updated in the subsequent Bulletin 17B publication (IACWD, 1982) which includes procedures for dealing with outliers and conditional probability adjustment. Potter and Letenmeier (1990) showed that an index flood approach using a GEV distribution performed better than the procedures contained in Bulletin 17B.

According to Alexander (1990) no comprehensive studies of regional statistical analysis methods have been made in South Africa since the early 1970s. He outlines a generalised procedure for regional statistical analyses. According to Alexander (1990), the distribution of gauging stations in South Africa is too sparse to pre-determine hydrologically homogeneous regions. He recommends an alternative method of grouping stations which consists of plotting scaled growth curves and rejecting stations which have growth curves inconsistent with the remaining stations.

McPherson (1984) investigated methods to estimate the mean annual and 2 year return period floods in South Africa. The catchment parameter method developed showed promising initial results, but has not been developed further.

A tentative regionalisation based on the regions identified by Kovacs (1988) was performed by Van Bladeren (1993) for the KwaZulu-Natal and former Transkei regions. He noted that further regionalisation was necessary and that a strong relationship existed between the mean annual flood and catchment area.

Mkhandi *et al.* (2000) used the L-moment based procedures developed by Hosking and Wallis (1993) to identify both discordant gauging stations and homogeneous flood producing regions in Southern Africa. Thirteen homogeneous regions were delineated utilising drainage regions in South Africa and the Pearson Type 3 distribution fitted by PWM was found to be the most appropriate distribution to use in 12 of the regions. In the western coastal region of South Africa the LP3 distribution fitted by MM was found to be the most appropriate distribution.

A initial regionalisation of the annual maximum series of peak discharges for KwaZulu-Natal in South Africa has been derived by Kjeldsen *et al*. (2002). The index flood method, as proposed by Hosking and Wallis (1993; 1997) was utilised in the study. Two homogeneous regions were identified and suitable regional frequency distributions were sought. In order to estimate a design flood at an ungauged site, it is necessary to re-scale the regional growth curve by an estimate of the index flood at the site. Kjeldsen *et al*. (2001) developed relationships to estimate the index flood as a function of the MAP and catchment area.

The run-hydrograph technique as detailed in Hiemstra *et al.* (Hiemstra *et al.*, 1976) Hiemstra and Francis (1979), Hiemstra *et al*. (1979) and Hiemstra (1981), is based on a regional analysis of historical data but was recommended, soon after its development, only to be used to check the results from other methods (SANRA, 1986). Although no further evaluation of the method has been documented since the report by SANRA (1986), Alexander (1990) does not recommend the run-hydrograph procedure for general use in South Africa, while Alexander (2001) concedes that the run-hydrograph method has advantages compared to the unit hydrograph method and concludes that the run-hydrograph method requires further development. The run-hydrograph method is endorsed for use in South Africa by Pegram (1994).

6.3.3 Maximum envelopes

In the maximum envelope approach, the largest observed discharges are usually plotted against catchment area, both on logarithmic axes. An envelope is sketched to include all the data points. Approximate estimates are possible, providing that data from catchments similar to the one of interest was included in the analysis (Cordery and Pilgrim, 2000). Maximum peak discharges can be determined at ungauged sites using envelope curves (ASCE, 1997). The envelope tends to increase as the record length increases and larger floods are observed.

The HRU (1972) provided a set of regionalised maximum observed flood peak envelopes for South Africa. Kovacs (1988) developed comprehensive regional maximum flood envelopes for South Africa. This approach has been stated to be reliable in medium sized catchments (Alexander, 1990).

6.4 Rainfall Based Methods

The situation which faces design engineers and hydrologists most frequently is when no, or inadequate, streamflow data are available at the site of interest. As indicated in Figure 76, the choices available in such a situation are between event and continuous rainfall based methods. Both deterministic and probabilistic models are used. The advantages of rainfall-runoff models may be summarised as follows (Schulze, 1989; Rahman *et al.*, 1998):

- Generally longer rainfall records at more sites, and with better quality, are available for analysis compared to streamflow records.

- Measurement errors, inconsistencies in the data and non-homogeneous streamflows make the data unsatisfactory for direct frequency analysis.
- Similarly, non-stationary streamflow records as a result of changing catchment conditions can render the streamflow record unsatisfactory for direct frequency analysis.
- Areal extrapolation of rainfall records can be achieved more easily than runoff records.
- Physical features of a catchment can be incorporated into a rainfall-runoff model.
- The historical, current or expected future conditions of land use within a catchment can be modelled.

6.4.1 Design event models

The widespread use of design event models is related to their lumping of complex, heterogeneous catchment processes into a single process, their ability to handle individual events, and simple model application (Houghton-Carr, 1999). The event based approach greatly simplifies the estimation of catchment conditions prior to the occurrence of an extreme event, even when rainfall-runoff modelling is performed to estimate the flood hydrograph (Cameron *et al.*, 1999).

Design event based models assume that, for representative inputs and model parameters, the frequency of the estimated flood is equal to the frequency of the input rainfall. This assumption is likely to introduce significant bias in the frequency of flood estimates and the validity of this assumption is crucial to the accuracy of this approach (Rahman *et al.*, 1998). Much uncertainty is present in inputs such as storm duration, the spatial and temporal distribution of the design storm and model parameters (Rahman *et al.*, 1998). Design event based approaches consider the probabilistic nature of rainfall, but ignore the probabilistic behaviour of other inputs and parameters. Four general approaches are suggested by Pilgrim and Cordery (1993) to maintain the required probability for the selected flood, with the last two options listed below showing the greatest practical value:

- frequency analysis of synthetic streamflow generated by a continuous rainfall-runoff from long records of rainfall,
- joint probability analysis of variables contributing to the flood discharge,
- use of median values for model parameters, and
- values derived by comparison of floods and rain of the same probability.

Three approaches have been adopted in Australia in an attempt to estimate a flood with the required return period (Pilgrim, 1987; Pilgrim and Cordery, 1993):

- The use of median values of input, other than rainfall, to models:
  The use of "worst" design parameters (e.g. high runoff coefficients and low losses) result in flood estimates with exceedance probabilities lower than that of the input rainfall.
- The derivation of relationships that link directly the rainfall and runoff for the same exceedance level:
  An example of this approach being the probabilistic approach to the Rational Method.
- The use of joint probabilities to the variables which contribute to the flood:
  Although superior to the above two approaches, uncertainties increase for larger return periods.

For small to medium sized catchments in Australia, Pilgrim (1987) recommends the probabilistic Rational Method with regionalised coefficients, regional flood frequency methods, design hydrograph methods which include unit hydrograph and loss function methods, synthetic unit hydrographs and runoff routing and the USDA's SCS technique as appropriate methods for design flood estimation. The Rational, SCS, Gradex, Unit Hydrograph and runoff-routing are listed by Cordery and Pilgrim (2000) as commonly used design rainfall event methods for flood estimation. These are briefly discussed in the following sections.

6.4.1.1 Rational method

The Rational Method is widely used throughout the world for both small rural and urban catchments (Pilgrim and Cordery, 1993; Alexander, 2001). The Rational Method is viewed as an approximate simplified technique for design flood estimation in the USA which requires little effort to apply (ASCE, 1997). The method is an approximate deterministic method and a major weakness is the judgement required to determine the appropriate runoff coefficient and the variability of the coefficients between different hydrological regimes (Pilgrim and Cordery, 1993). The Rational Method computes only flood peaks and is sensitive to the input design rainfall intensity, the selection of the runoff coefficient, the experience of the user and should not be used for catchments > 15 km^2 . The experience of the user and the selection of appropriate runoff coefficients are essential for the application of the Rational Method, which can give realistic results when used circumspectly (SANRA, 1986). In addition, Cordery and Pilgrim (2000) identify the practical difficulties of estimating the catchment response time because regional differences in the time of concentration cannot be easily explained by measured catchment characteristics. The assumed uniform rainfall intensity and the exclusion of temporary storage limits the application of the deterministic Rational Method to urban and small rural catchments (Cordery and Pilgrim, 2000). Hence, Pilgrim and Cordery (1993) and Cordery and Pilgrim (2000) recommend a probabilistic approach to determine the runoff coefficient for the Rational Method.

The probabilistic Rational Method has been developed for Australia with the runoff coefficient for different return periods either mapped or related by regression to catchment based physical variables. Studies in Australia have shown the superior performance of the probabilistic Rational Method, which is suitable for catchments of up to 250 km^2, compared to the very poor performance of the deterministic approach (Pilgrim and Cordery, 1993). Contrary to the deterministic approach, the probabilistic runoff coefficients did not show much variation with catchment characteristics (Pilgrim and Cordery, 1993). According to Pilgrim (1987), the use of the probabilistic interpretation of the Rational Method is acceptable for estimating design events, but the method is not suitable for estimating the flood peak for a particular rainfall event.

The HRU (1972) outlines a deterministic Rational Method approach to design flood estimation in South Africa which is suitable for application in catchments with areas of up to 15 km^2 and the Rational Method is also recommended by SANRA (1986) and Alexander (1990; 2001). The runoff coefficient may be estimated as a function of MAP, catchment land cover, permeability and steepness, vegetation cover and return period. The return period adjustment factor decreases the runoff coefficient for events with return periods < 50 years. Differing values for the return period adjustment factor in South Africa are presented by SANRA (1986) and Alexander (2001).

Alexander (1990) advocates the calibration of the Rational Method with local data, where it is available.

Alexander (2002) developed a “Standard Design Flood” method, which is in effect a calibrated Rational Method. Raingauges were assigned to 29 representative catchments in South Africa which have observed flow data and the Rational runoff coefficient (“C” factor) was calibrated until the design flood estimated using design rainfall values equalled that computed directly from the gauged flow data. Some subjective adjustment was performed to the calibrated runoff coefficients to “produce a more conservative estimate”. The 29 catchments were grouped into 8 larger regions and verifications were performed at 84 sites where, on average, the standard design flood exceeded the at-site values by 60%. According to Görgens (2002) the “Standard Design Flood” method is a conservative approach and would not be suitable, for example, in the design of dam spillways.

