AN ASSESSMENT OF SCALE ISSUES RELATED TO THE CONFIGURATION OF THE ACRU MODEL FOR DESIGN FLOOD ESTIMATION

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ABSTRACT

There is a frequent need for estimates of design floods by hydrologists and engineers for the design of hydraulic structures. There are various techniques for estimating these design floods which are dependent largely on the availability of data. The two main approaches to design flood estimation are categorised as methods based on the analysis of floods and those based on rainfall-runoff relationships. Amongst the methods based on the analysis of floods, regional flood frequency analysis is seen as a reliable and robust method and is the recommended approach. Design event models are commonly used for design flood estimation in rainfall-runoff based analyses. However, these have several simplifying assumptions which are important in design flood estimation. A continuous simulation approach to design flood estimation has many advantages and overcomes many of the limitations of the design event approach. A major concern with continuous simulation using a hydrological model is the scale at which should take place. According to Martina (2004) the “level” of representation that will preserve the “physical chain” of the hydrological processes, both in terms of scale of representation and level of description of the physical parameters for the modelling process, is a critical question to be addressed. The objectives of this study were to review the literature on different approaches commonly used in South Africa and internationally for design flood estimation and, based on the literature, assess the potential for the use of a continuous simulation approach to design flood estimation. Objectives of both case studies undertaken in this research were to determine the optimum levels of catchment discretisation, optimum levels of soil and land cover information required and, to assess the optimum use of daily rainfall stations for the configuration of the *ACRU* agrohydrological model when used as a continuous simulation model for design flood estimation. The last objective was to compare design flood estimates from flows simulated by the *ACRU* model with design flood estimates obtained from observed data. Results obtained for selected quaternary catchments in the Thukela Catchment and Lions River catchment indicated that modelling at the level of hydrological response units (HRU’s), using area weighted soils information and more than one driver rainfall station where possible, produced the most realistic results when comparing observed and simulated streamflows. Design flood estimates from simulated flows compared reasonably well with design flood estimates obtained from observed data only for QC59 and QCU20B.

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1. INTRODUCTION

Globally, flooding has caused great distress and disruption to human activities and has resulted in the deaths of millions of people over the centuries. The damage to property and infrastructure caused by flooding events and the resultant loss of livelihoods has huge economic implications. The impact of floods therefore provides incentives to improve the ability to predict both the magnitude and frequency of floods, thus enabling the capacity to issue improved flood warnings and enhance the design of hydraulic structures.

Estimates of design floods are often required by engineers and hydrologists for the design of hydraulic structures such as dams, bridges or culverts (Smithers and Schulze, 2000). Under or over-design of even small hydraulic structures can result in a considerable waste of resources. Healy (2000) emphasised that in the pursuit of a professional engineering code of ethics, which includes protection of life and property, it is important to select design flood estimation techniques and design parameters that produce conservative results with adequate safety factors.

According to Cameron *et al,* (1999) the choice of an acceptable and cost-effective engineering, or management, solution is dependent upon having reliable estimates of frequency of floods, both in terms of both peak flows and volumes of water. This, however, currently remains a challenge in hydrology. Cordery and Pilgrim (2000) expressed concern that research in techniques for design flood estimation is on the decline and there is a large gap between flood research and practice. They caution that this situation needs to be rectified if the “state of the art” of design flood estimation is to make further improvements.

A design flood is defined by Pilgrim (1987) as a probabilistic, or statistical, estimate based on a probability analysis of flood or rainfall data, where an average recurrence interval, or exceedance probability, is associated with the estimate. This applies not only to routine design, but also to probable maximum estimates, where the intention is to obtain a design value with an extremely low probability of exceedance (Pilgrim, 1987).

There are many different techniques available for design flood estimation, but the availability of hydrological data has a significant influence on the use of these techniques and on the results obtained. Methods based on the analysis of flood data are used when adequately long records of observed streamflow (runoff) exist. However, appropriately long records of good quality runoff data seldom exist. As a consequence, rainfall data monitored with a denser raingauge network and with longer records than the flow gauging network are frequently used in rainfall-runoff based methods for design flood estimation. These approaches encompass design event models and continuous soil water budget approaches to flood estimation.

Design flood estimation practice in South Africa depends largely on event based approaches and empirical formulae developed in the early 1970's with little or no subsequent modification. These approaches have several limitations which include the simplifying assumption that the T-year return period rainfall produces the T-year return period runoff (Rahman *et al.*, 1998; Cameron *et al.*, 1999). Assumptions based on antecedent catchment conditions and the ability of these methods to lump certain heterogeneous complex process adds to the limitations of these approaches.

According to Calver and Lamb (2000), the continuous simulation approach to design flood estimation constitutes the ”next generation” of British flood frequency estimation methodology for design purposes. Rahman *et al.,* (1998) concur and also believe that continuous simulation could prove to be a powerful means of estimating flood frequencies from rainfall in the future.

The continuous simulation approach to design flood estimation is seen to hold a great deal of potential as inferred by several authors (Hromadka, 1987; Rahman *et al*., 1998; Cameron *et al*., 1999; Reed, 1999). The advantages of the continuous simulation approach are that it overcomes many of the limitations of the design event models (Rahman *et al.*, 1998; Cameron *et al.*, 1999). In the continuous simulation approach antecedent moisture conditions are explicitly accounted for, the concepts are more physically based than with other procedures, the effects of complex hydrological systems and river engineered systems can be and, a complete hydrograph is obtained, not only peak discharges (Rahman *et al.*, 1998; Cameron *et al.*, 1999; Boughton and Droop, 2003).

According to Martina (2004) event-based approaches do not follow the “physical chain” of hydrological processes adequately in order to assess the role of each of the variables involved in rainfall-runoff processes. However, a continuous simulation modelling approach attempts to preserve the physical relationships between variables. Therefore, in terms of a continuous simulation approach for flood estimation, a critical question which needs to be addressed is the “level” of representation that will preserve the “physical chain” of the hydrological processes, both in terms of scale of representation and level of description for the modelling process (Martina, 2004).

Various studies have shown improved simulations from more detailed spatial scale and spatial resolution of physical characteristics of a catchment (Wood *et al.*, 1988; Seyfried and Wilcox, 1995). However investigations from Reed 2004 indicate that this type of distributed modelling may not always provide improved simulations. Studies by Loague and Freeze (1985) also indicate that “there are often problems with quasi-physically based models when used for design flood estimation, especially in terms of scale and the spatial variability of rainfall and soils”. These contradictory findings indicate the need to further investigate the appropriate scales at which continuous simulation modelling should be applied for improved design flood estimates.

Therefore the main objectives of this dissertation are:

- Objective I: To review the literature on different approaches commonly used in South Africa and internationally for design flood estimation and, based on the literature, assess the potential for the use of a continuous simulation approach to design flood estimation.
- Objective II: To assess the *ACRU* agrohydrological model as a tool for design flood estimation based on continuous simulation by investigating in selected catchments:
  - (a) the appropriate scale at which continuous simulation should be implemented;
  - (b) the aggregation level of soils and land cover information required to produce optimum simulated results; and
  - (c) the optimum use of daily rainfall stations for the configuration of the *ACRU* model.

- Objective III: To compare design flood estimates, both in the form of streamflow volumes and peak discharge, from flows simulated by the *ACRU* model with design flood estimates obtained from observed data.

A detailed review of techniques for design flood estimation is presented in Chapter 2 of this document. In this chapter different approaches available for design flood estimation are categorised and commonly used methods are summarised and evaluated. Concepts of continuous simulation, the advantages and disadvantages of the approach and the application of continuous simulation models for design flood estimation and scale issues in configuring a continuous simulation model, are detailed in Chapter 3. Chapter 4 provides details of the methodology employed in this study and includes the general research approach, concepts of the *ACRU* model, the description and configuration of selected catchments, scenarios, and the analysis of observed data. The results obtained from the investigations carried out in the Thukela and Lions River study areas are presented in Chapter 5. Discussion and conclusions drawn from the results as well as recommendations for future research are detailed in Chapter 6.

* * * * *

The research carried out in this MSc study contributed significantly to a Water Research Commission (WRC) project (K5/1318) titled "The Development of a Continuous Simulation System for Design Flood Estimation in South Africa". The literature review and case study presented in this thesis form an integral part of the WRC project report by Smithers *et al.* (2007). A scientific paper based on preliminary investigations conducted in this research study has also been published by Chetty and Smithers (2005) in the Journal of Physics and Chemistry of the Earth

2. A REVIEW OF TECHNIQUES FOR DESIGN FLOOD ESTIMATION

There are many different techniques available for design flood estimation, but the availability of hydrological data has a significant influence on the use of these techniques and thus the results obtained. In this literature review chapter different methods for design flood estimation are categorised and summarised.

2.1. Approaches to Design Flood Estimation

The approach adopted to estimate design floods primarily depends on the type of data available for the area in question. Various sources of literature (Alexander, 1990; Maidment, 1993; Reed, 1999, Beven, 2000; Pilgrim, 2001) indicate several other factors which influence the choice of technique to be used. These include:

- the general accuracy associated with the method;
- whether a deterministic or probabilistic estimate is needed;
- the time available and costs involved in estimating the flood;
- the expertise available for more complex methods and
- the required end product, whether it is the peak discharge or the entire hydrograph.

Approaches to design flood estimation have been classified differently in the literature reviewed. According to Alexander (1990) approaches to flood estimation in South Africa can be classified as direct statistical analyses, regional statistical analyses, deterministic and, empirical methods. The American Society of Civil Engineers (ASCE, 1997) categorised flood estimation techniques as follows:

- simplified methods such as formulae, regression equations and envelope curves,
- frequency analysis of streamflow data where adequate data are available,
- event based rainfall-runoff analysis of storm events where inadequate, or no, streamflow data exist, and
- period of record rainfall-runoff analysis, where a historical sequences of rainfall are input to a rainfall-runoff model to generate the variable of interest, which can then be subjected to frequency analyses, i.e. continuous simulation .

The Flood Estimation Handbook (FEH), which was developed to provide generalised procedures for rainfall and flood frequency estimation in the United Kingdom (UK), provides two main approaches to flood frequency estimation (Reed, 1999). The first approach involves the statistical analysis of peak flows which is utilised when there is a long record of gauged flow at, or close to, the subject site. The second approach is the Flood Studies Report by the Natural Environment Research Council (NERC) (1975) rainfall-runoff method which estimates flood frequency from rainfall frequency using a hydrological model to link rainfall to resultant runoff.

The Australian Rainfall and Runoff reports (Pilgrim, 2001) are a guide for flood estimation in Australia and classify design flood estimation approaches as either statistical analyses, applied at either a single location or across a region, and either deterministic or probabilistic based rainfall-runoff . Similarly, Beven (2000) and Cordery and Pilgrim (2000) distinguish between statistical analyses based on observed flood data, regional analyses for sites with no data and rainfall-runoff approaches. In summary, Figure 2.1 provides a classification of the general approaches to design flood estimation based on the availability of runoff or rainfall data.

The two main approaches to design flood estimation are methods based on the analysis of the streamflow data and rainfall-runoff based methods. Methods based on the analysis of streamflow data (flood data) are used when streamflow data are available. These methods include empirical formulae, maximum flood envelopes and flood frequency analysis, either at-site or regional approaches. When there is inadequate or no streamflow data available but adequate rainfall data is available, rainfall-runoff based methods may be used for design flood estimation. Rainfall-runoff based methods include design event models, joint probability approaches and continuous simulation. The next section of this chapter addresses techniques based on the analysis of streamflow records, with particular reference to methods used in South Africa.

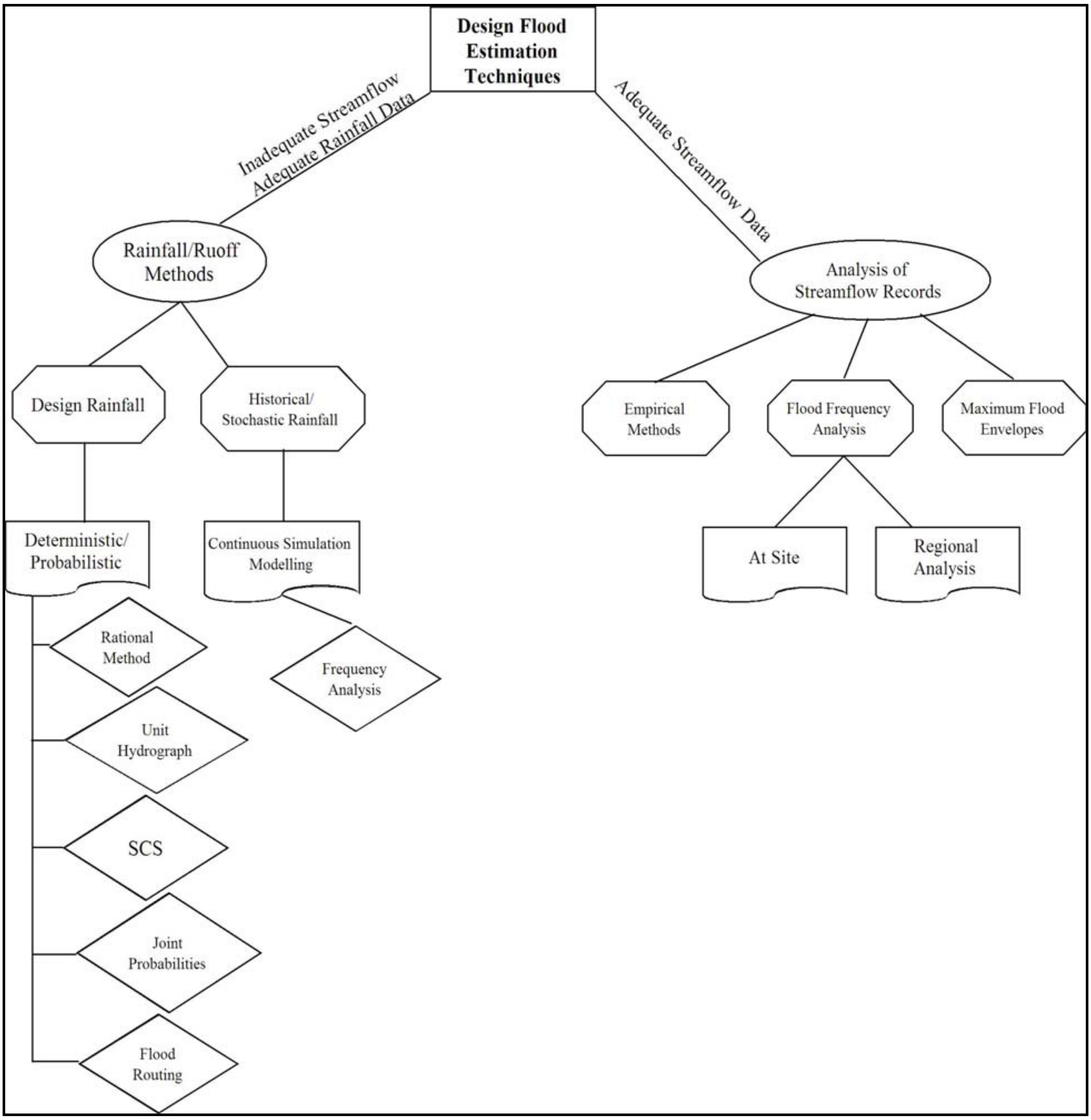

Figure 2.1 Summary of the approaches to design flood estimation (after Smithers and Schulze, 2001)

2.2. Methods Based on the Analysis of Streamflow Data

Statistical analyses of long records of streamflow data, either at a location or across a region, provides a basis for estimating the frequency of occurrence of a flood with a given magnitudes. The methods are inherently probabilistic and are, therefore, suitable for estimating floods for design purposes (Cordery and Pilgrim, 2000). They can be classified as empirical methods, maximum flood envelopes and regional analyses.