6.4.1.2 SCS method

The SCS method for design flood estimation is widely used and has, in the USA, replaced the Rational Method (Pilgrim and Cordery, 1993). This is attributed by Pilgrim and Cordery (1993) to the wider apparent database and the manner in which the physical catchment characteristics are incorporated. Inconsistencies in the application of the method are the result of the choice of procedures for estimating the time of concentration and in choosing a relevant curve number (CN). Pilgrim and Cordery (1993) summarise the following with regard to the SCS method:

- The SCS model performed poorly in simulating actual peak discharges from runoff plots in the USA.
- The assumed antecedent moisture conditions had a major effect on the results.
- The model performed better on catchments with sparse vegetation than those with dense vegetation.
- The SCS method was applied in a probabilistic manner in Australia and the derived CN showed little agreement with those estimated by conventional means. The derived CN was affected both by the method used to estimate the catchment lag time and on the return period.

The above results led Pilgrim and Cordery (1993) to doubt the accuracy and validity of the SCS method and suggest that the results from the SCS method should be checked against observed flood data in the region in which it is applied. Cordery and Pilgrim (2000) express the opinion that the SCS method is vaguely intuitive and cannot be expected to provide reliable design estimates.

Haan and Schulze (1987) treated the input variables in the SCS equation as random variables in order to correctly transform the rainfall with a given exceedance probability into runoff with the same probability. They found that the traditional SCS method of accounting for antecedent moisture conditions resulted in reasonable estimates of runoff.

The SCS method adapted for South Africa by Schmidt and Schulze (1987) utilised the developments and verifications by Schulze and Arnold (1979), Schulze (1982), Schmidt and Schulze (1984) and Dunsmore *et al*. (1986). These adaptions were computerised by Schulze *et al*. (1992) and the method is now widely used for the estimation of design floods from small catchments in South Africa. The SCS method is not as sensitive as the Rational Method to user inputs. It can compute the entire hydrograph and is recommended for both urban and rural catchments with areas < 10 km^2 (Campbell *et al.*, 1986; SANRA, 1986). A further statistical analysis of the results presented by Campbell *et al.* (1986) was performed by Schulze *et al.* (1986), who excluded rainfall events less than 20 mm, and concluded that the the SCS-based models, particularly the South African adaptions, performed well enough to be recommended for design on a considerable range of land use and catchment size categories.

6.4.1.3 Unit hydrograph method

The unit hydrograph approach to design flood estimation is detailed in most hydrology texts (e.g. Chow *et al.*, 1988; Maidment, 1993). The method assumes a characteristic linear response from a catchment and hence may not be accurate for estimating large floods. However, careful use can provide good flood estimates. A limitation of a unit hydrograph approach is the assumption of spatial uniformity of rainfall (Chow *et al.*, 1988; Maidment, 1993). An advantage of the method is the estimation of the entire hydrograph, which is important where storage within a catchment is found.

For the UK the FEH re-states the FSR rainfall-runoff method for design flood estimation with new estimates of model parameters (Houghton-Carr, 1999). The FSR model is a deterministic 3 parameter model of catchment response and consists of a unit hydrograph and a loss model (Houghton-Carr, 1999). The parameters relate to the catchment response time, the proportion of rainfall which contributes directly to flow in the river and the quantity of baseflow in the river prior to the event. The parameters for the model may be derived from observed rainfall and runoff records if these are available or, at ungauged sites, either from physical and climatic descriptors of the catchment or by the transfer of information from donor gauged catchments. The point design rainfall for the target return period flood is converted to an areal rainfall using an areal reduction factor and disaggregated temporally to form a hyetograph. The estimated runoff is converted into a hydrograph using the catchment unit hydrograph and baseflow is added to complete the design hydrograph (Houghton-Carr, 1999).

The FSR unit hydrograph and loss model is widely used for three reasons (Houghton-Carr, 1999):

- The model is relatively well understood;
- The model can be easily and generally derived for any site; and
- The simple structure of the model allows the incorporation of local data.

Houghton-Carr (1999) identifies the most general weakness of the FSR model to be the assumption that a unique combination of the four specific inputs will estimate a design flood with the required return period. The performance of the original FSR model has been shown to vary regionally, which is attributed to the approach adopted for model calibration, with the calibrations performed at a national scale (Houghton-Carr, 1999). No evaluations of the current versions of the model have been made (Houghton-Carr, 1999).

For catchment areas ranging from 15 - 5000 km^2, the HRU (1972) describes a unit hydrograph technique for application in South Africa, which was updated by Bauer and Midgley (1974). Data from only 92 gauges with catchment areas ranging from 21 to 22163 km^2 were used in the analysis. Nine veld zone types were identified in South Africa and dimensionless unit hydrographs were derived for each zone. The number of catchments represented in each zone ranged from 5 to 18. A co-axial diagram to estimate mean storm losses in the 9 zones was developed. SANRA (1986) recommend that in South Africa the unit hydrograph approach is a reliable method for catchments ranging in size from 15 - 5000 km^2. Bauer and Midgley (1974) developed the simple-to-apply lag-route method of design flood estimation in South Africa, based on the results of the unit hydrograph technique.

6.4.2 Continuous simulation modelling

6.4.2.1 Review

Continuous simulation models attempt to represent the major processes which convert rainfall into runoff. Historical data or stochastic rainfall series are used to generate outflow hydrographs over long time periods and the simulated flow can be subjected to standard frequency analysis techniques. Thus, model parameters determined using a relatively short period of calibration and verification can be used together with a long climate series to yield flood frequency estimates (Calver and Lamb, 1995). If the model parameters can be related to the catchment characteristics, then the model parameters can be transferred to similar catchments.

It is the opinion of Reed (1999) and Houghton-Carr (1999) that continuous simulation modelling for design flood estimation is still in the experimental and developmental stage. Reviewing recent literature, Cameron *et al*. (1999) express the opinion that, although not fully proven, the use of continuous modelling for design flood estimation has resulted in encouraging output. The use of continuous simulation modelling is conceptually attractive in that a continuous moisture balance is maintained and hence the state of the catchment before each storm is implicitly determined. However, the number of variables to calibrate may be substantial (ASCE, 1997).

In a variation to continuous simulation modelling, Rahman *et al*. (1998) summarise a "runoff file" approach, where the outputs from continuous simulation for selected conditions are stored for subsequent use. This reduces the expertise required for setting up the model and repeated model calibration by different users.

The use of historical rainfall and the continuous simulation of catchment soil moisture make the simplifying assumptions of event based modelling unnecessary (Cameron *et al.*, 1999). Reed (1999) refers to "whole catchment modelling" which integrates hydrological, hydraulic and various impact models. The data demands of continuous simulation modelling are of concern to Reed (1999), but he concedes that such an approach overcomes many limitations of the design event approach and the complications of the joint probability approach.

Schulze (1989) argues for a continuous simulation modelling approach to design flood estimation, because:

- long periods of record are necessary for accurate estimation of design values,
- long series of observed flood data are generally not available, often contain inconsistencies and are frequently both non-homogeneous and non-stationary,

- in comparison to runoff data, longer data sets of rainfall of better quality are usually available for most regions in South Africa, and
- the exceedance probability of floods is generally not related to the exceedance probability of rainfall, as assumed in simple event based models.

The advantage of the modelling approach is that a complete hydrograph is generated and not only a peak discharge (Reed, 1999). Rahman *et al.* (1998) refers to numerous publications and summarise the advantages of continuous simulation models as follows:

- No synthetic storms are required, as actual storm records are used and hence critical storm duration is not an issue.
- Antecedent moisture conditions (AMC) are modelled explicitly and hence any subjectivity in attempting to account for AMC is removed.
- The statistical analysis of output implies that the return period of the output is not assumed to be equal to that of the input rainfall.

In a similar vein, Boughton and Hill (1997) list the following advantages of such a system:

- actual rainfall data from the area are used and not general regionalised design values,
- the use of a calibrated rainfall-runoff model avoids the needs for assumptions about losses, and
- sequences equal in length to the assumed return period of the probable maximum flood can be generated and hence no assumption regarding the shape of the distribution in this range are necessary.

Rahman *et al.* (1998) refer to numerous publications and summarises the disadvantages of continuous simulation models as follows:

- The difficulties in adequately modelling the soil moisture balance and obtaining input data at the required temporal and spatial scale,
- the loss of "sharp" events if the modelling time scale is too coarse,
- the extensive data requirements which result in significant time and effort to obtain and prepare the input data, and
- the expertise required to determine parameter values such that historical hydrographs are adequately simulated.

Pilgrim and Cordery (1993) refer to the use of storage type models where the runoff processes are represented in more detail. These may be simple models such as the ILLUDAS model or network models such as the HEC-1 model and RORB model.

Calver and Lamb (1995) illustrated the use of continuous simulation modelling for design flood estimation on 10 varied catchments in the UK, ranging in size from 1 to over 400 $km^{2.}$ Two models with between 5 and 10 parameters were used and acceptable results were obtained. Calver and Lamb (1995) question if the models used were sufficiently robust and highlight the sensitivity of the results to the quality of the input data.

Boughton and Hill (1997) combined a daily rainfall generating model to generate long streamflow sequences with daily rainfall as input to a calibrated rainfall-runoff model. A procedure relating annual maxima peak flow rates to annual maxima daily runoff volume is utilised. Daily rainfall records are generally longer and more abundant than streamflow records and, with the use of data generation techniques, are not limited to the length of the historical rainfall record. The stochastic rainfall model attempts to simulate the annual maxima daily rainfalls to reflect the actual distribution of observed annual maxima. The Australian Water Balance Model (AWBM) is an explicit water balance model, capable of operating at daily or hourly time steps and simulates three surface storages with different capacities to represent partial area runoff. A limitation to the continuous modelling system developed by Boughton and Hill (1997) is the need for concurrent rainfall and runoff records to calibrate the model and to estimate peak discharges as a function of runoff volume. The calibration of the stochastic rainfall model to annual maxima may compromise other characteristics of rainfall, e.g. wet-wet sequences which may influence the simulated runoff. No uncertainty is built into the parameters of the model and hence the simulated sequences only reflect the variability of rainfall. No reference is made to catchment size limitations and the application of the model on large heterogeneous catchments is not discussed.

The IHACRES model was used by Steel (1998) to simulate instantaneous peak flows dating back to the 1870s for 11 rivers in Scotland using long homogeneous daily rainfall series. The low variability of the simulated flow in some rivers is attributed by Steel *et al*. (1999) to be the consequence of using a daily time step in the model. The importance of a longer simulated record for design flood estimation is illustrated by Steel *et al*. (1999).

Cameron *et al*. (1999) used TOPMODEL to derive the frequency distribution of extreme discharges by continuous simulation. They simulated runoff from a 10.6 km^2 catchment in Wales, UK, and showed that parameter sets for TOPMODEL could be found that satisfied both hydrograph and flood frequency simulation.

Alexander (1990; 2001) refers to literature that recommend simulation models for design flood estimation in small catchments and expresses the opinion that no simulation models are generally applicable for flood determination in South Africa. Alexander (2001) does recommend the SCS method for agricultural catchments with areas < 8 km^2.

In summary, the advantages of continuous simulation models are the simulation of the complete hydrograph and continuous simulation of antecedent moisture conditions. These need to be weighed against the challenges of input data preparation, assigning values to model parameters and regionalisation (Houghton-Carr, 1999). The currently available increased computing power and sub-daily rainfall and flow data in digital form, enables the continuous simulation of hydrographs to become a standard technique for estimating design floods (Cameron *et al.*, 1999). In the application of continuous simulation models for design flood estimation, the requirement that consistent model parameterisations are necessary for both continuous flow series and flood frequency simulation, expressed by Cameron *et al*. (1999), needs to be borne in mind.

6.4.2.2 Application of continuous simulation modelling for design hydrology in South Africa

In South Africa the use of the conceptual-physical, daily time step *ACRU* model (Schulze, 1995) has been used to estimate design peak discharges. For example, Smithers *et al.* (1995; 1997) applied the *ACRU* model on the 760 km^2 Lions and Mpofana tributaries of the Mgeni River. The location, catchment discretisation and schematic flow paths used in the study reported by Smithers *et al.* (1995; 1997) are shown in Figure 77.

Of the two gauging stations for which observed data were available for model verification, only data from gauging station U2H013 could be utilsed, as the observed daily peak discharges at U2H007 did not exceed a threshold of 31.7 $m^3.s^{-1}$, presumably because the gauging structure was not designed to measure events exceeding this value. Examples of daily observed and simulated peak discharges are illustrated in Figure 78. The design floods estimated using the General Extreme Value (GEV) distribution fitted to the annual maximum series extracted from the observed and simulated series at U2H013 are depicted in Figure 79. From results such as these it was concluded that a continuous simulation approach could reliably be used for design flood estimation in the study area.

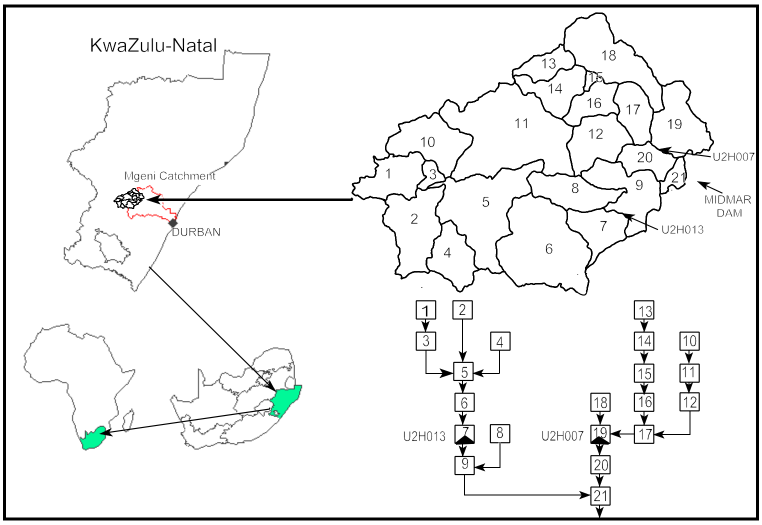


Figure 77 Location, catchment discretisation and schematic flow path

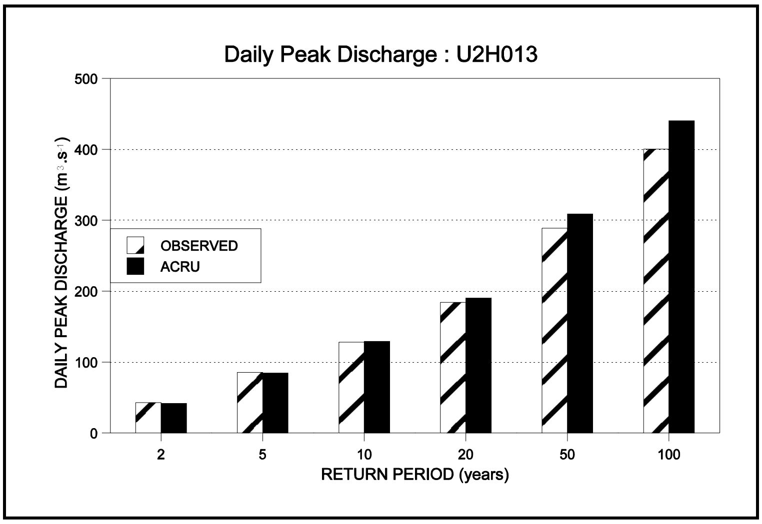


Figure 78 Design flood estimates for simulated (*ACRU* model) and observed data at gauging station U2H013 (after Smithers *et al.*, 1997)

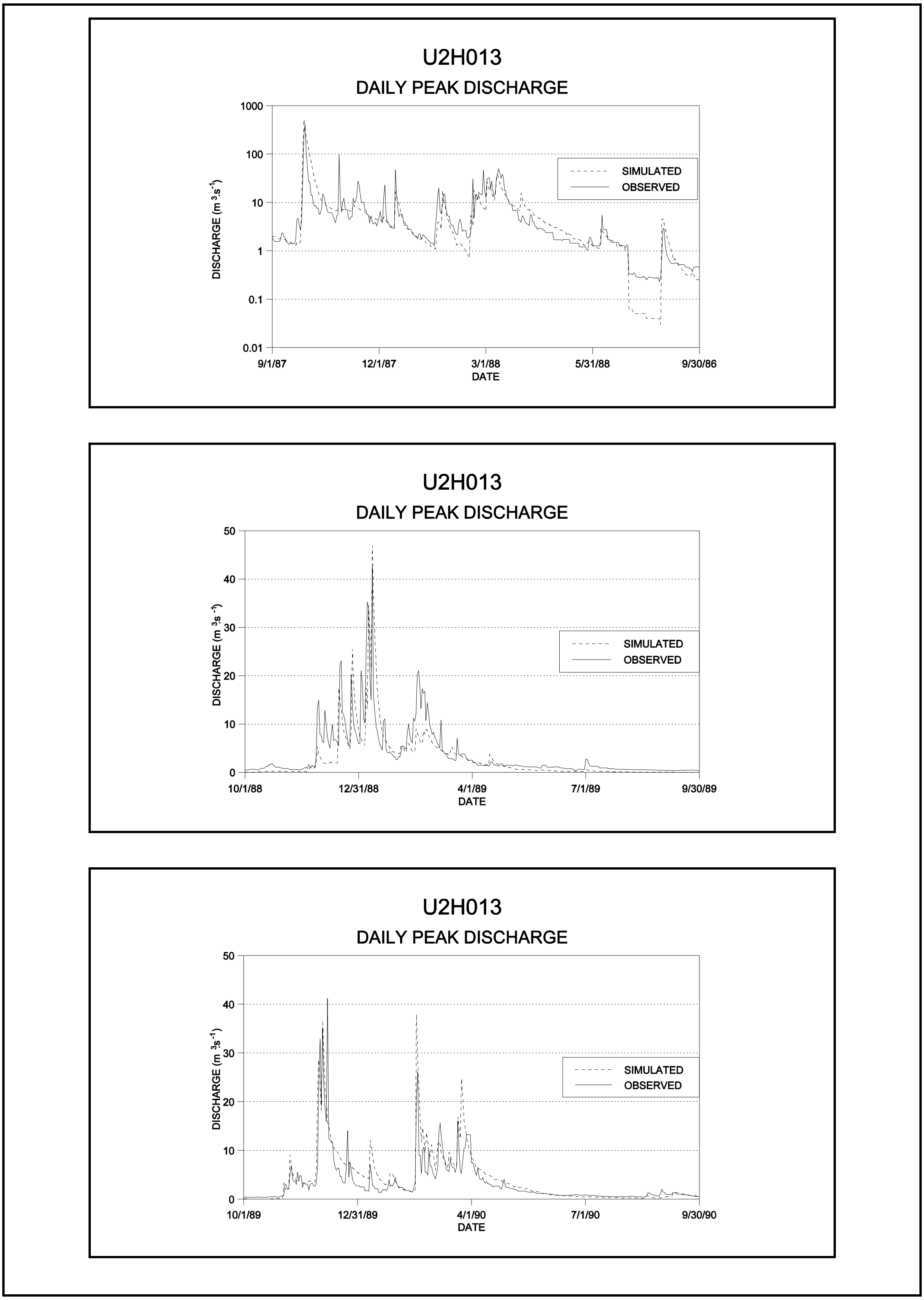


Figure 79 Examples of simulated (*ACRU* model) and observed daily peak discharge at U2H013 (after Smithers *et al.*, 1997)

More recently, a continuous simulation modelling approach was adopted by Smithers *et al*. (2000) to investigate the spatial variability, magnitudes and probabilities of the floods which occurred during the February 2000 in the Sabie River catchment. Again, the data from many gauging structures were not suitable for verification of floods simulated by the model, with overtopping of the weirs evident at many gauges. Examples of frequency analyses of observed and simulated daily peak discharges at gauging weirs X3H001 (173 km^2) and X3H006 (766 km^2) are shown in Figure 80. Peak discharges and return periods of the February 2000 floods estimated from the simulated series compared favourably with initial, hydraulically based assessments of the flood magnitudes made by Van Bladeren and Van der Spuy (2000).