2.2.1. Empirical methods

Empirical methods use empirical formulae which generally relate peak discharge to catchment size and other physiographical and climatic catchment characteristics. According to Rahman (1998), these methods are of a “black box” model type i.e. they do not incorporate any hydrologic knowledge in the system, and are simply a statistical means of converting a known rainfall input into a design flood output.

According to Alexander (1990), the SCS method is a commonly used and accepted empirical method, although some researchers (Schulze *et al*., 1987; Ponce and Hawkins, 1996) consider the method to be a conceptual one. The Creager method and the Francou Rodier Method are other common empirical methods (Alexander, 1990). Roberts (1963; 1965), cited by (Alexander, 1990), developed a method to estimate design peak discharges in South Africa as a function of catchment area, a catchment coefficient and a coefficient derived from the Hazen distribution. Pitman and Midgley (1967) identified 7 homogeneous flood producing regions in South Africa and developed a co-axial diagram with four variables *viz*. return period, locality, catchment area and peak discharge in order to estimate design floods in South Africa. Herbst (1968), cited by (Alexander, 1990), developed this relationship further and included the mean annual precipitation (MAP) and coefficient of variation of floods, as variables. The United States Geological Survey (USGS) quantile regression methods and the Probabilistic Rational method used in Australia are also examples of empirical methods (Rahman *et al.*, 1998).

Empirical methods are generally used for maximum flood estimation and estimates therefore tend to be conservative (Alexander, 1990). Advantages of using empirical methods are that the coefficients can be derived to directly link flood and rainfall exceedance probabilities which overcome one of the limitations of design event models. However, this limits the application of empirical methods to within the range of conditions where they have been calibrated (Rahman *et al.*, 1998). According to Cordery and Pilgrim (2000), if empirical methods are not calibrated from the catchment in question, their use in extrapolation can be hazardous and should be avoided. The South African National Roads Agency Limited (SANRAL, 2006) states that empirical methods should be used for checking results obtained by other techniques as their use requires a combination of experience, historical data and/or results from other methods.

2.2.2. Maximum Flood Envelopes

The maximum envelope approach involves plotting the largest observed discharges against catchment area, both on logarithmic axes. An upper envelope is then sketched to include all the data points. Envelopes are extended with an increase in runoff record length and when larger flood events are observed. According the ASCE (1997), the envelope approach can facilitate peak discharge determination at ungauged sites. In South Africa, flood envelopes were developed by the Hydrological Research Unit (1972) and later comprehensive regional maximum flood envelopes based on the Francou Rodier approach, were developed by Kovacs (1989). Görgens *et al.* (2007) have recently revisited the Hydrological Research Unit flood envelope method. The aim of the research undertaken was to verify the flood envelope curves for large and small area storms, against estimates based on the latest available runoff records (Görgens *et al.*, 2007). Results from the study indicated that for large and small area storms, the Hydrological Research Unit method may be underestimating the maximum precipitation and therefore the probable maximum flood. Recommendations to hydrological practioners were to practice due caution when applying this method (Görgens *et al*., 2007).

2.2.3. Flood Frequency Analysis

As a consequence of the large economic and environmental impact of floods, flood frequency analysis is a subject of importance and interest (Bobee and Rasmussen, 1995). Flood frequency analysis approaches to design flood estimation can be categorised as at-site and regional flood frequency analyses. These approaches are discussed in Sections 2.2.3.1 and 2.2.3.2, with particular reference to design flood estimation practice in South Africa.

2.2.3.1. At-site analysis

Where sufficiently long records of data exist, either in the form of an annual maximum series or a partial duration series, a frequency analysis can be performed and probability distributions are fitted to the data in order to estimate design values for particular return periods (Smithers and Schulze, 2001). According to Cunnane (1989) the choice of distribution should account for descriptive abilities, ensuring that the shape of the distribution resembles that of the samples distribution, and predictive abilities, implying that estimates of candidate distributions are robust with small errors and little bias. Goodness-of-fit tests and hypothesis tests are then employed to aid in the selection of the most appropriate distributions. These tests do not necessarily lead to unique choices of distributions, but can be used to reject unsuitable distributions. Tests which focus on the ability of alternative probability distributions to approximate the data are performed (Smithers, 1996).

According to Smithers and Schulze (2000), approaches available for estimating the parameters of a selected distribution can be summarised as Method of Moments (MoM), Maximum Likelihood Procedure (MLP), Probability Weighted Moments (PWM), L-Moments (LM), Bayesian Inference and non-parametric methods. The method of L-Moments has become the generally accepted method to estimate the parameters of the probability distributions. L-Moments summarise theoretical probability distributions and observed samples. Hence L-Moments can be used for parameter estimation, interval estimation and hypothesis testing (Vogel *et al.*, 1993b). L-Moments have several important advantages over ordinary product moments. In order to estimate sample variance and sample skew, ordinary product moments require the squaring and cubing of the observations respectively, whereas L-Moments are linear combinations of the ranked observations and do not require squaring or cubing of the observations (Vogel *et al.*, 1993a). L-Moments are therefore, subject to less bias than ordinary product moments (Hosking and Wallis, 1993). According to Bobee and Rasmussen (1995) and Cordery and Pilgrim (2000), a shortcoming of the method is the problem of selecting an appropriate distribution for a sample from a population with an unknown distribution. Another concern is the way in which the L-Moments approach assigns less significance to outliers.

2.2.3.2. Regional analysis

In many instances hydrological data such as annual maximum series or partial duration series at sites are inadequate for frequency analysis because available records are either too short or there are no records at all. In these instances, techniques other than direct statistical analyses have to be employed. Regional analysis methods utilise data from several sites to estimate a regional frequency distribution which may be used to estimate design values at locations with inadequate data (Hosking and Wallis, 1997).

In a regional analysis it is assumed 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; Hosking and Wallis, 1997). Regionalisation therefore assists with performing frequency analyses with short records of annual floods by aiding in 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).

Many research studies have shown that regional analyses are more reliable than methods that utilise data from a single site (Cunnane, 1989; Hosking and Wallis, 1993). After a review of available literature, Hosking and Wallis (1993) encourage 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”. Even when regions are “slightly” heterogeneous, regional analysis is likely to yield more realistic design estimates than at-site analysis(Cunnane, 1989; Hosking and Wallis, 1997). According to Alexander (1990), regional statistical analyses provide a basis for improving the estimates of the design values of the distribution at both gauged sites with short records and at ungauged sites. Cordery and Pilgrim (2000) conclude that regional approaches are "the only sure basis for improved flood prediction". The advantages of regionalisation are thus evident from a wide range of previous studies. The index flood, regional regression and record augmentation are regional analysis procedures.

2.2.3.2.1. The Index Flood method

According to Stedinger *et al.* (1993) the index flood method is a simple regionalisation technique that uses several data sets in an effort to construct more reliable flood quantile estimates. The underlying concept behind the index flood approach is that the distributions of floods at different sites in a homogenous region are the same except for a scale, or index flood, parameter which reflects the size, rainfall and runoff characteristics of each catchment (Stedinger *et al.*, 1993).

The index flood method and adaptations have been used in many studies. Smithers and Schulze (2000a; 2000b) used an index rainfall-based procedure developed by Hosking and Wallis (1993; 1997) to estimate both short and long duration design rainfalls in South Africa. The index flood method, as proposed by Hosking and Wallis (1993; 1997), was also successfully utilised in studies undertaken in by Kjeldsen *et al*. (2001) and Mkhandi *et al.,* (2000). Kjeldsen *et al*. (2001) developed relationships to estimate the index flood as a function of the mean annual precipitation and catchment area. The derived index flood at the site was used to re-scale the regional growth curve in order to obtain design flood estimates at an ungauged site. The study undertaken by Mkhandi *et al.* (2000) also used the same L-moment based procedures to identify discordant gauging stations and homogeneous flood producing regions in Southern Africa.

The Flood Studies Report used in the UK (NERC, 1975) has been updated and revised and is now called the Flood Estimation Handbook (FEH) (Reed, 1999), and also uses an index flood based methodology. According to Reed (1999), the statistical method aims to make best use of flood data at the subject site and to build in knowledge gained from other gauged catchments, so as to obtain robust and reliable estimates. The approach constructs a flood frequency curve as the product of the index flood, which is the two year return period annual maximum flood and, the flood growth curve. The growth curve is a standardised or scaled version of the flood frequency curve. It has the same shape as the flood frequency curve but it is scaled to have a value of one (1) at the two year return period. The choice of method for estimating the index flood depends on the length of record and is summarised in Table 2.1. Where record lengths are longer than 13 years, the median is used to estimate the index flood. In the absence of observed flood peak data, the index can be estimated from catchment descriptors (Reed, 1999).

Table 2.1 Recommended methods for estimating index flood (Reed, 1999)

Length of Record	**Index Flood Estimation Method**
< 2 years	data transfer from donor site
2 to 13 years	peaks-over-threshold data
> 13 years	median of annual maxima

The median is used by the FEH as an index flood as it is more robust than the mean and, can be interpreted directly as the 2 year return period event (Reed, 1999). The growth curve, according to Reed (1999), is derived from data in annual maximum format and depends on the length of record and the required return period for the design flood to be estimated.

Where streamflow records are too short, data is pooled from other hydrologically similar catchments and this approach is referred to as a pooled analysis. According to Reed (1999), if the site record is long enough for site analysis to play a direct role in growth curve estimation, the site is excluded from the pooled analysis. This case does not occur very often because gauged data are rarely as long as the required return period; hence the growth curve will frequently be based on a pooled analysis Reed (1999).

2.2.3.2.2. Regional regression and record augmentation

Stedinger *et al* .(1993) recommends regional regression based methods for use in ungauged catchments as regressions can be used to derive equations to predict the values of various hydrologic statistics, including means, standard deviations and quantiles, as a function of physiographic characteristics. Tests in the United States of America (USA) proved that regression models performed as well as, and even better, than more complex models (Stedinger *et al.*, 1993).

Record augmentation is used when missing observations in a short record can be in-filled by using a longer nearby record with which observations in the short record are highly correlated. This can be used to fill in a limited number of missing observations, extend the shorter record and improve the estimates of the mean and variance at the short record site (Stedinger *et al.*, 1993). According to Cordery and Pilgrim (2000), care must be exercised to ensure that the regionalisation approach is not applied outside of the region where the method was developed or outside of the range of observations used to develop the method.

2.2.3.3. Evaluation of flood frequency analysis

Flood frequency analysis is widely used for design flood estimation provided adequate data is available to perform the analyses. Beven (2000) identifies the following limitations of a frequency analysis:

- 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 may only represent 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 the land use characteristics may have changed during the period of historical measurement.

The scenario of adequate streamflow data being available for design flood estimation has been discussed in this section. In practice adequate streamflow data are seldom available and rainfall data have to be used in rainfall-runoff relationships to estimate design floods. The different rainfall-runoff based methods are discussed in the following section.

2.3. Rainfall – Runoff Methods

According to Beven (2000), there are many different reasons why the rainfall- runoff processes in hydrology is . The main reason is, however, a result of the limitations of hydrological measurement networks. It is not possible to measure every flux in the hydrological system and a means of extrapolating, in both space and time, from observations to ungauged locations, is required for decision making. Engineers and hydrologist are often faced with the problem of inadequate streamflow data at the point of interest. It is in such situations that rainfall based flood estimation techniques are adopted. Rahman *et al.*, (1998) outlined the important aspects of rainfall based flood estimation as follows:

- Longer rainfall records from a denser network than streamflow records are normally available and their conjunctive use with a rainfall-runoff model allows for estimates of floods at ungauged sites.
- Areal extrapolation of rainfall records can be achieved more easily than runoff records.
- Representations of physical features are incorporated into these models which facilitate extreme flood estimation.

There are a number of rainfall - runoff based methods in widespread use. However, only those that are commonly used are reviewed in this document. Many rainfall-runoff methods can be used for either probabilistic design estimates or for the prediction of actual floods, but the validity of parameter estimation and the likely accuracies of the procedures may vary (Cordery and Pilgrim, 2000). The methods that are categorised as design event models are discussed first, followed by the joint probability approach and finally continuous simulation.

2.3.1. Design event models

Event based methods are commonly used to estimate design floods and often form part of the standard techniques developed for design flood estimation in many countries (Pilgrim, 1987; Cameron *et al.*, 1999; Houghton-Carr, 1999; Boughton and Droop, 2003). The widespread use of event based methods is often attributed to the simplicity in applying the method to estimate design floods (Cameron *et al.*, 1999; Houghton-Carr, 1999; Boughton and Droop, 2003). According to Rahman *et al.* (1998) these methods use design rainfall intensity for specified durations and annual exceedance probabilities with other relevant input parameters to produce design floods. Cameron *et al.* (1999) explain that a design event approach usually assumes that it is feasible to use a combination of storm depth, storm duration, profile and antecedent wetness to produce a flood hydrograph with a peak of a given return period.

According to Rahman *et al.* (1998), this approach assumes that for relevant inputs and model parameters, the frequency of the estimated flood is equal to the frequency of the input rainfall. Many researchers agree that this assumption is a major limitation of event based methods (Rahman *et al.*, 1998; Cameron *et al.*, 1999; Boughton and Droop, 2003) According to Rahman *et al.* (1998) assuming that the "T-year" rainfall will produce the "T-year" return period runoff, could introduce significant bias in the frequency of flood estimates.