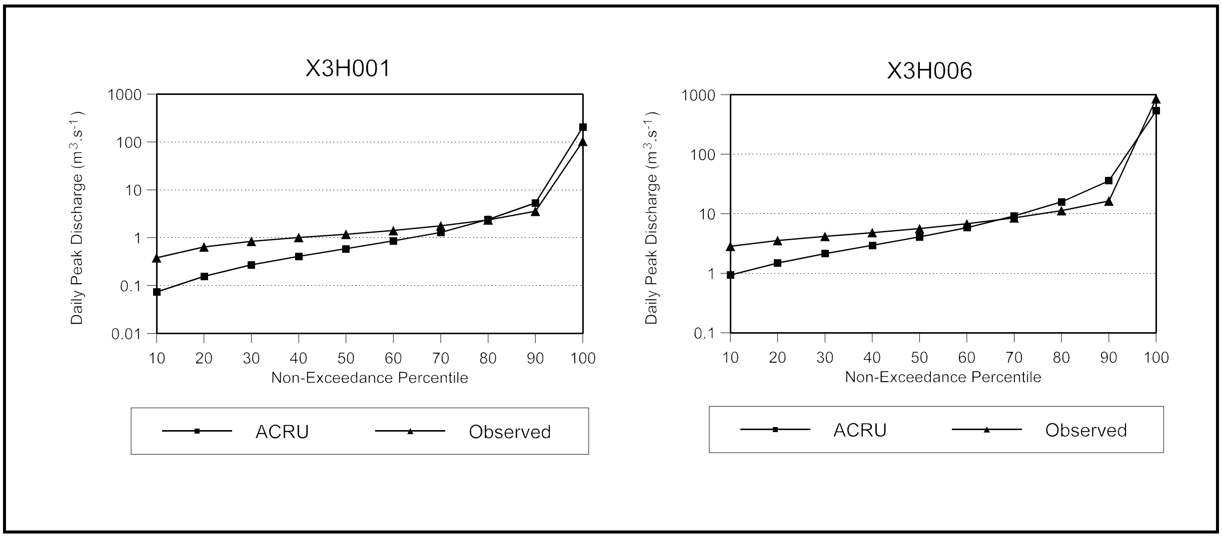


Figure 80 Frequency analysis of simulated and observed daily peak discharges at Gauging Weirs X3H001 and X3H006 (after Smithers *et al.*, 2001)

6.5 Chapter Discussion and Conclusions

Design flood estimation may be performed by a frequency analysis of observed flows where these are available and are adequate in length and quality. While the analysis may be performed at a single site, a regional approach should preferably be adopted. The advantages of a regional approach to frequency analysis for design flood estimation are evident from the studies reviewed. This has led to the adoption of a regional approach as the recommended approach for design flood estimation by some countries (e.g. Australia and UK). Alexander (1990; 2001) advocates a regional approach for South Africa and details a methodology and as well as providing software for the implementation of the regional approach, but states that overseas concepts of identifying homogeneous regions are not valid in South Africa. Using his approach, users are expected to visually interpret the data and decide subjectively which data can be used beneficially to improve the estimates of the parameters of the distribution being fitted to the data. This raises the question of inconsistency in the results between different users and places an onerous burden on each user who has to collect the raw data for the stations in the region and then proceed with the analysis. Furthermore, it is probable that similar analyses would be performed by different users for the same regions and valuable human resource time would be wasted. It is argued that a research project, undertaken by respected experts, to develop a regional approach on national scale could save significant effort by individual users and improve the consistency of results. An argument against this computerised "cook book" approach is that it may be applied by an inexperienced designer outside of the bounds under which it was developed. However, it is postulated that far larger errors and inconsistencies will result when the current manual approaches are applied by inexperienced designers.

For direct statistical analysis Alexander (1990; 2001) recommends either the Method of Moments or Probability Weighted Moments for fitting distributions. The literature indicates that L-moments are widely used and have been adopted as a standard approach in, for example, the UK. Although some caution and criticism of the use of L-moments is also evident in the literature, further investigation of L-moments for possible general use in South Africa is warranted.

When no recorded streamflow data are available at the site of interest, or the records are inadequate, the recommended rainfall-runoff event based methods for design flood estimation in South Africa include the Rational Method, unit hydrograph and SCS methods.

No developments or refinements of the unit hydrograph methods have been published since they were developed by the HRU (1972) in the late 1960s and early 1970s. Subsequent to these studies, regional techniques for frequency analysis have become the standard and preferred approach in some countries. In addition, longer rainfall and streamflow records are currently available for analysis, computing power has expanded enormously and detailed databases of climatic and catchment physiographic characteristics are available at a national scale. While the regionalisation of South Africa into nine veld zone types, based on data from only 92 flow gauging stations, was pioneering work at the time, it is postulated that refined regionalisation of homogeneous hydrological response regions in the country is now possible. Furthermore, the event based methods are generally applied in a deterministic manner and hence suffer from the limitations of this approach, which includes the uncertainty of the real exceedance probability associated with the computed design flood, the spatial and temporal distribution of rainfall and conditions in the catchment prior to extreme events. Although a return period adjustment factor for the application of the Rational Method in South Africa is advocated, the method is still applied in a deterministic manner and the adjustment factor does not constitute a probabilistic approach. A probabilistic approach would enable the conversion of a design rainfall event into a design flood event with the same return period.

The calibrated Rational method developed by Alexander (2002), and termed the "Standard Flood", is a probabilistic-based approach which has the ingredients to overcome some of the deficiencies evident in the techniques currently used for design flood estimation in South Africa. In this study no in-depth analysis of the standard flood methodology has been performed, but the use of single site and outdated design rainfall values (TR102), the subjective adjustments made, the method of incorporation of variability within regions and the method of regionalisation are all aspects which warrant further investigation.

The adaptions for southern African conditions to the SCS approach, as detailed by Schmidt and Schulze (1987), accounts for regional differences in median antecedent soil moisture conditions prior to large events and for the joint association between rainfall and runoff. However, improved computing power and currently available databases could be utilised to further refine the method. For example, the regionalisation of South Africa could be improved to, at the broadest scale, reflect the 1946 Quaternary Catchments into which South Africa has been delineated and, where necessary, could also reflect heterogeneity of soils and current land use within each Quaternary Catchment. The method used to account for regional differences in AMC could be improved by utilising improved modelling inputs. For example, estimates of reference potential evaporation as well as maximum evaporation (i.e. considering transpiration by vegetation and evaporation from vegetation and soil surfaces) could be improved by using currently available information. The use of median conditions to account for AMC needs to be re-evaluated and possibly improved by the use of continuous simulation modelling. It is probable that the soil moisture status could be a function of the exceedance probability of the intended design. The method used to account for the joint association between rainfall and runoff could also be improved by the use a continuous simulation approach and could include events larger than those equivalent to the 20 year return period, to which the 1987 adaption of the SCS technique for SA is currently limited.

An important aspect is the need for consistency when the various methods are applied by different users, i.e. similar results should be obtained by different users when applying the same method. Alexander (1990) states that the subjectivity in the estimation of design storms is a major limitation in the consistent estimation of design floods in South Africa. For a specified catchment response time, the RLMA&SI procedures to estimate design rainfall will, when applied on a 1' x 1' gridded scale in South Africa, overcome the subjectivity in rainfall input. However, considerable inconsistency remains in the estimation of the catchment response time, and hence in the estimation of the critical duration of rainfall, and in the selection of other model inputs which are based on text book values for the Rational Method and, to a lesser extent, the SCS techniques.

In a recent review in the current state of the art of flood frequency analysis, the gap between flood research and practice is emphasised by Cordery and Pilgrim (2000), with research being required to improve the estimates of both specific and probabilistic floods. Although the gap between flood research and practice may not be large in South Africa, with relatively little research having been undertaken in the past 25 years, the need to refine existing methods and to evaluate new methods which have been adopted for design flood estimation in other countries, currently requires urgent attention and funding in South Africa.

6.6 Summary of Research Needs for South Africa

The following research needs have been identified and are listed in a perceived priority which takes into account the need to introduce new and internationally accepted techniques and to refine existing techniques:

- A continuous simulation approach to design flood estimation should be further evaluated and developed. Such an approach overcomes many of the limitations of the design event approach and can accommodate current and projected future conditions in a catchment, such as anticipated land use or climate change. Limitations of the gauged flow data and changes in catchment conditions within the period of gauging may be overcome using this approach. It may be necessary to combine this approach with, for example, unit hydrographs to estimate the peak discharge. The output from a continuous simulation approach could be pre-run and packaged for hydrologically homogeneous regions/Quaternary Catchments to enable simple and rapid use by practitioners.

- Areal Reduction Factors (ARFs), which convert design rainfall estimated at a point to an areal rainfall, need to be re-investigated in the light of recent extreme events and as longer periods of record are now available for analysis, and also in the way in which ARFs may vary in South Africa with recurrence interval and with rainfall producing mechanisms.
- Techniques for the temporal disaggregation and spatial estimation of daily rainfall need to be revised and refined.
- A joint probability approach to design flood estimation, which derives the flood frequency distribution by the incorporation of uncertainties in the inputs to the model, should be investigated.
- A revision and updating of the SCS method for design flood estimation on small catchments in South Africa should be undertaken to incorporate the increased spatial resolution of information now available, the updated and improved design rainfall values, while simultaneously improving the technique to account for antecedent moisture conditions.
- A regional statistical approach for flood frequency should be developed, i.e. the identification of homogeneous regions, the development of growth curves for each reach and the development of algorithms to estimate the scaling factor at ungauged sites. Regionalisation based both on a cluster analysis of site characteristics and the region of influence approach, as adopted by the Flood Estimation Handbook (FEH) for the UK (Reed, 1999), should be investigated.
- Improved and consistent methods to estimate catchment lag should be evaluated.
- A probabilistic approach to the use of the Rational Method should be investigated. The observed streamflow data required for this approach could be supplemented with the output of the continuous simulation approach, i.e. this could constitute one of the simple approaches which could be synthesised from the output of the continuous simulation approach. Alexander (2002) has developed a "standard design flood" using this approach, which may require further refinement.
- The run-hydrograph technique should be re-evaluated and, if necessary, further refined for use by practitioners.
- The unit hydrograph approach, including the estimation of storm losses, should be refined, utilising longer records, improved regionalisation and currently available detailed databases and geographic information systems.

CHAPTER 7

DESIGN FLOOD ESTIMATION USING AN INDEX FLOOD BASED APPROACH IN KWAZULU-NATAL, SOUTH AFRICA

7.1 Regionalisation

A regional frequency analysis of annual maximum series of flood flows from relatively unregulated rivers in the KwaZulu-Natal province of South Africa has been conducted, including the identification of homogeneous regions and suitable regional frequency distributions for the regions. The study area was divided into two homogeneous regions based on an index of monthly rainfall concentration. Region 1 covers the coastal and midlands area and Region 2 the north-western parts of the study area. The General Normal, Pearson Type 3 and General Pareto distributions were found to be suitable for annual maximum series of flood flows in Region 2. The occurrence of a few flood events of extreme magnitude in Region 1 resulted in no suitable regional frequency distribution for this region. Full details of this study are contained in Kjeldsen *et al*. (2002).