A summary of limitations of design event based approaches to flood estimation from various literature are listed below:

- design based approaches account for the probabilistic nature of the input rainfall, but don not consider the probabilistic behaviour of other inputs and parameters such as rainfall duration, losses and baseflow (Rahman *et al.*, 1998).
- the event based approaches greatly simplify essential catchment conditions prior to the occurrence of an event, even when a rainfall-ruoff model is used to specify the entire hydrograph of the flood event (Cameron *et al.*, 1999).
- 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).

- Event-based flood hydrograph models such as the unit hydrograph, based on surface runoff only, can be prone to significant error because of the subjective nature of streamflow partitioning in a short section of streamflow during a flood event. This is most likely when the baseflow component of flow is large (Boughton and Droop, 2003).
- There is subjectivity in selecting a critical storm duration in order to fix the rainfall intensity, and then selecting a temporal distribution of that rainfall in event based flood estimation approaches (Boughton and Droop, 2003).

Even though event based flood estimation methods have several limitations they are commonly used in practice. The Rational method, unit hydrograph method, the US Soil Conservation Service (SCS) method and runoff routing methods are commonly used event based approaches. These will be discussed in the sub-sections which follow.

2.3.1.1. The Rational method

The Rational method was developed in Ireland in 1855 and is considered to be the most common method of flood estimation used in practice internationally (Alexander, 1990). The method, despite some criticism, is also considered the most useful and readily applicable design methodology (Alexander, 1990).

The Rational method assumes that if a rainfall of intensity I begins instantaneously and continues indefinitely, the rate of runoff will increase until the Time of Concentration (Tc), when the entire catchment is contributing to flow at the outlet. The Rational formula is (Alexander, 1990):

$$q_p = 0.278\, C\, I\, A \qquad \text{Equation 2.1}$$

where q_p = peak discharge ($m^3.s^{-1}$),

C = runoff coefficient,

I = intensity of rainfall ($mm.h^{-1}$), and

A = catchment area (km^2).

The calculation is quick to perform, but the accuracy of the results depends on the experience of the user, as the formula used has no scientific basis (Alexander, 1990). When viewed as a deterministic model, the *C* factor in the Rational equation represents the percentage of total rain converted into runoff. Joint rainfall-runoff probabilities are not taken into account and the X-year return period runoff event is assumed to result from the X-year rainfall event (Alexander, 1990). Alexander (1990) follows the Department of Water Affairs and Forestry's approach which views the rational formula as a deterministic model, which contains probabilistic elements, since the value of *C* is adjusted by a factor dependent on the return period (Alexander, 1990). According to Alexander (1990) the Rational method is based on the following assumptions:

- The design storm produces an equal intensity of rainfall over the whole area.
- The peak flow at the catchment exit occurs when runoff from the remotest point in the catchment arrives at the exit. The time taken for this to occur is *Tc* and, it is assumed that the storm lasts at least for this time of concentration.
- The percentage of total storm volume converted into runoff is constant for a particular catchment.

The Rational method is a deterministic method in which 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). There are also practical difficulties of estimating the catchment response time since regional differences in the time of concentration cannot be explained or easily measured by catchment characteristics (Cordery and Pilgrim, 2000). The assumed uniform of rainfall intensity and the exclusion of temporary storage limit the application of the deterministic Rational Method to urban and small rural catchments (Cordery and Pilgrim, 2000). Several researchers recommend a probabilistic approach to determine the runoff coefficient for the Rational method as applied in South Africa and Australia (Alexander, 1990; Pilgrim and Cordery, 1993; Cordery and Pilgrim, 2000).

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 (Pilgrim and Cordery, 1993). Comparative studies performed in Australia using the probabilistic and deterministic approaches show that the probabilistic

Rational method performs better and is suitable for catchments of up to 250 km^2, compared with the very poor performance of the deterministic approach (Pilgrim and Cordery, 1993).

Alexander (2002) has introduced a “new approach” to design flood estimation called the Standard Design Flood (SDF). The approach uses the Rational method with a calibrated runoff coefficient instead of a catchment related coefficient as in the conventional Rational method. He maintains that the method is applicable on all catchment sizes. According to Görgens (2002) the SDF is a “conscious over-design approach” which would not be acceptable for spillway design and therefore should be seen as a conservative approach. Pegram (2003) has also introduced the Modified Rational formula for use on larger catchments. This method was further investigated in a study by Parak and Pegram (2005) where, the Modified Rational Formula with the use of a runoff coefficient estimated by a probabilistic approach, was used to check the Rational formula for estimating flood peaks on a wide range of catchment sizes.

2.3.1.2. The unit hydrograph method

According to Alexander (1990) the unit hydrograph method was first proposed in the United States in 1932. The basic assumption in the unit hydrograph method is that a unit of effective precipitation, uniformly distributed over the catchment in both time and space, will result in a uniquely shaped hydrograph for that catchment (Alexander, 1990). Implicit in this assumption is that the catchment acts as a lumped system (Maidment, 1993). Further assumptions are that the ordinates of hydrograph are linearly proportional to the volume of effective precipitation, and that the shape is independent of antecedent conditions. This implies that the hydrograph is related to the average state of the catchment (Alexander, 1990).

Various versions of the unit hydrograph approach are widely used and often form an integral part of standard techniques developed and recommended for use for flood estimation in different countries including, the USA, UK, Australia and South Africa. The UK FEH (Reed, 1999) rainfall-runoff method uses a unit hydrograph/losses model with three parameters. One parameter controls the temporal characteristics of the runoff response to rainfall, and hence the time to peak. The second parameter influences the volumetric characteristics of the runoff response and the third parameter represents the river flow prior to the flood event i.e. the baseflow (Reed, 1999).

Pilgrim (1987; 2001) recommends the unit hydrograph approach for estimating design flood hydrographs in Australia. Both the standard unit hydrograph method as well as the synthetic unit hydrograph approach is utilised depending on the design situation. The Hydrological Research Unit (1972) developed a unit hydrograph technique for application in South Africa for a wide range of catchment areas. Nine veld zone types were identified and dimensionless unit hydrographs were derived for each zone. A co-axial diagram to estimate mean storm losses in the nine zones was also developed.

According to Chow *et al.* (1988), the unit hydrograph method assumes a characteristic linear response from a catchment and may not be accurate for estimating large floods. However, cautious use of the method can provide acceptable estimates (Dunne and Leopold, 1978; Chow *et al.*, 1988; Pilgrim, 2001). An advantage of the unit hydrograph approach is the estimation of the entire hydrograph, which is important where storage is involved e.g. dam design, and when hydrographs from dissimilar tributary areas are added and routed down stream to a channel of interest (Dunne and Leopold, 1978). A major limitation of the unit hydrograph approach is the assumption of spatial uniformity (Dunne and Leopold, 1978). The complexity of deriving unit hydrographs from multi period storms and the difficulty in applying the unit hydrograph approach to catchments with major non-linear response e.g. urban catchments and very small catchments are also limitations according to Pilgrim (1987; 2001). However, the unit hydrograph method can be applied to gauged and ungauged catchments and is widely used due to its simplicity (Houghton-Carr, 1999; Pilgrim, 2001).

2.3.1.3. The SCS method

Schulze *et al.* (1992) pointed out that there is a frequent need for hydrological information for use in the planning, design and management of water resources systems on small catchments, i.e. with areas < 30 km^2. However, data limitations for small catchments frequently result in difficulties in design flood estimation (Pilgrim, 1987; Marshall and

Bayliss, 1994). Stormflow volume and peak discharge rates are commonly required for selected design return periods and these values often need to be estimated with the use of simulation models. One such model which is well known and has become established for use on small catchments in South Africa is the SCS method (Alexander, 1990; Schulze *et al.*, 1992; Alexander, 2001; Görgens, 2002). According to Schulze *et al.* (1992) the method is recommended by many institutions and has been tested and used widely in South Africa. The SCS-SA model requires estimates of design rainfall and an ability to relate local soil and vegetation characteristics to those that are given in tables and nomograms which are used to estimate model parameters (Cordery and Pilgrim, 2000). The SCS method adapted for South Africa by Schmidt and Schulze (Schmidt and Schulze, 1987), is widely used for estimation of design floods on small catchments in South Africa. Research and modification of individual components of the SCS equations include the following:

- classification of all soil series identified in South Africa into hydrological response classes;
- introduction of three intermediate SCS soil hydrological groups to the original groups A, B, C and D for South African soil series *viz*, A/B, B/C and C/D.
- the inclusion of soil water budgeting techniques to adjust the stormflow response from the original SCS approach to account for typical catchment antecedent moisture status using two methods *viz*. the median condition method and joint association method (Dunsmore, 1985; Schmidt and Schulze, 1987);
- evaluation of a new lag equation termed the Schmidt and Schulze lag equation, against the original SCS lag equation to determine peak discharge estimates more accurately (Schmidt, 1981);
- the regionalisation of 4 synthetic storm distributions that depict the variation of design rainfall intensity with time (Weddepohl, 1988); and
- a re-evaluation, based on observed hydrographs and a re-analysis of the United States Department of Agriculture data, of the coefficient of initial abstraction for use with design storms (Weddepohl, 1988).

Recent adaptations to the SCS-SA model include the development of the SCS method for limited hydrological information (SCS-LHI) by Ghile (2004). The aim of this study was to approach the soil water status of a catchment as a climatologically driven variable using

Köppen climate classes to determine regional changes in soil moisture (ΔS) : Mean Annual Precipitation (MAP) relationships (Smithers *et al.*, 2007):

The SCS method has also been applied in a probabilistic manner in Australia and the derived curve numbers (CNs) showed little agreement with those estimated by conventional means. The derived CN was affected by the method used to estimate the catchment lag time and also depended on the return period. The above findings 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. However, if the method was modified so that parameters were based on local data and information, in a similar manner to the ideas used in the probabilistic Rational method, it could be expected to provide more accurate flood estimates (Cordery and Pilgrim, 2000).

2.3.2. Runoff routing

The runoff routing approach, which also produces a complete hydrograph, was developed to overcome some of the limitations of the unit hydrograph approach, *viz.* the assumptions of spatial uniformity of rainfall and linearity of flood production processes (Cordery and Pilgrim, 2000). Procedures for runoff routing, according to Cordery and Pilgrim (2000), involves dividing the catchment into sub-catchments which can each have different rainfall excess characteristics and then routing the runoff from each sub-catchment through downstream sub-catchments to the catchment outlet.

The major advantage of runoff routing, according to Cordery and Pilgrim (2000), is the possibility of changes to the catchment surface or channel conditions which allows for the examination of effects of such changes on flood hydrographs. Another advantage is that the spatial distribution of rainfall can be accounted for. The Muskingham method and the Lag-route method are examples of flood estimation using flood routing techniques (Bauer and Midgley, 1974).

2.3.3. Joint probabilities approach

A joint probability approach to flood estimation incorporates the concept that any design flood characteristics (e.g. peak flow) could result from a variety of combinations of flood producing factors, rather than from a single combination, as in the design event approach (Rahman *et al.*, 1998). For example, the same peak flood could result from a small storm on a saturated catchment or a large storm on a dry catchment. It therefore appears that a joint probability approach which considers the outcomes of events with all possible combinations of input values and, if necessary their correlation structure, will lead to better estimates of design flows (Rahman *et al.*, 1998).

According to Rahman *et al*, (1998) probability distributed inputs are used to form probability distributed outputs. Hence, subjectivity in the selection of inputs and parameter values is eliminated by considering the input as random variables. Three stages are required to develop a design flood estimation technique based on the joint probability approach (Rahman *et al.*, 1998), *viz.*

- The selection of flood producing variables and assigning probability distributions to these variables.
- The selection of a suitable rainfall-runoff model.
- The selection of a mathematical framework within which the above two components can be combined to determine the derived flood frequency distribution.

Pilgrim (1987) clarifies that by using the same component models as the current design event approaches, but treating inputs and parameter values to the design as random variables, the joint probability approach attempts to eliminate subjective criteria in specifying input. The flood output will have a probability distribution instead of a single value (Pilgrim, 1987).

2.3.4. Continuous simulation

The use of a continuous simulation is, according to the ASCE (1997), receiving increasing interest and use in the United States of America due to the continuing decrease in the cost of computer and the increase in computing power and the number of hydrological models with continuous simulation ability. The concept of developing a framework within which hydrological models can be integrated to provide whole catchment is of importance (Reed, 1999). According to Rahman *et al.* (1998), continuous simulation may prove to be the most powerful means of estimating flood frequencies from rainfall in the near future. Smithers and Schulze (2001), in identifying research needs for design flood estimation in South Africa, point out that a continuous simulation approach to design flood estimation should be further evaluated and developed for South Africa.

* * * * *

This chapter addressed Objective I outlined in Chapter 1 of this dissertation. A detailed review of techniques commonly used for design flood estimation both internationally and locally is presented. It is evident from this review that several methods are available for flood estimation however; their use is limited by the quantity and quality of data available. Design event based rainfall-runoff methods are commonly used for design flood estimation but these have several limitations. The continuous simulation modelling approach to design flood estimation is gaining much recognition since it can overcome many of the limitations of the currently adopted design flood estimation techniques. Continuous simulation modelling is a major component of this study given the potential it holds for design flood estimation in the future. The concepts of continuous simulation modelling, its application in flood estimation studies and scale issues in configuring a continuous simulation model for design flood estimation are discussed and detailed in the next chapter.

3. CONTINUOUS SIMULATION

According to Rahman *et al.* (1998), continuous simulation models aim to represent the major processes responsible for converting catchment rainfall inputs into flood outputs. Outflow hydrographs are generated over long periods of time from the input of historical or stochastic rainfall series, potential evaporation and other climatological information. An important characteristic of these models is the continuous use of a water budget model for the catchment so that antecedent soil moisture conditions to each storm are known (Rahman *et al.*, 1998). A relatively sophisticated hydrological model, capable of simulating all aspects of the hydrological cycle is required by the method (ASCE, 1997).

According to (Cameron *et al*., 1999) the use of a continuous rainfall series, either observed or stochastically generated, as input into a continuous hydrological model and, the subsequent analysis of resultant flood peaks of the simulated flow series, overcomes the assumptions on which the design event approach is based. The data requirements for continuous simulation models are of concern to Reed (1999) but he concedes that such an approach overcomes many limitations of the design event approach and the complexity associated with the joint probability approach.