7.2 Estimation of the Index Flood

Use of the index-flood method at ungauged sites requires methods for the estimation of the index-flood parameter at these sites. This study attempts to relate the mean annual flood to catchment characteristics in KwaZulu-Natal, South Africa. The ordinary, weighted and generalised least square methods for estimating model parameters are compared and found to perform equally well, with preference given to the generalised least square model. A separation of KwaZulu-Natal into two regions was found to improve predictive ability of the models in the western and north-western parts of the study area. The study also revealed problems with the estimation of the mean annual flood in the coastal areas of the study region. Full details of this study are contained in Kjeldsen *et al*. (2001).

CHAPTER 8

DISCUSSION AND CONCLUSIONS

The two major objectives of this project were related to the estimation design rainfall in South Africa and techniques for design flood estimation. These two aspects are discussed in Section 8.1 and 8.2 respectively. Section 8.3 contains recommendations for future research.

8.1 Design Rainfall Estimation

Regional index storm based approaches which utilise L-moments for design rainfall estimation were developed by Smithers and Schulze (2000a) for durations $\leq$ 24 h using digitised rainfall data from 172 stations which had at least 10 years of record, and for 1 to 7 day durations by Smithers and Schulze (2000b) using daily rainfall from 1 789 stations which had at least 40 years of record. A comparison of the growth curves for the 24 h duration indicated inconsistencies in the results from the two studies. Possible explanations for the inconsistencies were attributed to the different periods of data used in the two studies and the differences in the annual maximum series, which were extracted using a sliding window from the continuously recorded data and using a fixed period window from the daily rainfall data. The results obtained in Chapter 3 indicate that there are no systematic differences between higher order L-moment ratios for annual maximum series extracted using fixed and sliding windows. It was also established that the 24 h growth curve, derived from digitised data using a sliding 24 h window, and the 1 day growth curve derived from daily rainfall data, should be the same. Hence, the differences in the short and long duration growth curves are attributed largely to the different periods and length of records used in the analyses and, to a lesser extent, to the errors in the digitised rainfall data.

The scaling properties of the L-moment ratios and growth curves with duration was also investigated in Chapter 3. It was noted that the long duration (1 to 7 days) growth curves derived from the daily rainfall data were relatively scale invariant with duration, whereas the short growth curves derived from the digitised rainfall data did not display the same degree of scale invariance. Results in the literature indicate evidence of scale invariance of the L-moment ratios of extreme rainfall. Hence, is was postulated that the departure from scale invariance of the short duration growth curves could be attributed to a combination of sampling variability, errors in the digitised rainfall data and limitations in the resolution of measurement of the rainfall data.

The sampling variability of the annual maximum rainfall series was estimated using three approaches. The first utilised windows of data extracted from the entire period of record, the second utilised stochastic modelling of the rainfall process and the third approach implemented a bootstrapping technique. The results indicate that there is considerable variation with duration in observed higher order L-moments. This is associated with the sampling variability and length and period of record. The most reliable estimates of the L-moment ratios are computed from the more reliable daily rainfall data, which are more abundant and have longer record lengths than the digitised rainfall data. It is thus postulated that the 1 day L-moment ratios, and hence growth curves, are the most reliable estimate of the L-moment ratios for all durations. Thus, design rainfalls for all durations may be estimated as the product of the 1 day growth curves and an estimate of the mean of the annual maximum series (index value) for the duration in question.

As detailed in Chapter 4, the methodology developed for estimating the mean of the annual maximum series for all durations at an ungauged location is dependent on the mean of 1 day annual maximum series. Using a cluster analysis of site characteristics, the 78 long duration clusters were grouped into 7 regions for the estimation of the mean of the 1 day annual maximum series. Multiple linear regression relationships with site characteristics (MAP, latitude, altitude) as independent variables enabled the mean of the 1 day annual maximum series to be estimated at any location in South Africa. Gridded residual errors at stations which had at least 40 years of data were used to correct the estimated values at these sites and ensure that the estimated value were the same as the observed values at these sites. This approach was shown to result in reliable and consistent estimates of the 1 day annual maximum series.

For durations longer than 1 day, the mean of the D day ($2 \leq D \leq 7$) duration values were noted to scale linearly as a function of the 1 day values. The parameters of the regression were found to scale (by a power law relationship) with duration, and three parameters were derived to describe the relationship between the two regression parameters (coefficient and intercept) and duration. Thus, 6 parameters in all were derived for each of the 7 regions which enable the estimation of the mean of the annual maximum series for durations ranging from 2 to 7 days at any location in South Africa.

For durations shorter than 1 day, the mean of the H minute ($H \leq 1440$) duration values were found to scale linearly as a function of the 24 h values. Thus, for each of the 15 short duration clusters and for 15 durations ranging from 5 to 1200 minutes, linear regression coefficients were derived.

The approach adopted to estimate the mean of the annual maximum series for any duration is a two step process. Firstly, the mean of the 1 day annual maximum series is estimated at the required location using regionalised regressions. Secondly, the mean of the annual maximum series for durations longer than 1 day are scaled directly from the 1 day value. For durations shorter than 1 day, the values are scaled from the 24 h value, which in turn is estimated directly from the 1 day value for the location. This approach for durations < 24 h was shown to be more efficient than the methodology developed by Smithers and Schulze (2000a).

The more reliable daily rainfall database, with many more stations and longer records lengths than those contained in the digitised rainfall database, is utilised in the estimation of the mean of the annual maximum series for all durations. Thus, inconsistencies in the digitised rainfall database are, to some extent, compensated for by scaling from the daily values.

In the application of the regression relationships to estimate the mean of the annual maximum series for durations shorter and longer than 1 day, it was noted that inconsistencies between values estimated could arise if 1 day values which were outside of the range of values used to develop the relationships, were input to the equations. This could result in, for example, the mean of the annual maximum series for a particular duration being larger than the value estimated for a longer duration. Thus, the concept of the slope between the mean of the annual maximum series and duration, for a range of selected durations, was introduced. It was noted from the observed data at numerous sites that, if changes in scaling do occur, they typically occur at durations of 15 min, 2 h, 1 day and 3 days. These durations were therefore used as pivotal durations, with the regression based approach used to estimate the mean of the annual maximum series at these durations, and the mean of the annual maximum series for intermediate durations scaled from these values. This application of the Regional L-Moment Algorithm, in conjunction with a Scale Invariance approach has been termed the RLMA&SI.

The performance of the RLMA&SI procedures has been assessed in a number of ways. At 10 sites located in different climatic regions of South Africa and which each have at least 40 years of daily rainfall data, and which were not used in the regionalisation process, the RLMA&SI procedures generally exceeded the design values estimated directly from the at-site data for return periods greater than 20 years. A similar trend was evident at all daily rainfall stations which have at least 40 years of record.

A comparison at 2 184 daily rainfall stations between design rainfall estimated by Adamson (1981) and by the RLMA&SI procedures indicated that for return periods of less than 50 years, the differences between the two estimates were generally less than 20%, while for longer return periods the differences were greater, with the Adamson values generally exceeding the RLMA&SI design rainfalls. These differences are attributed to:

- the longer record lengths used in the regional approach;
- the stringent data quality control procedures developed by Smithers and Schulze (2000b) and used in this study;
- the different approaches to design rainfall estimation used in the two studies,
  - with Adamson (1981) using a single site approach with a censored LN distribution while
  - the regional approach using the RLMA&SI procedures adopted the GEV distribution; and
- the L-moments used in the RLMA&SI approach to fitting the GEV distribution being less influenced by outliers in the data.

However, it has been shown that design rainfall depths computed using the regional approach generally exceed the values computed directly from the at-site data. In addition, the regional approach has been shown in many international studies (e.g. Potter, 1987; Cunnane, 1989; Hosking and Wallis, 1997) to result in more reliable and robust estimates compared to design values computed using only single at-site data. Therefore, it is postulated that the 1 to 7 day design rainfall values computed using the RLMA&SI procedures may be used with confidence.

Further comparisons between design rainfall estimated using different approaches for durations $\leq$ 24 h were performed. These included design rainfall estimated from the observed data, by the RLMA&SI procedures, using the equation developed by Alexander (2001), the equation developed by Adamson (1981) in DWAF Report TR102 and by Midgley and Pitman (1978) in HRU Report HRU2/78. Generally, the design rainfalls estimated using the RLMA&SI and HRU2/78 procedures were similar and, where no obvious anomalies were evident in the data, follow the trends in design rainfalls estimated directly from the observed data. It was evident that the Alexander (2001) equation generally overestimates design rainfalls for durations ranging from 10 minutes to 24 h, with the maximum overestimation occurring at durations of approximately 1 h and inconsistencies between the estimated 24 h event and the TR102 1 day value, on which the equation is based, were evident. The functional relationship of the Alexander equation does not seem to accommodate the curvilinear relationship between design rainfall depth and log transformed duration, which is evident at most stations investigated.

From the comparisons performed in this study is evident that, compared to the observed data and other techniques for estimating design rainfalls, the RLMA&SI procedures developed generally result in reasonable estimates of design rainfall which are frequently more consistent than other estimates. This is evident for 1 to 7 day durations where RLMA&SI values are generally similar to the values computed directly from the at-site data and display a consistent trend for these durations, whereas inconsistencies in both the TR102 values and observed data are evident. The RLMA&SI values are consistent over the entire range of durations, whereas, the other techniques considered are frequently inconsistent for duration shorter and longer than 24 h.

In summary, the RLMA&SI procedures utilise the more reliable, consistent and longer records of the daily rainfall database to estimate design rainfalls for shorter durations, thus compensating for deficiencies in the digitised rainfall database. It is thus concluded that the RLMA&SI procedures may be used with confidence to estimate design rainfalls in South Africa for durations up to 7 days.

A graphical user interface has been developed in Java to estimate design rainfall depths for any location in South Africa. This software implements the procedures developed in this study and enables the estimation of design rainfall at a spatial resolution of 1 arc minute and for durations ranging from 5 minutes to 7 days and for return periods of 2 to 200 years.