Schulze (1989) stressed the importance of a continuous simulation approach to design flood estimation. He highlighted that:

- long periods of record are necessary for accurate estimation of design values,
- long flood series are generally not available, often contain inconsistencies and are frequently both non-homogeneous and non-stationary,
- compared to runoff data, longer data sets of rainfall of better quality are usually available in greater abundance than runoff records for most regions, and
- the exceedance probability of floods is generally not related to the exceedance probability of rainfall, as assumed in event based models.

3.1. Advantages and Disadvantages of Continuous Simulation

Many researchers agree that the continuous simulation modelling approach to design flood estimation has several advantages (Hromadka, 1987; Rahman *et al.*, 1998; Reed, 1999; Boughton and Droop, 2003). The most significant of these advantages relates to the way in which initial or antecedent moisture is explicitly accounted for or at each time step and its influence on runoff generation (Rahman *et al*., 1998). Another significant advantage is that a frequency analysis of the variable of interest is undertaken by statistically analysing the time series of model output, as opposed to assuming that the return period of the output is equal to that of the input rainfall (Rahman *et al*., 1998).

The views of several researchers on advantages of continuous simulation include the following:

- a complete hydrograph is generated and not only a peak discharge enabling better analyses (Reed, 1999),
- the concepts are more physically based than other methods (Hromadka, 1987),
- continuous simulation can be used in unique catchments where other procedures such as statistical ones are not applicable (Hromadka, 1987),
- annual peak floods at various locations in the catchment can be determined automatically (Hromadka, 1987),
- effects of complex hydrological systems and water engineered systems can be (Hromadka, 1987),
- the concepts are easily understood (Hromadka, 1987),
- streamflow can be considered as a single term without explicit prior separation into stormflow and baseflow (Reed, 1999),
- actual rainfall from the area is used and not general regionalised design values Boughton and Hill (1997),
- assumptions about losses are avoided (Boughton and Hill, 1997),
- 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 is necessary (Boughton and Hill, 1997).

According to Rahman *et al.* (1998) the main problems with the continuous simulation approach arise from the difficulties in adequately representing a realistic soil moisture balance in the model, synthesising long records of rainfall and evaporation at the appropriate temporal and spatial resolutions, as well as accounting for correlations between inputs. Other difficulties are summarised by Rahman *et al*. (1998) as:

- the loss of "sharp" events if the time scale is too large,
- the extensive data requirements, which result in significant time and effort to obtain and prepare the input data,
- the management of a large amount of data and of time series output, and
- the expertise required to determine parameter values such that historical hydrographs are adequately simulated.

Cameron *et al*. (1999) caution that consistent model parameterisations are necessary when simulating continuous flow series for both water resource assessments and for flood frequency estimation. Despite the limitations of the approach, many studies reported in the literature concur that continuous simulation for design flood estimation has the potential to be a powerful means of estimating flood frequency from rainfall (ASCE, 1997; Rahman *et al.*, 1998; Cameron *et al.*, 1999; Bouvier, 2002; Boughton and Droop, 2003).

3.2. Applications of Continuous Simulation

According to Boughton and Droop (2003) continuous simulation of catchment runoff began in the early 20th century with manual calculations and was driven primarily by the need for improved flood forecasting. The SCS curve number approach were leaders in this field of continuous simulation (Boughton and Droop, 2003). However, as shown above the SCS method is considered to be a design event method. According to Boughton and Droop (2003) the first continuous computer simulation streamflow model, the Stanford Watershed Model, was developed at Stanford University by Linsley and Crawford (1960). Subsequent to these developments various other models were introduced in a number of applications of continuous simulation modelling for flood estimation.

According to the ASCE (1997), general applications of continuous simulation modelling which have been undertaken include the following:

- Extension of streamflow records where the record length of streamflow data is shorter than available climate data and the continuous simulation approach is seen to be a logical method of extending the streamflow record.
- The generation of streamflow series for ungauged sites using continuous simulation has been used. The method relies on the fact that adjacent catchments are most likely to have similar subterranean characteristics, so that if a detailed simulation model is developed on a catchment with observed streamflow data, subsurface and groundwater characteristics can be transferred to the ungauged site with a relatively high degree of confidence.
- The analysis of the effects of catchment modifications such as urbanisation or land use change on runoff.
- The long term forecasting of runoff for operational purposes, where a statistical representation of future conditions may be produced.

Applications of continuous simulation modelling have been undertaken in many international studies but very few local studies. The remaining section of this chapter reviews different applications of continuous simulation , both internationally and locally in South Africa.

Conventionally, in the UK, flood frequency estimation has been based on the analysis of events using procedures such as those embodied in the FSR (Calver and Lamb, 1996). However, the concept of developing a framework within which hydrological models can be integrated to provide whole catchment was recognized to be of importance (Reed, 1999). At the time of publication of the FEH, the continuous simulation approach to flood frequency analysis in the UK was still in the experimental stages, according to Reed (1999). However, continuous simulation has been used for research in the UK.

Calver and Lamb (1996) used a continuous simulation modelling approach to design flood estimation on ten catchments in the UK with catchment areas ranging from 1 km^2 to 400 km^2 and with a range of geological and topographical characteristics.   The catchments included a variety of land uses from urban to rural and ranged in degree of water use for agricultural and industrial purposes. The partial duration series was used for establishing the flood frequency curves. A Poisson distribution was assumed for the occurrence of peaks and a generalised Pareto distribution for their magnitudes. The flood frequency curves were compared to those obtained from the observed data. For the group of ten catchments as a whole, the results fell in an acceptable range, while indicating some areas where improvements were necessary (Calver and Lamb, 1996). The authors concluded that the results they reported show that it is possible, given two years of hourly flow and rainfall data, to calibrate the models for catchments to a reasonably satisfactory degree. If rainfall series are then available for longer periods, models can, without further flow data, produce a representative flood frequency curve for an extended period.

Calver and Lamb (2000) presented a method for estimating flood frequencies based on rainfall-runoff undertaken on a continuous time basis that could be generalised such that application was possible at both gauged and ungauged sites. It was concluded from the research that, although the method is said to be generic, this generality is based upon a region being comparatively rich in amount and quality of hydrological data. According to Calver and Lamb (2000), the continuous simulation approach is likely to produce good site specific time series, as a basis for expressing flood frequency. A procedure for a continuous simulation approach to design flood estimation is well advanced in the UK and the method used is potentially capable of wider application if care is exercised to check the hydrological appropriateness of input used (Calver and Lamb, 2000).

The potential of using generated data in conjunction with a daily water balance model on a continuous basis was demonstrated in Australia by Boughton and Hill (1997). A daily rainfall generating model was used, calibrated using relevant statistics from an observed record, to generate very long sequences of daily rainfall. The synthetic sequence was input into the Australian Water Balance Model (AWBM), a daily rainfall-runoff model which generates a corresponding sequence of daily runoff values (Boughton and Hill, 1997). Using a relationship between daily volumes of runoff and peak rates of runoff, the annual maxima of daily runoff were used to estimate the annual maxima distribution of peak rates of runoff. The results obtained for higher recurrence interval range correlated well with the values derived from the observed data. For lower return periods, the model slightly overestimated values which was attributed to the daily rainfall generation model (Boughton and Hill, 1997).

Cameron *et al.* (1999) explored flood frequency estimation for a gauged catchment through the use of continuous simulation within an uncertainty framework. Simulations based on observed rainfalls and a stochastic rainstorm generation model as input to a rainfall-runoff model (TOPMODEL) were utilised. Acceptable parameter sets were found for both flood frequency estimation and hydrograph simulation for the study catchment. According to Cameron *et al.* (1999) the methodology presented should be applicable to other catchments in other environments using appropriate choices of rainstorm and rainfall-runoff models.

The simulation of historical peak flows for eleven Scottish rivers was undertaken by (Steel *et al.,* 1999). The Identification of Unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data (IHACRES) rainfall-runoff model, was used as the continuous simulation model (Steel *et al.*, 1999). The simulated runoff values obtained were then used in a flood risk assessment. It was found that changes in risk assessment for the hundred year flood were greatest for sites where less than 30 years of observed data exist. It was concluded that further work with long synthetic records, similar to those used in the study were important and could allow for possible changes in flood risk assessment Steel *et al.* (1999).

Blazkova and Beven (2000) demonstrated a methodology for the estimation of flood frequency characteristics for both small and large catchments, given limited hydrological information. The evaluation was carried out within the Generalised Likelihood Uncertainty Estimation (GLUE) framework where parameter sets could be constrained within the model. The TOPMODEL rainfall-runoff model was then used within the GLUE framework to estimate cumulative distributions of peak flows at higher return periods (Blazkova and Beven, 2000). The uncertainty was expressed in terms of likelihood prediction bounds of the flood frequency curves derived from continuous simulation. According to Blazkova and Beven (2000) this method then produced a realistic reflection of the uncertainty in the estimation.

Comparisons between design floods estimated from output simulated by continuous simulation model, computed directly from the observed data and estimated by a commonly used event-based design method was undertaken by Boughton *et al*. (2000). Three catchments of sizes of 62, 108 and 259 km^2 in Victoria, Australia, were used in the study.

The results showed that the flood frequency estimates computed from the observed data were considered to be reliable for the 2–10 years return periods since they were influenced by the relatively short lengths of available data. Longer records of rainfall were used with the continuous simulation rainfall-runoff methods, hence the frequency analysis derived from continuous simulation produced more reliable estimates for the larger return period floods (Boughton *et al.*, 2000). Results similar to those obtained by Boughton *et al.* (2000) were achieved in a study undertaken by Newton and Walton (2000) on the 13,000 km^2 Moore River catchment in Western Australia, where results from continuous simulation were compared with other flood estimation methods.

Improving dam safety assessment in a large catchment in the Czech Republic, by adopting a continuous simulation modelling approach to estimate design floods, was undertaken by Blazkova and Beven (2004). The 1186 km^2 Zelivka catchment, divided into four sub-catchments, was using the TOPMODEL as the continuous hydrological model. Uncertainty analyses of parameters were calculated using the GLUE framework. According to Blazkova and Beven (2004) the results obtained from the study indicate that the continuous simulation approach has adequate functionality to estimate observed flood estimates in the study area after conditioning of the available data (Blazkova and Beven, 2004). They concur with the findings of Cameron *et al.*(2000) that "the continuous simulation approach provides a framework for accounting for the factors involved, in a logical and consistent way in estimating probabilities of exceedance".

Booij (2005) used a continuous simulation approach to investigate the impacts of climate change on flooding in the river Meuse in western Europe. The use of different spatial scales to test the appropriate model resolution and its effects on the flood frequency estimates were adopted in this study. The Meuse catchment was as a lumped catchment, then discretised into fifteen sub-catchments and finally 118 sub-catchments (Booij, 2005). Conclusions drawn from the study indicated that the model reproduced the observed runoff well (Booij, 2005). According to Booij (2005) the simulated results improved with increasing spatial resolution from lumped catchment modelling to modelling 118 sub-catchments.

The importance of spatial rainfall and soil properties aggregation for distributed modelling, using a continuous simulation model to estimate flash floods in the Sesia river basin, Italy was investigated by Sangati *et al.*(2009). Spatially derived rainfall and soil properties at different input resolutions with grid sizes of 1, 4, 8 and 16 km, were used to simulate runoff volumes and peak discharge using the Kinematic Local Excess Model for four catchments ranging in size from 75 to 983 km^2 (Sangati *et al.*, 2009). This study also focused on the sensitivity of the simulated runoff volumes and peak discharge to changes in spatially derived rainfall and soil properties.

A continuous simulation approach to design flood estimation in South Africa was undertaken by Smithers *et al.* (1995; 1997) where the 760 km^2 Lions and Mpofana tributaries of the Mgeni River were with the use of the physical conceptual, daily time step *ACRU* model (Schulze and Pike, 1995). Results showed that the design flood estimates computed from the simulated results compared well with those computed from gauged flow data.

Smithers *et al*. (2001) also used a approach to investigate the spatial variability, magnitudes and probabilities of the floods which occurred in February 2000 in the eastern parts of South Africa and Mozambique. Results showed that design discharges computed from the model output were acceptable in the Sabie River catchment. In both these studies, the inadequacies of many gauging flow gauging stations to monitor large floods were highlighted (e.g. overtopping and damage) and the advantages of a continuous simulation approach to design flood estimation were illustrated (Smithers and Schulze, 2001).

3.3. Scale Issues in Configuring Continuous Simulation Models

Applications of continuous simulation modelling have been reported in section 3.2 of this chapter. Only a few of the studies reviewed adequately detail the configuration of the continuous models used or the appropriate spatial scales and optimum levels of soils and land cover information employed to produce acceptable design flood estimates. Adequate representation of soils or land cover information is vital in physically based hydrological models since they are the key regulators of a catchments response to rainfall. This section details the issues around adopting appropriate scales of representation in hydrological modelling for design flood estimation.

The transfer of information across scales of both space and time and the problems associated with it is referred to as scale issues (Blöschl and Sivapalan, 1995). “Variability in both space and time is not only an important and significant feature in hydrological science, but one of the many challenges in applied hydrology” (Woods, 2004). The influence of spatial variability and scale on the hydrologic response of catchments and their importance in hydrological modelling have been widely studied by numerous researchers (Wood *et al.*, 1988; Blöschl and Sivapalan, 1995; Seyfried and Wilcox, 1995; Reed *et al.*, 2004; Smith *et al.*, 2004; Booij, 2005; Chaplot, 2005; Das *et al.*, 2008). In the context of catchment scale hydrological modelling, heterogeneity and variability within catchments pose challenges for dealing with scale issues in hydrology (Blöschl and Sivapalan, 1995). Added to this, the use of distributed hydrological models, which aim to link conceptualized parameters and processes across scales, makes scale issues a very important component of any hydrological modelling applications (Blöschl and Sivapalan, 1995).