8.2 Design Flood Estimation

Design flood estimation may be performed by a frequency analysis of observed flows where these are available and adequate in length and quality. The analysis may be performed at a single site, or preferably a regional approach should be adopted. The advantages of a regional approach to frequency analysis for design flood estimation are evident from the studies reviewed. This has led to the adoption of a regional approach as the recommended approach for design flood estimation by some countries (e.g. Australia and UK). Alexander (1990; 2001) advocates a regional approach for South Africa and details a methodology and provides software for the implementation of the regional approach, but states that overseas concepts of identifying homogeneous regions are not valid in South Africa. Using Alexander's approach, users are expected to visually interpret the data and decide subjectively which data can be used beneficially to improve the estimates of the parameters of the distribution being fitted to the data. This raises the question of inconsistency in the results between different users and places an onerous burden on each user, who has to collect the raw data for the stations in the region and then proceed with the analysis. Furthermore, it is probable that similar analyses would be performed by different users for the same regions and valuable human resource time would be wasted. It is argued that a research project, undertaken by respected experts, to develop a regional approach on a national scale could thus save significant effort by individual users and improve the consistency of results. An argument against this computerised “cook book” approach is that it may be applied by inexperienced designers outside of the bounds under which it was developed. However, it is postulated that far larger errors and inconsistencies will result when the current manual approaches are applied by inexperienced designers.

For direct statistical analysis Alexander (1990; 2001) recommends either the Method of Moments or Probability Weighted Moments for fitting distributions. A review of the literature indicates that L-moments are widely used and have been adopted as a standard approach in, for example, the UK. Although some caution and criticism of the use of L-moments is also evident in the literature, further investigation of L-moments for possible general use in South Africa is warranted.

When no recorded streamflow data are available at the site of interest, or the records are inadequate, the recommended event-based rainfall : runoff methods for design flood estimation in South Africa include the unit hydrograph, Rational and SCS methods.

No development or refinement of the unit hydrograph methods for South Africa have been published since they were developed by the HRU (1972) in the late 1960s and early 1970s. Subsequent to these studies, regional techniques for frequency analysis have become the standard and preferred approach in some countries. In addition, longer rainfall and streamflow records are currently available for analysis, computing power has expanded enormously and detailed databases of climatic and catchment physiographic characteristics are available at a national scale. While the regionalisation of South Africa into nine veld zone types, based on data from only 92 flow gauging stations, was pioneering work in the 1960s, it is postulated that a refined regionalisation of homogeneous hydrological response regions in South Africa is now possible. Furthermore, the event based methods are generally applied in a deterministic manner and hence suffer from the limitations of this approach, which includes the uncertainty of the real exceedance probability associated with the computed design flood, the spatial as well as the temporal distribution of rainfall and soil moisture conditions in the catchment prior to extreme events. Although a return period adjustment factor for the application of the Rational Method in South Africa is advocated, the method is still applied in a deterministic manner and the adjustment factor does not constitute a probabilistic approach. A probabilistic approach would enable the conversion of a design rainfall event into a design flood event with the same return period.

The calibrated Rational Method developed by Alexander (2002), and termed the "Standard Flood", is a probabilistic-based approach which has the ingredients to overcome some of the deficiencies evident in the techniques currently used for design flood estimation in South Africa. In this study no in-depth analysis of the standard flood has been performed, but the use of a single rainfall site and outdated design rainfall values (TR102), the subjective adjustments made, the method of incorporation of variability within regions and the method of regionalisation are all aspects which warrant further investigation.

The adaptions for southern African conditions to the SCS approach, as detailed by Schmidt and Schulze (1987), accounts for regional differences in median antecedent soil moisture conditions prior to large events and for the joint association between rainfall and runoff. However, improved computing power and currently available databases could be utilised to further refine the method. For example, the regionalisation of South Africa could be improved to, at the broadest scale, reflect the 1946 Quaternary Catchments into which South Africa has been delineated and, where necessary, could also reflect heterogeneity of soils and current land use within each Quaternary Catchment. The method used to account for regional differences in AMC could be improved by utilising improved modelling inputs. For example, estimates of reference potential evaporation as well as maximum evaporation (i.e. considering transpiration by vegetation and evaporation from vegetation and soil surfaces) could be improved by using currently available information.

The use of median conditions to account for AMC needs to be re-evaluated and possibly improved by the use of continuous simulation modelling. It is probable that the soil moisture status could be a function of the exceedance probability of the intended design. The method used to account for the joint association between rainfall and runoff could also be improved by the use a continuous simulation approach and could include events larger than those equivalent to the 20 year return period, to which the 1987 adaption of the SCS technique for SA is currently limited.

An important aspect for design flood estimation is the need for consistency when the various methods are applied by different users, i.e. similar results should be obtained by different users when applying the same method. Alexander (1990) states that the subjectivity in the estimation of design storms is a major limitation in the consistent estimation of design floods in South Africa. For a specified catchment response time, the RLMA&SI procedures to estimate design rainfall will, when applied on a 1' x 1' gridded scale in South Africa, overcome the subjectivity in rainfall input. However, considerable inconsistency remains in the estimation of the catchment response time, and hence in the estimation of the critical duration of rainfall, and in the selection of other model inputs based on text book values for the Rational Method and, to a lesser extent, the SCS techniques.

In a recent review of the current state of the art of flood frequency analysis, the gap between flood research and practice is emphasised by Cordery and Pilgrim (2000), with research required to improve the estimates of both specific and probabilistic floods. Although the gap between flood research and practice may not be large in South Africa, partially because relatively little research in design flood hydrology has been undertaken in the past 25 years, the need to refine existing methods and to evaluate new methods adopted for design flood estimation in other countries, currently requires urgent attention and funding in South Africa.

8.3 Conclusions

The major contractual objectives of the project have been met. The development of the RLMA&SI procedures for design rainfall estimation in South Africa not only adopts a novel approach by utilising the scale invariance of growth curves with duration, but enables reliable and consistent estimates of design rainfall to be made in South Africa by means of a Java-based computer programme with a graphical user interface.

The inconsistencies in the growth curves developed in the studies by Smithers and Schulze (2000a; 2000b) was unexpected and resulted in the development of the RLMA&SI procedures. Therefore, the development of new regionalised areal reduction factors, design and actual hyetographs, rainfall erosivity map and the impacts of climate change on design rainfall estimates for South Africa, as stated in the project objectives, were not achieved in this study and are recommended for future research.

The secondary contractual objective related to design flood estimation has been largely achieved. Both the South Africa and international literature on design flood estimation was reviewed and a summary of research needs for South Africa has been compiled. Pilot studies on the use of an index-flood and a continuous simulation modelling approach to design flood estimation in South Africa has been completed. The effects of climate change on design flood estimation was not undertaken and is recommended for future research.

The gap between flood research and practice is emphasised by Cordery and Pilgrim (2000), with research required to improve the estimates of both specific and probabilistic floods. Although the gap between flood research and practice may not be large in South Africa, partially because relatively little research in design flood hydrology has been undertaken in the past 25 years, the need to refine existing methods and to evaluate new methods adopted for design flood estimation in other countries, currently requires urgent attention and funding in South Africa.

8.4 Recommendations for Further Research

It is frequently necessary to estimate a design hydrograph which, in turn, requires the estimation of a design hyetograph. The RLMA&SI procedures developed in this study enable the estimation of a design rainfall depth for a particular duration. Hence, regionalised procedures need to be developed to enable the disaggregation of the design rainfall depth into a design hyetograph. An additional requirement which could be a by-product of this investigation are regionalised relationships to disaggregate measured daily rainfall data into a hyetograph with sub-daily time steps. These procedures are required when, for example, modelling certain sub-daily processes within a daily time step model (e.g. in flow routing or rainfall infiltration routines).

When estimating design flood hydrographs from a catchment it is necessary to convert the point rainfall measurements to areal rainfall depths using Areal Reduction Factors (ARF). These ARF relationships need to be re-investigated in the light of recent extreme events and as longer periods of record are now available for analysis, and also in the way in which ARF may vary in South Africa with recurrence interval and with rainfall producing mechanisms.

The following research needs in design flood hydrology for South Africa have been identified and are listed in a perceived priority which takes into account the need to introduce new and internationally accepted techniques and to refine existing techniques:

- A continuous simulation approach to design flood estimation should be further evaluated and developed. Such an approach overcomes many of the limitations of the design event approach and can accommodate current and projected future conditions in a catchment, such as anticipated land use or climate change. Limitations of the gauged flow data and changes in catchment conditions within the period of gauging may be overcome using this approach. It may be necessary to combine this approach with, for example, unit hydrographs to estimate the peak discharge. The output from a continuous simulation approach could be pre-run and packaged for hydrologically homogeneous regions/Quaternary Catchments to enable simple and rapid use by practitioners.
- Areal Reduction Factors (ARF), which convert design rainfall estimated at a point to an areal rainfall, need to be re-investigated in the light of recent extreme events and as longer periods of record are now available for analysis, and also in the way in which ARF may vary in South Africa with recurrence interval and with rainfall producing mechanisms.
- Techniques for the temporal disaggregation and spatial estimation of daily rainfall need to be revised and refined.
- A joint probability approach to design flood estimation, which derives the flood frequency distribution by the incorporation of uncertainties in the inputs to the model, should be investigated.

- A revision and updating of the SCS method for design flood estimation on small catchments in South Africa should be undertaken to incorporate both the increased spatial resolution of information now available and the updated and improved design rainfall values, while simultaneously improving the technique to account for antecedent moisture conditions.
- A regional statistical approach for flood frequency should be developed, i.e. the identification of homogeneous regions, the development of growth curves for each reach and the development of algorithms to estimate the scaling factor at ungauged sites. Regionalisation based both on a cluster analysis of site characteristics and the region of influence approach, as adopted by the Flood Estimation Handbook (FEH) for the UK (Reed, 1999), should be investigated.
- Improved and consistent methods to estimate catchment lag should be evaluated.
- A probabilistic approach to the use of the Rational Method should be investigated. The observed streamflow data required for this approach could be supplemented with the output of the continuous simulation approach, i.e. this could constitute one of the simple approaches which could be synthesised from the output of the continuous simulation approach. Alexander (2002) has developed a "standard design flood" using this approach, which may require further refinement.
- The run-hydrograph technique should be re-evaluated and, if necessary, further refined for use by practitioners.
- The unit hydrograph approach, including the estimation of storm losses, should be refined utilising the longer records, improved regionalisation and currently available detailed databases and geographic information systems.

CHAPTER 9

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APPENDIX A

DESIGN RAINFALL ESTIMATION IN SOUTH AFRICA: USER MANUAL

A computer programme with a graphical user interface has been developed in Java to estimate design rainfall depths for any location in South Africa. This software implements the procedures detailed in Part A of this report which consists of Chapters 2 to 5. The objective of the first section in this chapter is to assist users with the installation and running of the software. The second section presents generalised maps of design rainfall in South Africa.