Incorporating detailed information on climate, elevation, soil and vegetation, physically based spatially distributed models have the potential to predict the effects of spatial variability by using parameters which have physical significance at the different spatial scales of interest (Woods, 2004). As spatial scale increases, spatial variability may significantly affect hydrological processes in catchments (Yildiz and Barros, 2009). Various studies have shown improved simulations from increased spatial scale and spatial resolution of physical characteristics of a catchment (Wood *et al.*, 1988; Seyfried and Wilcox, 1995). Wood *et al.*(1988) conducted research based on the Representative Elementary Area concept, finding the smallest critical representation of area at which implicit continuum assumptions of the spatially variable parameters may be based. (Wood *et al.*, 1988; Yildiz and Barros, 2009), However, Reed *et al.* (2004) suggest that this type of distributed modelling may not always provide improved simulations when compared to lumped models due to errors in data, model structure and model parameters. Studies conducted by Chaplot (2005) on the impact of varying digital elevation models (DEM) grid size from 20 m to 500 m within the Soil and Water Analysis Tool (SWAT) framework showed that runoff predictions were consistently accurate irrespective of the DEM mesh size used. However, in the same study by Chaplot (2005) it was found that the spatial scale of the soil map was of extreme importance for runoff simulation with the SWAT. According to Chaplot (2005), greater precision in the description of the spatial variations of soil and soil properties results in better estimates of soil-affected processes, such as runoff generation.

According to Sangati *et al.* (2009) the contrasting findings relating to appropriate spatial scales, provide little guidance as to the optimum scale of representation for both catchment area and spatially variable catchment properties such as soils and land cover, when configuring hydrological models for flood estimation purposes. Apart from the difficulties in selecting a model capable of representing complex hydrological processes are those of deciding the appropriate scale that such a model should be applied to, for design flood estimation purposes. Loague and Freeze (1985), when comparing three different methods for design flood estimation, found that accuracy decreased with an increase in complexity of the methods used, and that physically based model performed poorly. They claimed that the main difficulty was scale problems associated with the spatial variability of rainfall and soil properties. Chaplot *et al*. (2005) came to the same conclusion from a study using SWAT where it was found that the accuracy of models in predicting the runoff and erosion behavior depends, to a large extent, on the quality of the data with respect to the spatial distribution of rainfall which is the main driver of hydrological models.

From the review of literature in this section it is evident that the spatial scale and the representation of spatially variable properties such as soils, land cover and rainfall are very important for acceptable estimates of design floods, using a continuous simulation modelling approach. Very little information is documented on the configuration of continuous simulation models used to estimate design floods. It was therefore decided that the research case study of this dissertation should focus on scale issues for the configuration of a continuous simulation model for design flood estimation in South Africa.

*   *   *   *   *

Since the continuous simulation approach to design flood estimation is recognised internationally to hold much potential in the future for design flood estimation, the Water Research Commission (WRC) commissioned the University of KwaZulu-Natal to develop a methodology for a continuous simulation system for design flood estimation in South Africa. The research carried out in this MSc study contributed significantly to this WRC project and the literature review and case study presented in this thesis form an integral part of the WRC project report by Smithers *et al.* (2007). A scientific paper based on preliminary investigations conducted in this research study has also been published by Chetty and Smithers (2005) in the Journal of Physics and Chemistry of the Earth. The next chapter of this document describes the methodology used in this research and includes detailed information about the *ACRU* model concepts, configuration of catchments and modelling scenarios.

4. METHODOLOGY

An integral part of developing a continuous simulation system is the inclusion of a realistic water budget which is the core of the system. As illustrated in the previous section, various models have been used in different research projects as the continuous simulation model. The most important concern as with any project, is selecting a model that will best represent the hydrological processes occurring in the study area.

The *ACRU* model Schulze (1995) Version 3.31 was selected for use in this study as the continuous hydrological simulation system. It is a widely verified physical-conceptual model developed and tested for Southern African conditions. Verification studies are reported in Schulze (1995). In addition, the *ACRU* model has been used successfully for design flood estimation studies in South Africa (Smithers *et al.*, 1995; Smithers *et al.*, 1997; Smithers and Schulze, 2000; Smithers and Schulze, 2001) and is thus suitable to meet the objectives of the project.

According to Martina (2004) event-based or derived distribution approaches are not able to adequately follow the "physical chain" of hydrological processes in order to assess the role of each of the variables involved in rainfall-runoff processes, whereas a continuous simulation modelling approach attempts to preserve the physical relationships between variables. A time series contains not only extreme events but also other events. Therefore, in terms of a continuous simulation approach for flood estimation, a critical question which needs to be addressed is the "level" of representation that will preserve the "physical chain" of the hydrological processes, both in terms of scale of representation and level of description for the modelling process (Martina, 2004).

In the development of a continuous simulation system in this study, it is important that the performance of the continuous simulation model is optimum both for the runoff volume and peak discharges simulated. It is therefore necessary to investigate the appropriate range of scales at which the continuous simulation system could be applied to and identify the appropriate levels of spatial disaggregation which results in the best performance. Soil and land cover information also play an important role in the performance of a continuous simulation model as these are the prime regulators of a catchments response to rainfall, and therefore directly influence the hydrological response of a catchment. The *ACRU* model, which has been selected for use as a continuous simulation model in this study, can operate in lumped or distributed modes and soils and land cover information which are used as input to the model can be aggregated at different levels to represent spatial variability within a catchment. New and Schulze (1996) in a study in the Langrivier catchment in the Western Cape, South Africa, briefly looked at the sensitivity of *ACRU* model output to different degrees of model distribution *viz*. lumped versus an 18 cell distribution, at the level of a hill slope. They found that the *ACRU* model performed better in lumped mode in this catchment. However, Herpertz (1994) when using the *ACRU* model in the Brol catchment in Germany found that the *ACRU* model performed better when the catchment was discretised into 24 sub-catchments.

The primary objective of this component of the study is therefore, to investigate the appropriate scale at which the continuous simulation model should be configured with respect to levels of spatial disaggregation of a catchment and to assess the required aggregation of soil and land cover information to give optimum results. Investigations involving simulations at quaternary catchment (QC) scale and sub-quaternary scale (sub-QC), with different levels of soils and land cover information, have been undertaken in the Lions River catchment by Chetty *et al.* (2003) and further preliminary investigations undertaken in the Thukela catchment Chetty and Smithers (2005) provides the basis for this study.

4.1. General Approach to the Study

The general approach to this study is based on Objectives IIa, IIb, IIc and Objective III described in Chapter 1. The steps undertaken to achieve these objectives included the following:

- Selection of appropriate study area/s where adequate information is available to run the *ACRU* model.
- Analysing topographical, land cover and soils information to facilitate catchment discretization at different scales.
- Catchment discretization at different scales and configuration of selected catchments for use in the *ACRU* model.

- Derivation and definition of scenarios to address the specific aims of the study.
- Data analysis and processing of information for use in the *ACRU* input files (menus) for each of the defined scenarios.
- Defining the hydrological response units (HRU's)
- Populating the *ACRU* input menus with relevant data.
- the different scenarios and analysis of results obtained.
- Selection of best scale of representation for continuous simulation .
- Estimation and analysis of peak discharge.
- Estimation of design floods from best scale of representation.
- Comparison of design floods computed from the simulated output with design floods computed from the observed data.

Details of the methodology utilised in the overall research strategy described above are discussed in the subsequent sections of this chapter. Concepts of the *ACRU* model are explained, selected study areas are described, analysis and processing of data for input to the model for each of the selected catchments is detailed and the scenarios are described.

4.2. *ACRU* Model Concepts

The *ACRU* system was selected for use in this research project as it has several advantages. The *ACRU* agrohydrological model (Schulze, 1995) is a multi-purpose, daily time step, conceptual-physical model. It contains a multi-layer daily soil water budgeting routine, with outputs that include daily stormflow and baseflow contributions, sediment yield, reservoir yield, irrigation supply and demand. The *ACRU* model was originally developed in the early 1980s for studies of land use change and water resource assessment, and has subsequently undergone continuous development and enhancement. It is well suited for use in southern Africa, with links to appropriate local land use, soil and climate databases.

ACRU can operate in lumped mode for smaller catchments or as a distributed cell-type model for areas with more complex land uses or soils. Individually requested outputs for each sub-catchment (which may be different to those of other sub-catchments) or with different levels of information, may be generated. A schematic of the components in the multi-layer soil water budgeting in *ACRU* is depicted in Figure 4.1. The model also includes a dynamic input option to facilitate hydrological responses to climate or land use changes in a time series. The *ACRU* system has incorporated into it an interactive *ACRU* Utilities package (Smithers and Schulze, 1995) comprising of different programmes which aid in the extraction and preparation of the required input data and simulated output. The main utility is the "Menubuilder" which is used to compile catchment menus for application with the *ACRU* model. The menu forms the main input file with all the parameter specifications for the area being modelled. Another utility is the "CALC_PPTCOR" programme which is used to facilitate the selection of appropriate rainfall stations for the area in which the model is being used. A soils decision support system called "AUTOSOILS" (Pike and Schulze, 1995) is also included in the system. This programme is used to facilitate the extraction of the appropriate relevant soil characteristics required in the menus. Finally the "Outputbuilder" is a utility used to select the relevant variables to be output for graphical or statistical analyses.

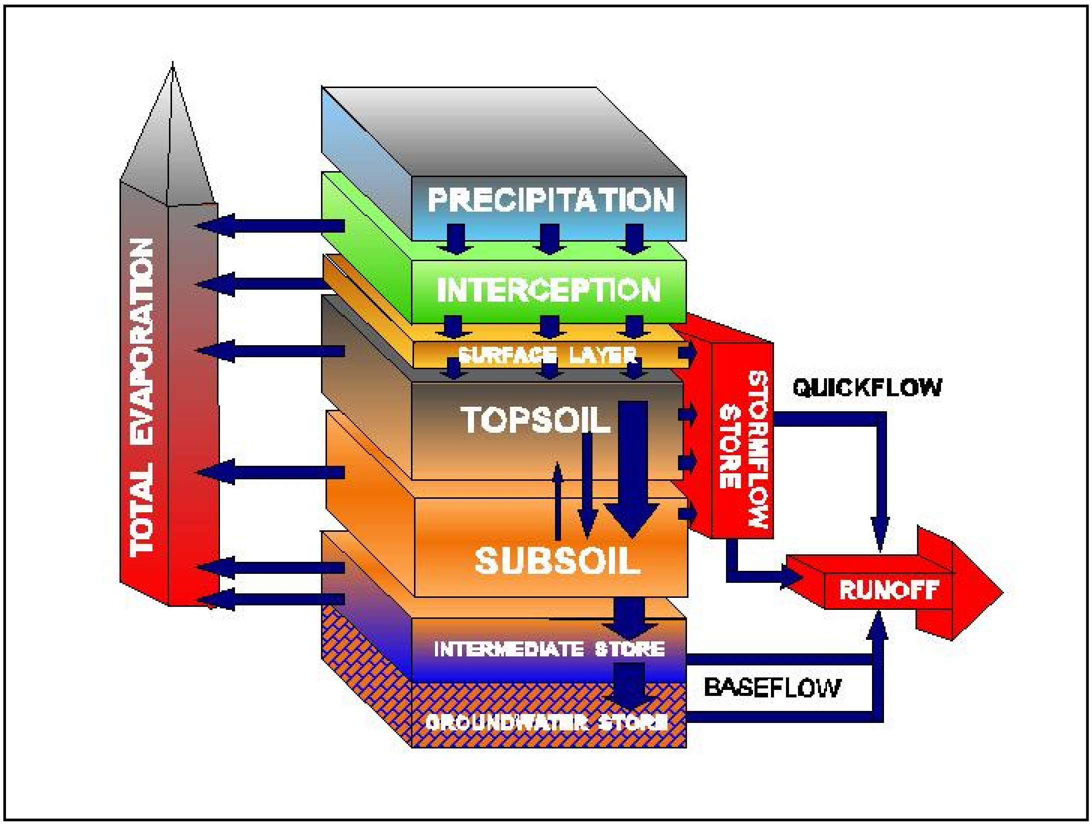

Figure 4.1 Components of the *ACRU* system after (Schulze, 1995)

The following sub-sections of this chapter briefly describe some of the core components of the *ACRU* model relevant to design flood estimation including the soil water budget, streamflow generation and peak discharge estimation which includes rainfall disaggregation and the estimation of catchment lag.

4.2.1. Continuous Soil Water Budgeting in the *ACRU* model

The heart of the multi-soil layer *ACRU* model is the daily soil water budget (Schulze, 1995). Soil water is partitioned and redistributed in various ways to realistically account for a continuous water budget. According to Schulze (1995)

> "rainfall not abstracted as interception or stormflow enters the surface layer and stays in the top soil horizon until field capacity or drained upper limit is reached, after which excess water percolates into the sub soil horizons. If the sub soil is saturated vertical drainage occurs into the immediate layers and eventually the groundwater store from which baseflow may be generated. The rates of soil water movement are dictated by the type, texture and wetness of the soil. Unsaturated soil water is redistributed and accounted for at slower rates which are dependant on the wetness of adjacent soil layers. Evaporation takes place form previously intercepted water and the different soil horizons. It can be split into soil water evaporation occurring from the top soil, plant transpiration from the root zones or combined as total evaporation. Atmospheric demand and the plants growth stage are used to approximate the total evaporative demand. The soil water budget operates at a daily time step hence provides a soil water deficit on a daily basis. "

4.2.2. Streamflow Generation

The generation of daily streamflow in the *ACRU* model is based on the sum of the stormflow generated and the baseflow from the catchment in question (Schulze, 1995).

Stormflow generation is based on a refined version of the USDA's SCS approach as depicted in Equation 4.1:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad for\ P > I_a \qquad \text{Equation 4.1}$$

where

Q	=	daily stormflow depth (mm),
P	=	daily rainfall depth (mm), excluding intercepted rainfall,
S	=	potential maximum retention (mm), which is equated to a soil water deficit prior to the rainfall event and is computed for a critical response depth,
I_a	=	initial losses (abstractions) prior to the commencement of stormflow, comprising of interception, depression storage and initial infiltration (mm),
	=	c S,
c	=	input coefficient of initial abstraction which has a default value of 0.2, (Schulze, 1995).

According to Schulze (1995) , the potential maximum retention of the soil, *S*, is considered as a soil water deficit calculated by the multi-layer soil water budgeting technique in the *ACRU* model. The soil water deficit is estimated as the difference between water retention at porosity and the actual soil water content just before the rainfall event i.e. after total evaporation has been abstracted from the soil profile. The critical soil depth (*D*) for which *S* is calculated for stormflow generation, is a variable in the model which attempts to account for different dominant runoff producing mechanisms prevailing in different climates, catchment conditions and for different soil properties (Schulze, 1995). For example, a catchment with predominant short vegetation types which are shallow rooted would use the soil water defecit equivalent to the topsoil horizon depth in estimations of stormflow with the *ACRU* model. However, on landuse with dense canopy cover which can dissipate the rainfall's energy or has deep litter layer or highly leached soils resulting in high infiltratibility, the critical soil depth for calculating *S* may be deeper than the top soil horizon due to the perceived "push through" stormflow generation mechanism (Schulze, 1995).

The coefficient of initial abstraction, *c*, is a parameter which can change on a month-by-month basis depending on factors such as vegetation, location and management practices. A default value of 0.2 is suggested for use in the *ACRU* model. However, a forested catchment or a catchment recently ploughed could have a value up to 0.4 whereas a highly compacted soil could have a value of 0.05 (Schulze, 1995).

According to Schulze (1995) baseflow is derived from the intermediate and groundwater stores which are recharged by drainage out of the lower soil horizons.

4.2.3. Estimation of Peak Discharge

The *ACRU* model uses the United States Department of Agriculture's SCS techniques, National Engineering Handbook (1972) for the estimation of peak discharge which is based on a triangular shaped unit hydrograph. The unit hydrograph represents an average characteristic storm runoff response of a small catchment with 37.5% of the runoff occurring during the rising limb of the triangular unit hydrograph. The assumptions inherent in this technique are that the unit hydrograph represents the temporal distribution of stormflow for an incremental unit depth of stormflow, ΔQ, occurring in a unit duration of time, D. Peak discharge for an increment of time ΔD is defined by Equation 4.2:

$$\Delta q_p = \frac{0.2083 \Delta Q A}{\Delta D / 2 + L} \qquad \text{Equation 4.2}$$

where

Δq_p	=	peak discharge of incremental unit hydrograph ($m^3.s^{-1}$),
A	=	catchment area (km^2),
ΔQ	=	incremental stormflow depth (mm),
ΔD	=	unit duration of time (h), used with the distribution of daily rainfall to account for rainfall intensity variations, and
L	=	catchment lag (h), an index of the catchment's response time to the peak discharge (Schulze, 1995).

As shown in Figure 4.2, in order to determine the hydrograph response to a given rainfall event, incremental hydrographs are superimposed according to the distribution of stormflow over time, as determined from the time distribution of rainfall intensity and the stormflow response characteristics of the catchment. Thus daily rainfall input into the *ACRU* model is disaggregated within the model into sub-daily time steps using one of four regionalised synthetic rainfall distributions as shown in Figure 4.3 and which were developed by Weddepohl (1988) and also used for design flood estimation based on adaptations for South Africa to the SCS model (Schmidt and Schulze, 1987).

The temporal distribution of rainfall, *viz*. the distribution of rainfall intensity during a storm, is an important factor affecting the timing and magnitude of peak flow from a catchment and hence the flood-generating potential of rainfall events (Weddepohl, 1988). It is also one of the primary inputs into hydrological models used for the design of hydraulic structures. The temporal distribution of rainfall events may be influenced by many factors that need to be reflected in design temporal distributions. These factors include, *inter alia,* location, storm duration, storm depth and season of storm occurrence (Hoang *et al.*, 1999).

Rainfall disaggregation refers to producing high-resolution data that can be aggregated to give values equal to observed courser-scale totals. The use of high-resolution rainfall data inherently accounts for the temporal distribution of rainfall intensity. This is because the incremental time-steps are small enough, i.e. hourly or sub-hourly, to represent different intensities (Knoesen, 2005). The advantage of such a time-series is that they reflect all relevant rainfall characteristics from peak intensities with short duration to variations in annual rainfall (Mikkelsen *et al.*, 1988). However, data are generally only widely available at more aggregated levels of the model time-step, such as daily.

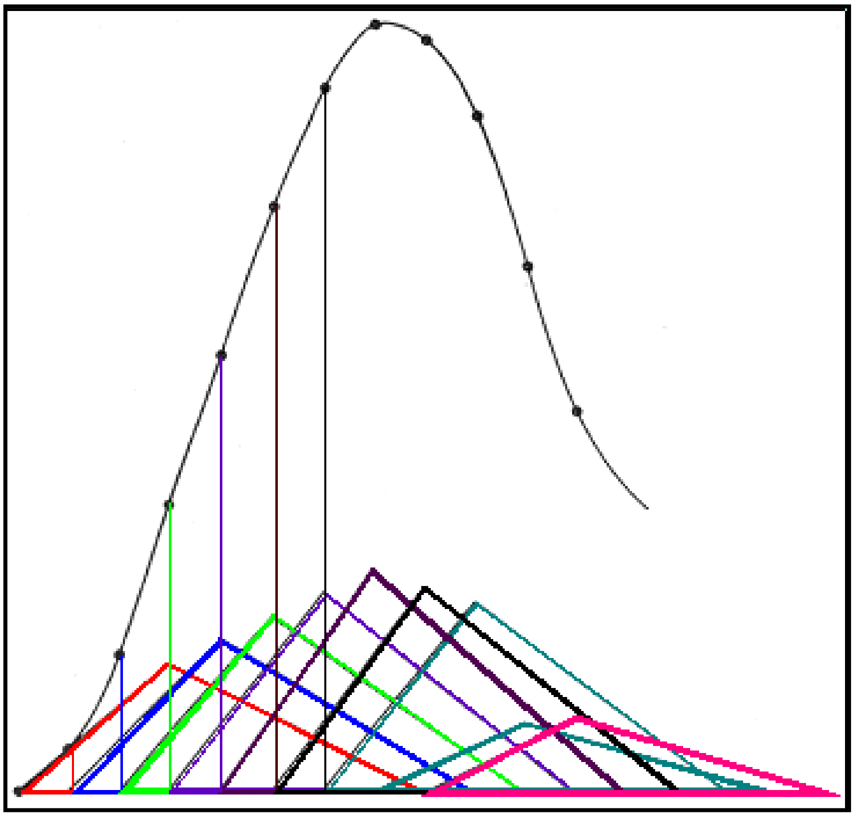

Figure 4.2 Superpositioning of incremental triangular unit hydrographs (after Schulze, 1995)

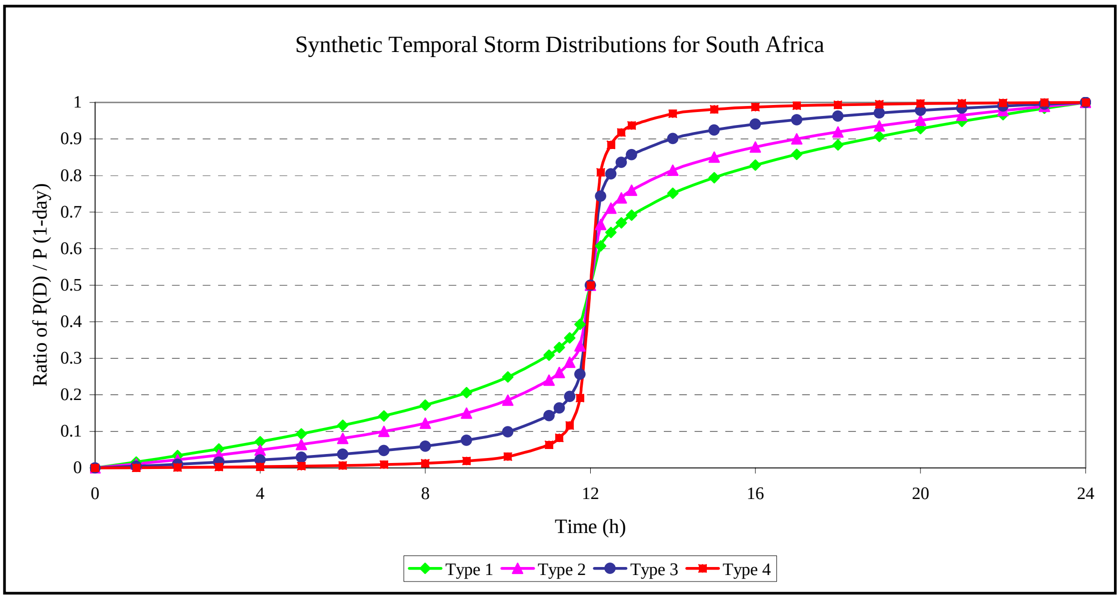

Figure 4.3 Synthetic temporal distributions for South Africa used in the *ACRU* model (after Schulze, 1995)

In the *ACRU* model the index of catchment response time or Lag, *L*, represents the weighted average of the time for stormflow from each point of the catchment to reach the catchment outlet. It is an important factor in determining peak discharge. Lag can be estimated from historical hydrographs or from specific catchment characteristics such as catchment slope, hydraulic length and flow retardance using hydraulic principles or empirical equations (Schulze, 1995).

Lag derived from hydraulic principles can be estimated from the time of concentration (Tc). This is calculated by summing the flow travel times along the various reaches comprising the flow path of water from the hydraulically most distant point in the catchment concerned (Schulze, 1995). In the *ACRU* model, empirically derived lag can be obtained using the SCS Lag Equation or the Schmidt-Schulze lag Equation. The SCS Lag Equation developed by the USDA, represents lag from catchments with a broad range of land uses, and is applicable for catchments less than 10 km^2. Schmidt and Schulze (1987) suggested that the poor estimates of peak discharge obtained when using this equation were due to the inability of the equation to distinguish between overland flow found in drier catchments and the marked subsurface flow response evident in many natural catchments found in moist climates.

The Schmidt-Schulze Lag Equation (Equation 4.3) developed using data from small catchments in the United States and southern Africa (Schmidt and Schulze, 1987) was introduced as an alternative to the original SCS Lag Equation. It incorporates catchment area and mean catchment slope which were determined as dominant physiographic parameters affecting peak discharge. The equation also accounts for climate which influences the soil, vegetation and rainfall patterns, all of which affect the extent to which rainfall enters the soil profile, and plays a major role in dominant runoff processes. Climate is represented through the Mean Annual Precipitation (MAP). The two-year return period 30-minute rainfall intensity was found to affect lag most significantly and was thus incorporated to the equation (Schmidt and Schulze, 1987).

The Schmidt-Schulze Lag Equation used to estimate lag in this study is given as:

$$L = \frac{A^{0.35}MAP^{1.1}}{41.67y^{0.3}I_{30}^{0.87}} \qquad \text{Equation 4.3}$$

where

A	=	catchment area (km^2),
y	=	average catchment slope (%),
MAP	=	mean annual precipitation (mm), and
I_{30}	=	regional mean of the most intense thirty minute period of rainfall, which can be estimated as the two-year return period 30-minute rainfall intensity ($mm.h^{-1}$).

4.3. Description of the Study Areas

Two study areas were selected for use in this research *viz*. the Thukela Catchment and the Lions River Catchment. Detailed descriptions of these catchments are provided in the subsequent sections of this document.

4.3.1 The Thukela Catchment

The Thukela Catchment is located in the KwaZulu-Natal province of South Africa (Figure 4.3) and extends latitudinally from 27^{o}E25' to 29^{o}E24'S and longitudinally from 28^{o}E58' to 31^{o}E26', covering an area of 29 035.9 km^2 (Schulze *et al*., 2007). The Thukela River, with its source in the Drakensberg mountain range in the west, is the main river in the catchment. The Thukela River flows eastward until it reaches the Indian Ocean. The Thukela Catchment has a wide range of altitudes from sea level at the outlet up to 3000 m at its source in the Drakensberg. The mean annual precipitation ranges between 600 and 2 000 mm in the catchment (Figure 4.4).