A. 1 User Manual

A. 1.1 Minimum system requirements

The minimum system requirements on a computer running the Windows operating system are:

- 32 Mb RAM,
- 140 Mb Hard Disk space, and
- Windows 98, or more recent Windows operating system.

A. 1.2 Installation of software

Three steps are required to install the software. These are:

- Step 1: Obtaining the software
- Step 2: Exploding zipped database file
- Step 3: Installing the Java runtime environment.

Step 1: Obtaining the software

The software may be installed from the CD which accompanies this report. Alternatively, the current version of the software may be downloaded from the following site:

http://www.beeh.unp.ac.za/HydroRisk/

and follow the "Design Rainfall" option.

The following files are contained on the CD or may be downloaded from the web site:

- rainfall2.jar (~ 1.4 Mb)
- sagrid.zip (~ 12.7 Mb)
- j2re-1_4_0-win-i.exe (~ 11.6 Mb)

It is suggested that these files be saved in the *C:\design_rainfall* directory, as the instructions in this chapter will assume that the files are at that location. However, any user specified directory can be used and the relevant path will need to be substituted in these instructions.

Any updates or changes to the installation procedure will also be available at this web address.

Step 2: Unzip the zipped database file

Unzip the Sagrid.zip file to create a Sagrid.dbf file.

Step 3: Installing the Java runtime environment

The Java runtime environment needs to be installed on the computers running the Windows operating system. This is performed by doubling clicking on the j2re-1_4_1_0-win-i.exe from Windows Explorer and following the instructions.

For computers not using the Windows operating system (e.g. Linux), the relevant Java runtime environment can be downloaded from http://java.sun.com and installed on the computer.

A. 1.3 Running of software

Once the Java runtime environment has been installed, the design rainfall software can be executed by running (double clicking) the Rainfall2.jar file. A graphical user interface as shown in Figure 81 should be visible.

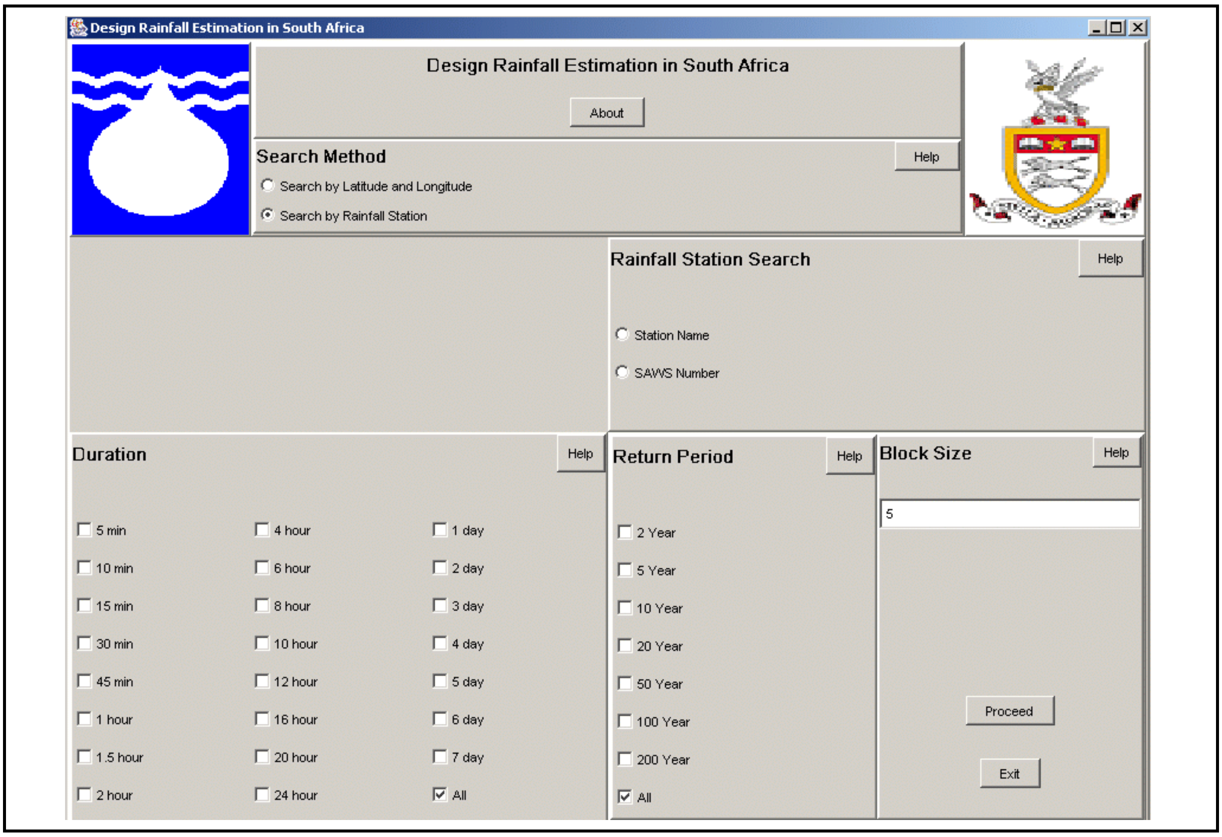

Figure 81 Graphical user interface for the estimation of design rainfall in South Africa

In order to specify the location for the design rainfall estimate, a user has two options (SEARCH METHOD). A user may either select to input the location by latitude and longitude or to search for the location of a daily rainfall station. If the latitude and longitude option is selected, a user may input the location either in decimal degrees, degrees and minutes or as minutes. Further options for searching for a rainfall station are by means of the South African Weather Service (SAWS), formerly known as the South African Weather Bureau (SAWB), station number (e.g. 0239482) or by entering a station name (e.g. Cedara). The user is required to input the duration of the design rainfall by selecting the appropriate check boxes, or by selecting the "ALL" check box which indicates that the user wants design rainfall estimated for all durations. Similarly, the user is expected to select the required return periods. If no values are specified by the user, the program default is to calculate design rainfall for all durations and all return periods.

Utilising the procedures developed, design rainfall can be estimated at a spatial resolution of 1'x1' latitude and longitude for any grid point in South Africa. The user can also specify a "radius", in minutes, from the point of interest and design rainfall will be estimated at each 1'x1' latitude and longitude point within this area. Thus the spatial variation of design rainfall within an area or catchment can be evaluated by the user. For example, if a block size of 2' is specified, then design rainfall will be estimated at a 1'x1' latitude and longitude grid consisting of 24 points surrounding the point of interest. If no value is specified by the user, the default block size (0) is used by the program.

Each panel in the interface has a "Help" button which provides a brief explanation of what information is required.

When all the information has been entered, the "Proceed" button must be activated. The program then checks that the user has input the minimum required information. If the minimum information has not been selected, a warning is issued and the user is returned to the initial screen.

After the input information has been checked, the user is prompted for the name of an output file. Thereafter, if the user has selected to search for a location using either a SAWS number or station name, a search for the desired location is performed. If more than 1 station meets the search criteria, the user is then supplied with the station numbers, stations names, latitude, longitude, altitude and mean annual precipitation (MAP) and is required to select a station before activating the proceed button. The results of the program are output to the user selected ASCII file, an example of which is contained in Figure 82.

The output file echoes the user selections and then lists the 1 to 7 day design rainfall depths for the selected station and the 5 closest daily rainfall stations to the site of interest. This is followed by the estimated design rainfall values for the specified location and each point in the specified block size. Ninety percent upper (U) and lower (L) bounds for all design rainfall values are also output. Examples of design rainfall, estimated using the programme are contained in Figures 83 and 84.

```
User selection has the following criteria:
Station Name: cedara
Durations requested: 5 m, 10 m, 15 m, 30 m, 45 m, 1 h, 1.5 h, 2 h, 4 h, 6 h, 8 h, 10 h, 12 h, 16 h, 20 h, 24 h, 1 d, 2 d, 3 d, 4 d, 5 d, 6 d, 7 d
Return Periods requested: 2 yr, 5 yr, 10 yr
Block Size requested: 0 minutes

Data extracted from Daily Rainfall Estimate Database File
The station selected and the five closest stations are listed

Station Name                SAWB       Distance  Record  Latitude Longitude  MAP Altitude Duration   Return Period (years)
                            Number         (km) (Years)  (°)  (')  (°)  (') (mm)      (m)  (m/h/d)        2       2L       2U        5       5L       5U       10      10L      10U

CEDARA COLLEGE              0239482_W      0.0      40   29   32   30   17  876     1134      1 d     55.6     55.2     55.8     77.8     77.3     78.2     95.2     94.0     96.1
                                                                                               2 d     70.0     69.4     70.6     98.5     97.6     98.9    122.1    120.5    123.7
                                                                                               3 d     79.8     79.1     80.6    112.7    111.7    113.1    140.2    138.2    142.2
                                                                                               4 d     87.4     86.5     88.2    123.1    122.0    123.7    152.6    150.0    154.9
                                                                                               5 d     92.0     91.1     92.8    128.8    127.6    129.4    158.6    155.7    160.9
                                                                                               6 d     99.0     98.1    100.0    138.1    136.7    139.0    168.9    165.8    171.3
                                                                                               7 d    102.5    101.6    103.5    142.0    140.7    143.0    172.8    169.7    175.3
.
.
.
BOTANIC GARDENS - PMB       0239605_P      9.0      83   29   35   30   21 1001      882      1 d     57.0     56.1     57.5     83.0     82.0     83.5    104.7    102.8    106.7
                                                                                               2 d     73.0     71.7     74.3    106.0    104.6    106.8    133.7    130.3    136.8
                                                                                               3 d     84.0     82.2     85.7    122.3    120.5    123.4    154.4    150.0    158.0
                                                                                               4 d     91.5     89.7     93.4    132.0    130.1    133.2    165.5    160.9    170.1
                                                                                               5 d     98.4     96.4    100.3    140.2    138.3    141.7    174.4    169.6    178.6
                                                                                               6 d    104.8    103.0    106.6    148.1    146.0    149.5    182.8    178.1    187.1
                                                                                               7 d    110.7    109.0    112.6    154.9    152.9    156.4    190.3    185.6    194.6

Gridded values of all points within the specified block
  Latitude Longitude  MAP Altitude Duration   Return Period (years)
  (°)  (')  (°)  (') (mm)      (m)  (m/h/d)        2       2L       2U        5       5L       5U       10      10L      10U

   29   32   30   17  876     1134      5 m     11.5      7.4     15.6     16.1     10.3     21.9     19.7     12.5     26.9
                                       10 m     15.5     10.6     20.4     21.7     14.9     28.6     26.6     18.1     35.1
                                       15 m     18.5     13.5     23.5     25.9     18.8     32.9     31.7     22.9     40.5
                                       30 m     23.3     17.2     29.4     32.6     24.1     41.2     39.9     29.3     50.6
                                       45 m     26.7     20.2     33.2     37.3     28.2     46.4     45.7     34.4     57.1
                                        1 h     29.3     22.6     36.1     41.1     31.6     50.6     50.3     38.4     62.2
                                      1.5 h     33.6     26.1     41.1     47.0     36.5     57.6     57.6     44.4     70.8
                                        2 h     37.0     29.1     44.9     51.8     40.7     62.9     63.3     49.5     77.3
                                        4 h     42.9     34.8     51.0     60.1     48.8     71.5     73.5     59.3     87.9
                                        6 h     46.8     40.0     53.6     65.6     56.0     75.1     80.2     68.2     92.4
                                        8 h     49.8     44.0     55.7     69.8     61.5     78.0     85.4     74.9     95.9
                                       10 h     52.3     47.5     57.0     73.2     66.4     79.9     89.6     80.9     98.2
                                       12 h     54.4     50.3     58.3     76.2     70.5     81.7     93.2     85.7    100.5
                                       16 h     57.1     53.5     60.5     79.9     74.9     84.8     97.7     91.1    104.2
                                       20 h     60.7     57.5     63.8     85.0     80.4     89.4    104.0     97.9    109.9
                                       24 h     63.1     59.8     66.4     88.4     83.6     93.0    108.2    101.8    114.3
                                        1 d     53.6     43.0     64.1     75.0     60.2     89.7     91.7     73.3    110.3
                                        2 d     66.1     61.2     70.8     92.5     85.7     99.2    113.2    104.3    121.9
                                        3 d     74.7     67.7     81.6    104.6     94.7    114.3    127.9    115.2    140.6
                                        4 d     81.2     72.7     89.6    113.7    101.7    125.5    139.1    123.8    154.4
                                        5 d     86.6     76.6     96.6    121.3    107.2    135.3    148.4    130.4    166.3
                                        6 d     91.3     79.6    102.9    127.9    111.5    144.2    156.5    135.7    177.3
                                        7 d     95.5     82.3    108.7    133.7    115.1    152.3    163.6    140.1    187.2
...
```