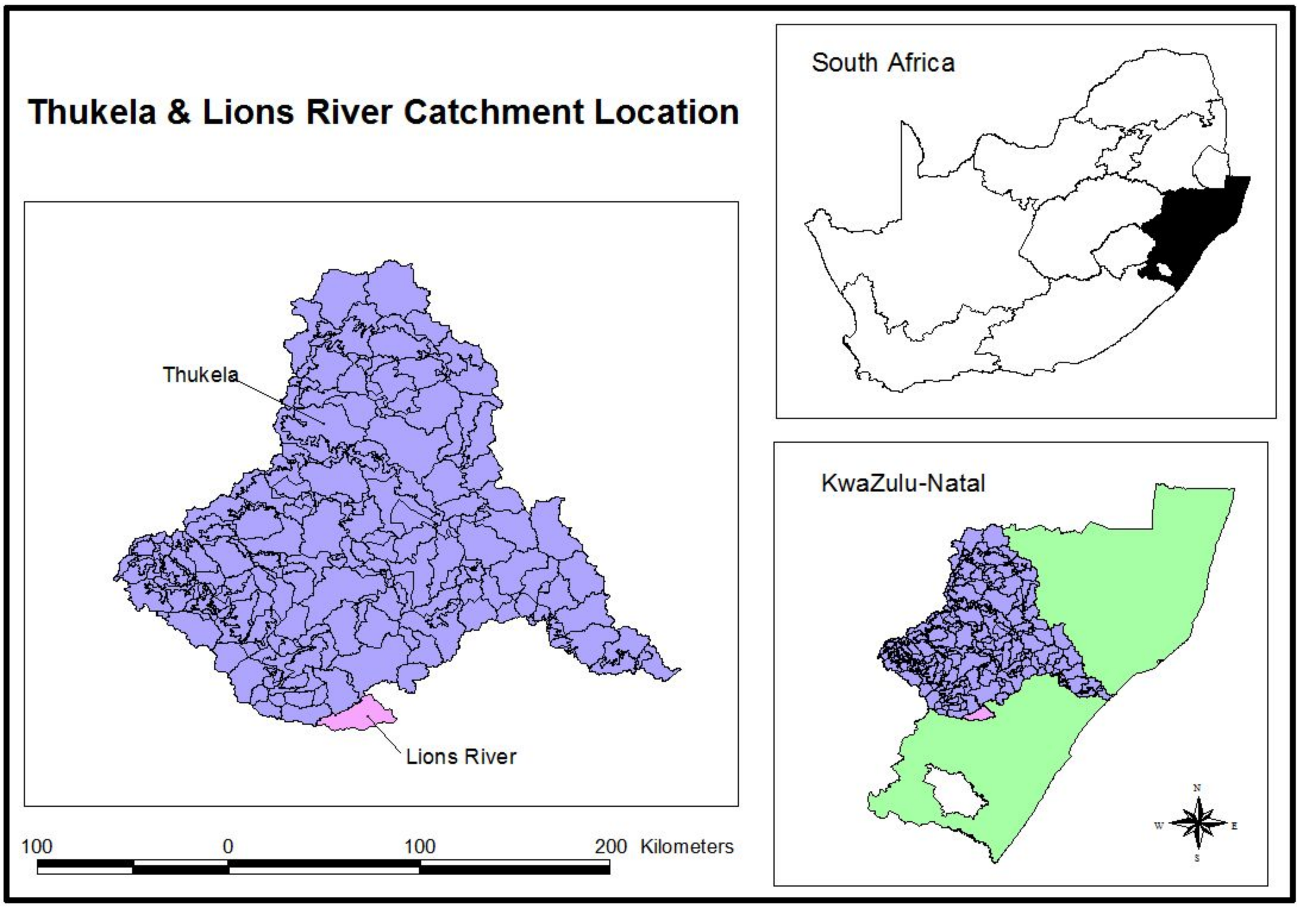

Figure 4.4 The Thukela and Lions River Catchments in KwaZulu-Natal, South Africa

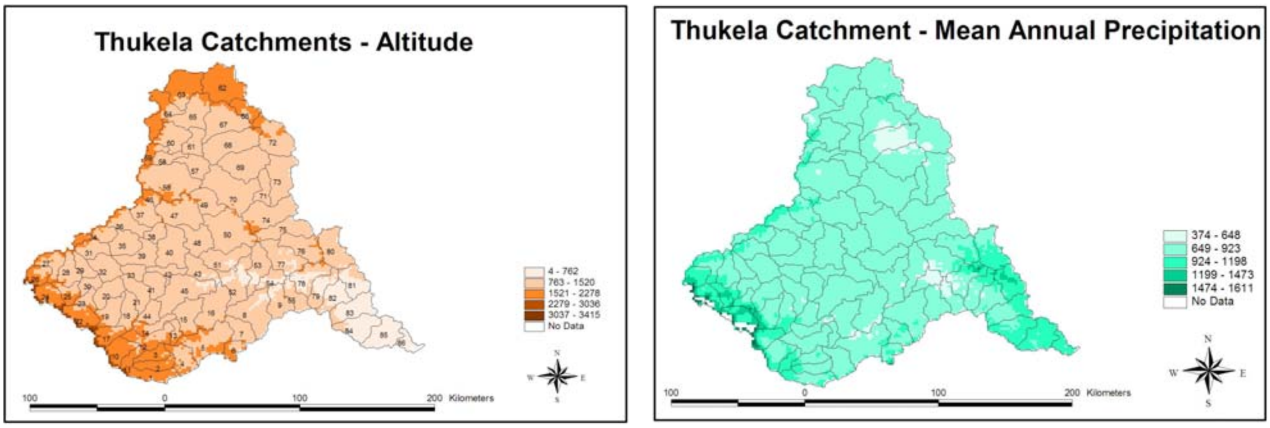

Figure 4.5 Ranges of Altitude and Mean Annual Precipitation in the Thukela Catchment

South Africa has been divided into primary, secondary and tertiary catchments by Department of Water Affairs and Forestry (DWAF). The tertiary catchments make up the nineteen water management areas described in the national water resources strategy (DWAF, 2004). The Thukela Catchment is one of the nineteen water management areas and at the fourth level of catchment delineation, the Thukela Catchment is divided into 86

Quaternary Catchments (QC's). As depicted in Figure 4.5, the area has several South African Weather Services (SAWS) rainfall stations and DWAF operated flow gauging stations located within the catchment. According to Smithers *et al.* (2007) the Thukela Catchment has a diverse range of soils and ecological regions and therefore represents a range of hydrological regimes to assess continuous simulation for design flood estimation.

Schulze *et al*. (2005b) further divided the 86 quaternary catchments of the Thukela into 235 sub-catchments as depicted in Figure 4.6. This delineation was mainly to accommodate the diverse hydrological response within many of the QCs and also to explicitly represent various heterogenic factors which included altitude, soils, topography, vegetation, channel based factors such as the locations of flow gauging stations and dams, the locations of environmental flow requirement sites, and political history which resulted in degraded vegetation (Schulze *et al.*, 2005a)

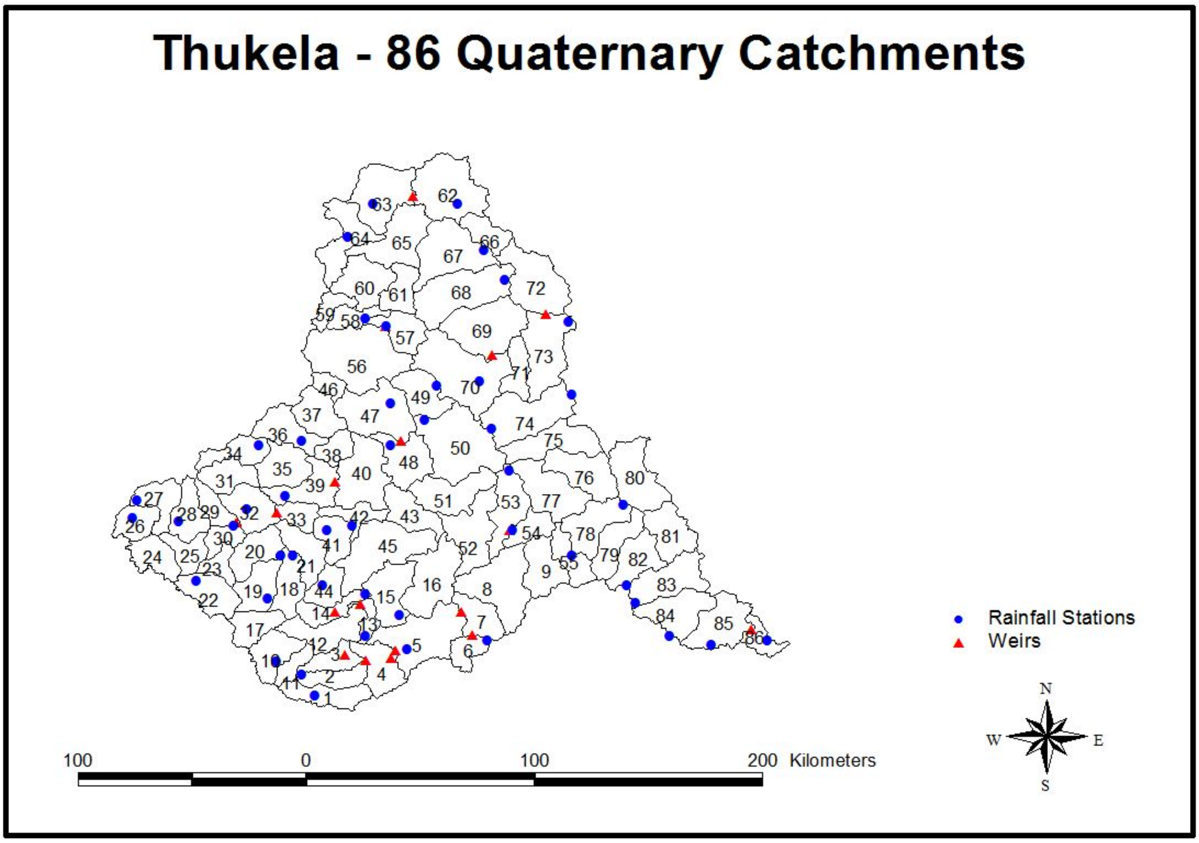

Figure 4.6 Distribution of the 86 quaternary catchments in the Thukela Catchment including the locations of flow gauging stations and rainfall stations

In order to meet the objective of this research project, upstream or external catchments were required. The use of external catchments excludes the uncertainty associated with flood routing. The use of internal catchments would have also required gauged inflow from upstream catchments. Another requirement for the selection of catchments was that the external catchments sought needed to be representative of the range of spatial scales in the Thukela catchment. Initially test catchments were selected according to the availability of reliable streamflow data using the flow gauging stations identified by Joubert and Hurley (1994) as having good quality data. Suitable catchments were also screened for records of rainfall data and were then selected according to the size of the catchment. In practice this proved a complicated task as it was difficult to select catchments from a wide range of catchment areas which met all of the required criteria. The availability of long records of reliable rainfall and runoff data were limiting factors in this exercise. According to Smithers *et al*. (2007) the use of data from an operational catchment where significant water transfer schemes and irrigation take place, as well the impacts of large dams in some sub-catchments, made the use of a continuous simulation model challenging.

Three QC's *viz*. QC 6, QC 59 and QC 72 with catchment areas of 129 km^2, 152 km^2 and 544 km^2 respectively were selected as test catchments for this study (Figure 4.6). This range of catchment area was found to be representative of the Thukela catchment as most QC's which constitute the Thukela are less than 500 km^2 (Figure 4.7) However, it was decided that the inclusion of a catchment of approximately 300 km^2 would represent a better range of test catchment areas. Since no suitable quaternary catchment of this magnitude was found in the Thukela, the 353 km^2 quaternary U20B (Lions River) of the neighbouring Mgeni Catchment was selected. A description of the Lions River catchment is presented in the following section.

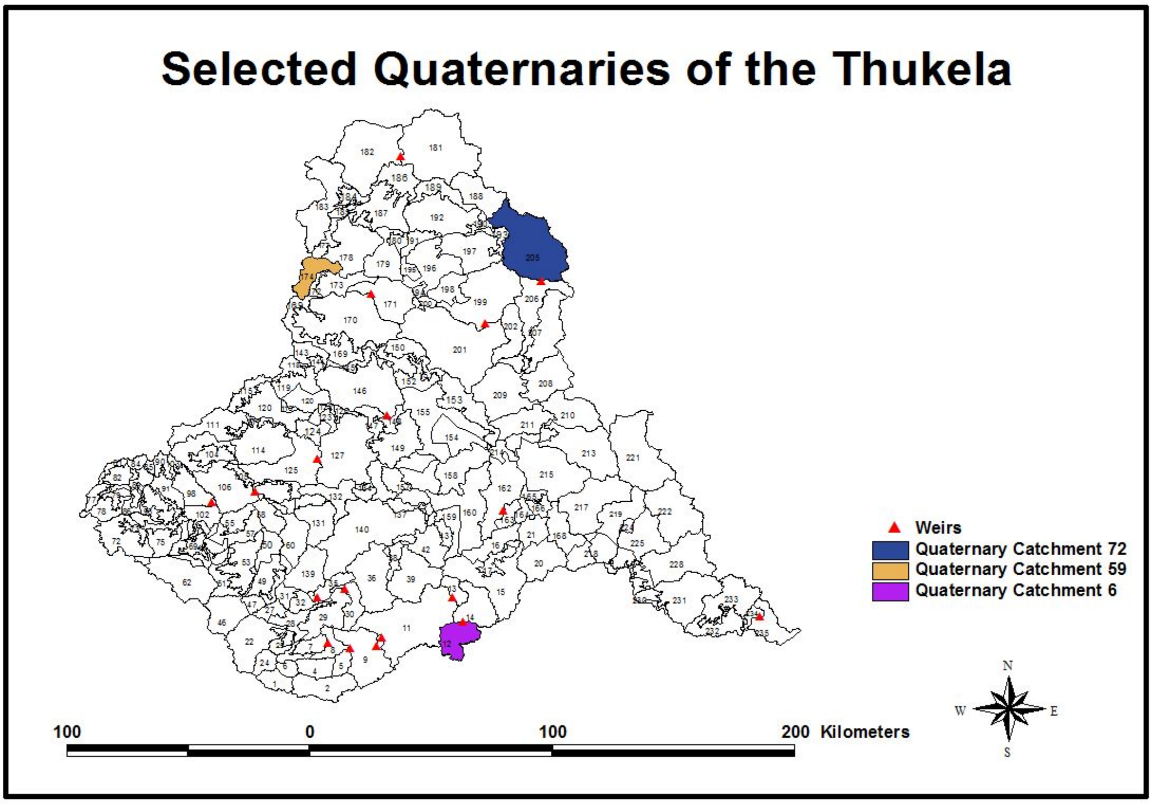

Figure 4.7 235 Sub-catcments of the Thukela with Selected Quaternary Catchments in the Thukela

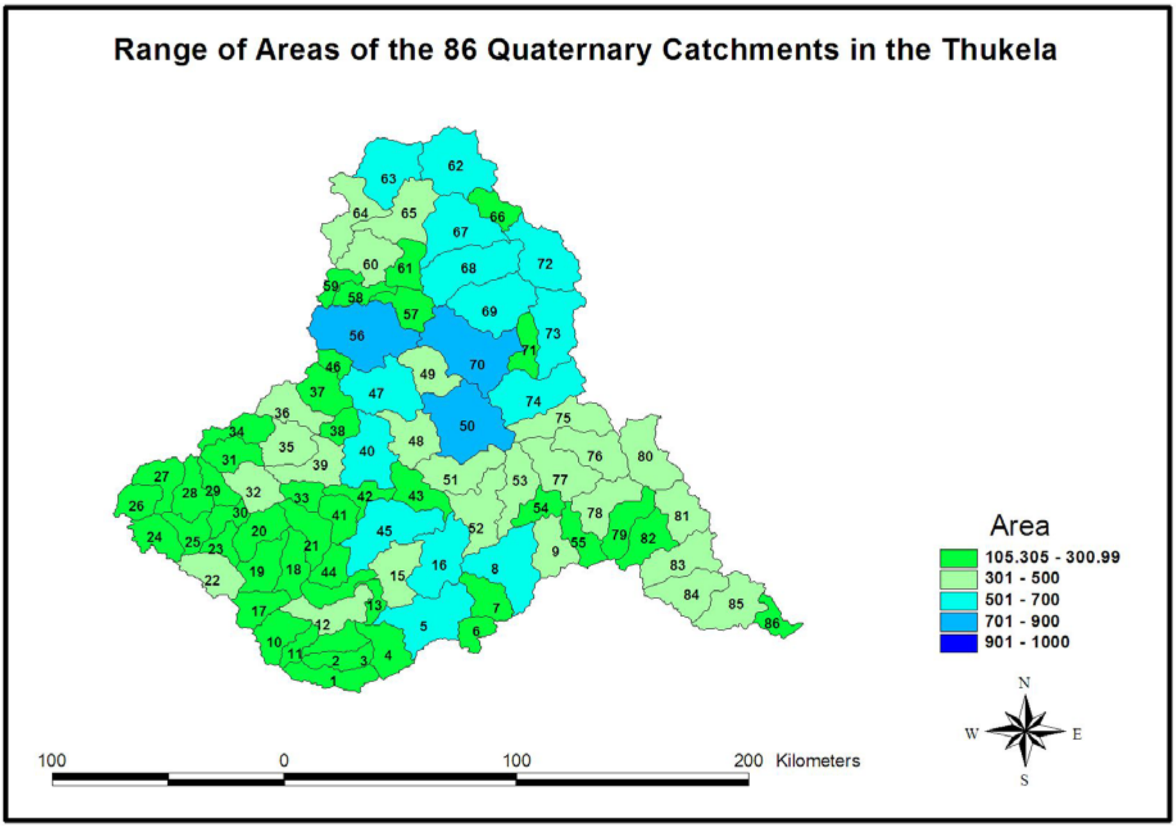

Figure 4.8 Range of Areas of the 86 QC's in Thukela

4.3.1 The Lions River Catchment

The Lions River catchment is 353 km^2 in extent and lies in the upper reaches of the Mgeni catchment, neighbouring the Thukela Catchment in KwaZulu Natal, South Africa (Figure 4.3). The main river flowing through the catchment is the Lions River. The mean annual precipitation for the catchment ranges from 870 to 1040 mm (Figure 4.8) and the altitudinal range is between 1070 m and 1970 m (Figure 4.9). The major land cover classifications in the catchments are natural grassland, bushveld, dryland and irrigated agriculture (maize and pastures) and commercial afforestation. A few SAWS rainfall stations are positioned in the catchment and a DWAF operated flow gauging station is located at the outlet of the catchment (Figure 4.13).