Figure 82 Example of design rainfall output

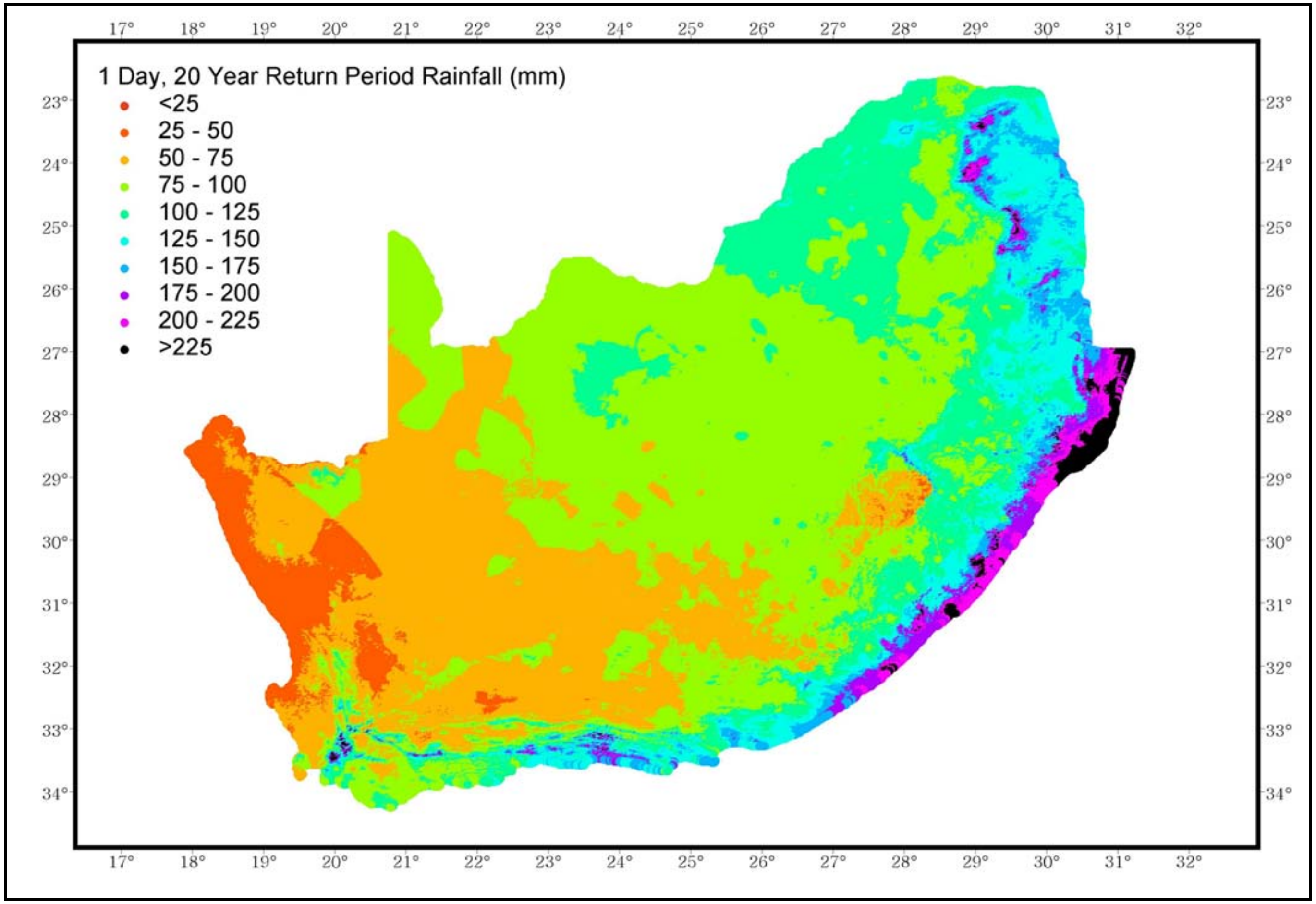

Figure 83 Colour map of 1 day, 20 year return period design rainfall in for South Africa

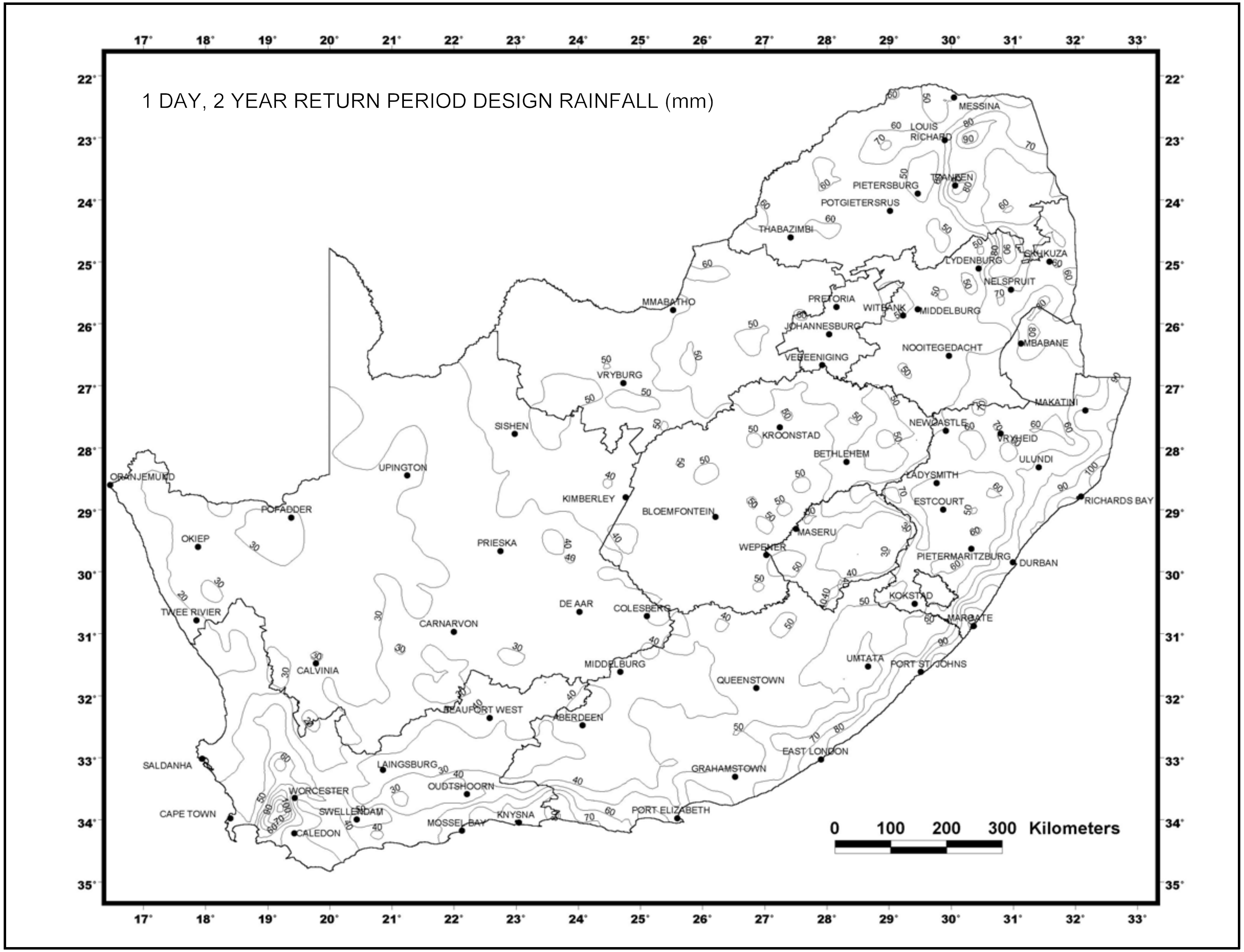

Figure 84 Contour map of 1 day, 2 year return period design rainfall in for South Africa