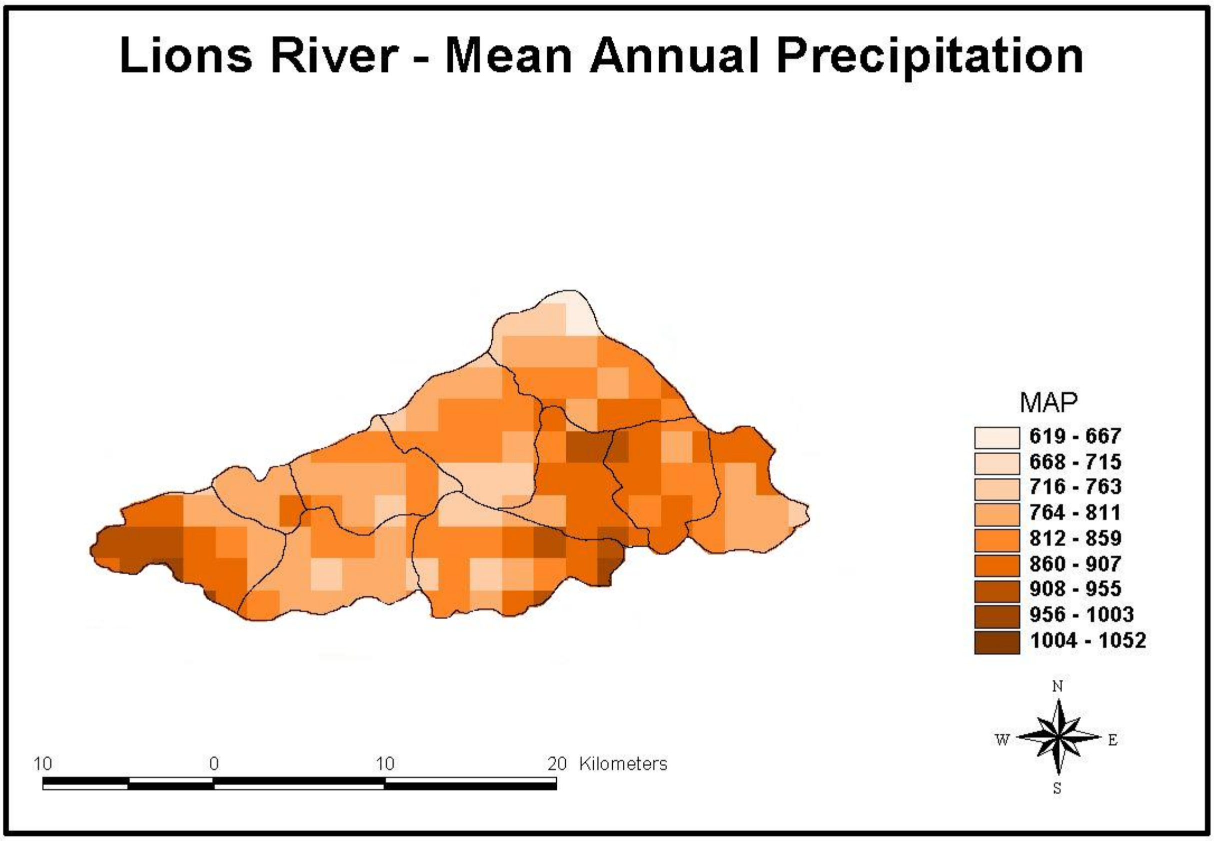

Figure 4.9 Mean Annual Precipitation (Lions River Catchment)

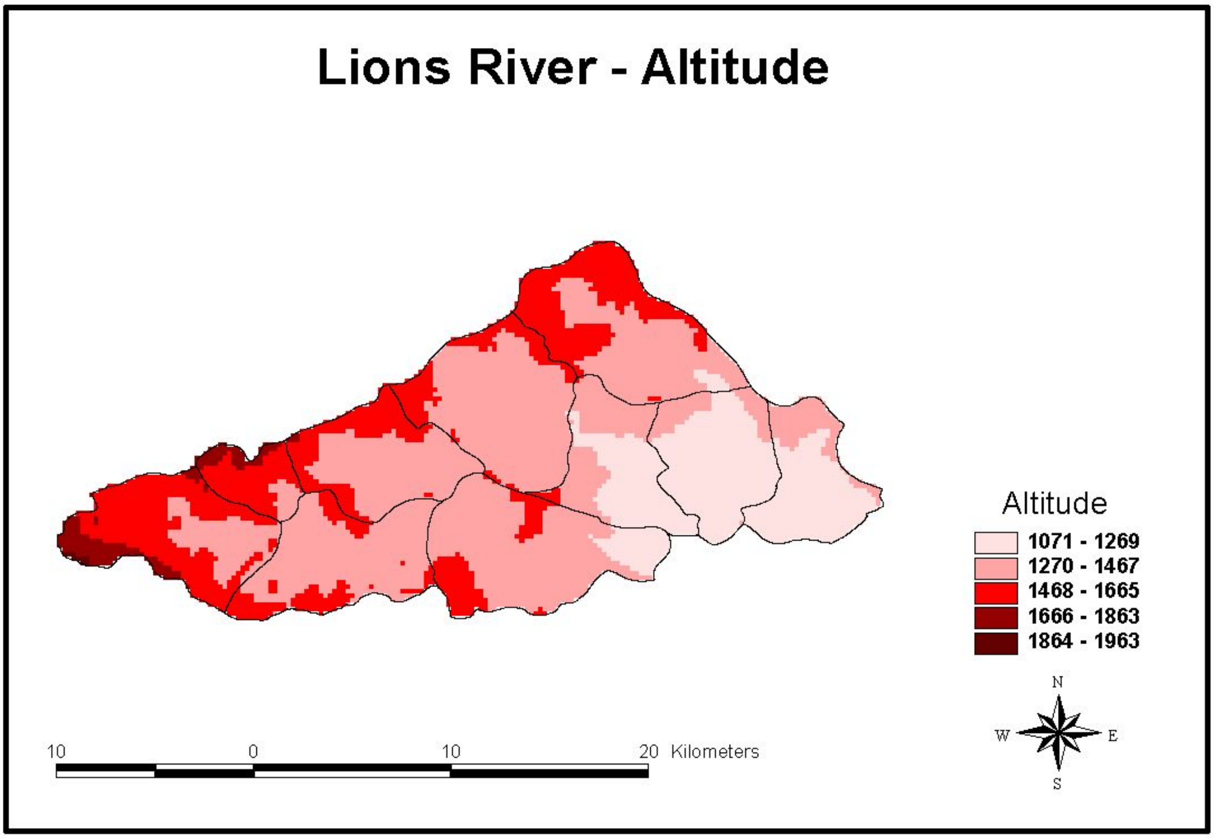

Figure 4.10 Altitudinal Range (Lions River Catchment)

4.4. Description and Configuration of the Selected QC Catchments

In order to set up input menus to run the *ACRU* model, detailed information about the climate and catchment is required. This section describes the general information used to set up the *ACRU* model and the detailed input data for each of the selected catchments.

There are 1946 quaternary catchments (QC's) in South Africa, each of which cascades to the next downstream catchment. For each QC, information on location, rainfall, averaged soils and land cover information, translated into *ACRU* variables, are stored in the quaternary catchments database (Schulze and Pike, 2004) developed by the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, for application of the *ACRU* model. Quaternary catchment level input data used in this study was obtained from this database.

Rainfall data was obtained from the daily rainfall database developed by Lynch (2004). Rainfall stations which fell within and around the Thukela and Lions River catchments were analysed for their suitability. *CalcPPTCor*, a utility in the *ACRU* suite of programs that provides an automated method to select the most representative rainfall station for a catchment, was used in this study. Suitable stations are ranked according to an index based on distance of the raingauge from the centroid of the catchment, rainfall record lengths and start and end years of record. The program also automatically calculates the month-by-month precipitation adjustment factors required for each sub-catchment. The gauged rainfall data from the selected raingauge are multiplied by the monthly correction factors to ensure that topographical and/or climatological influences within in the catchment are accounted for and the input rainfall is representative of the catchment. The program uses the gridded median monthly rainfall surfaces developed by Dent *et al*. (1987). The percentage of missing data and infilled data was also taken into consideration when selecting the driver rainfall stations for each sub-catchment.

As discussed in section 4.2.3 the temporal distribution of rainfall, *viz*. the distribution of rainfall intensity during a storm, is an important factor affecting the timing and magnitude of peak flow from a catchment and hence the flood-generating potential of rainfall events (Weddepohl, 1988). With reference to the rainfall intensity distribution zones map (Schmidt and Schulze, 1987) the selected cathments in the Thukela and Lions River catchment were assigned an intensity distribution Type 3 for use in the *ACRU* model. The intensity distribution Type 3 is associated with convective type storms.

Soils information was obtained from the Institute for Soils Climate and Water land type maps (Land Type Survey Staff. 1972 – 2001) at the 1:250000 scale which has been translated into *ACRU* variables by an automated program AUTOSOILS (Pike and Schulze, 1995). Output variables from this program include the thicknesses of the topsoil (A horizon) and subsoil horizons (B horizon), values of the soil water content at drained upper limit and saturation for both soil layers and saturated drainage redistribution rates from top- to sub soil and out of the sub soil horizons. Values of the variables were determined for each soil series making up a land type and then area-weighted according to the proportions of soil series within a land type for the various land types found within a sub-catchment.

Land cover information used in this study was obtained from the national land cover database (CSIR, 1999). Four major types of land cover were identified in the selected catchments. It was therefore decided to use these four types when the catchments. These land cover types included thicket and bushveld (T), cultivated crops (C), forestry (F) and grasslands (G) or when grouped referred to as TCFG.

The concept HRU's was introduced by Flügel in 1979 and further investigated in 1995 (Flügel, 1995). "HRU's are distributed, heterogeneously structured areas with common landuse and soil or topographic associations controlling their unique hydrological dynamics" (Flügel, 1995) . In this study the HRU's were defined by the four major land cover classes identified and the soils associated with that area. Basically each HRU is a unique combination of soils and land cover information representing an area homogenous in hydrological response. Details of the way in which HRU's were defined are explained in section 4.5. Table 4.1 provides a summary of general information for each of the selected QCs. Input menus were setup with this general information and other QC specific information for the different scenarios to be simulated. The following sub-sections detail the configuration of the selected QC's. Maps illustrating the different soil and land cover types, rainfall and gauging stations, sub-catchment delineation and altitudinal differences are included.

Table 4.1 Summary of information on selected quaternary catchments

QC	**Area (km^2)**	**Flow gauging station**	**No. of sub-QCs**	**Number of Land Cover Classes**	**Total No. of HRUs per QC**	**Dam**	**Evaporation Equation**	**Simulation period**
59	129	V3H007	3	4 (TCFG)	12	No	Hargraves & Samani (1985)	1950 - 1999
6	152	V2H016	1	4 (TCFG)	4	Yes	Hargraves & Samani (1985)	1950 - 1999
72	544	V3H011	2	4 (TCFG)	8	Yes	Hargraves & Samani (1985)	1950 – 1999
U20B	353	U2H007	11	4 (TCFG)	44	Yes	Hargraves & Samani (1985)	1950 - 1999

4.4.1. Quaternary Catchment 59 – Thukela

QC 59 is 152 km^2 in extent and lies in the south western parts of the Thukela Catchment. This catchment was divided into 3 sub-catchments by Schulze *et al*. (2005b). The altitude within the QC ranged from 1320 m to 2000 m. The driver rainfall stations selected for the QC were Stations 0370655A and 0370509W. Figure 4.11 provides information about the location of the rainfall stations and flow gauging station, altitudinal range, soil types and land cover used to model QC 59. The soil types illustrated are derived from the ISCW land type maps and the naming codes illustrated are representative of the soil family to which they belong.

4.4.2. Quaternary Catchment 6 – Thukela

QC 6 is 129 km^2 in extent and lies in the south western parts of the Thukela catchment. Based on its area, this catchment was not divided into sub-catchments and therefore remained a "lumped" catchment for purposes. The altitude within the QC ranged from 1200 to 1750. The driver rainfall station identified for the QC was station 0269532W. Figure 4.10 provides information about the location of the rainfall station, flow gauging station, altitudinal range, soil types and land cover used to model QC 6

4.4.3. Quaternary Catchment 72 - Thukela

QC 72 is 544 km^2 in extent and lies in the north eastern parts of the Thukela Catchment. This catchment was divided into 2 sub-catchments by Schulze *et al*. (2005b). The altitude within the QC ranged from 1150 to 1750. The driver rainfall station identified for the QC was Station 0371706W. Only one raingauge was found suitable for use in this catchment due to the sparcity of rainfall gauges with adequate records in this catchment. Figure 4.12 provides information about the location of the rainfall stations and flow gauging station, altitudinal range, soil types and land cover used to model QC 72

4.4.4. Quaternary Catchment U20B – Lions River

Quaternary U20B, the Lions River Catchment is 353 km^2 in extent and lies in the upper parts of the Mgeni catchment. This QC was divided into 11 sub-catchments representing relatively homogenous areas. The altitude within the QC ranged from 1070 m to 1970 m. Driver rainfall station identified for the QC was Station 0269111A. Other stations used when investigating Objective IIc included stations 0269114A, 028806A, 0269147A and 0269295A. Figure 4.13 provides information about the location of the rainfall stations and flow gauging station, altitudinal range, soil types and land cover used to model QC U20B.

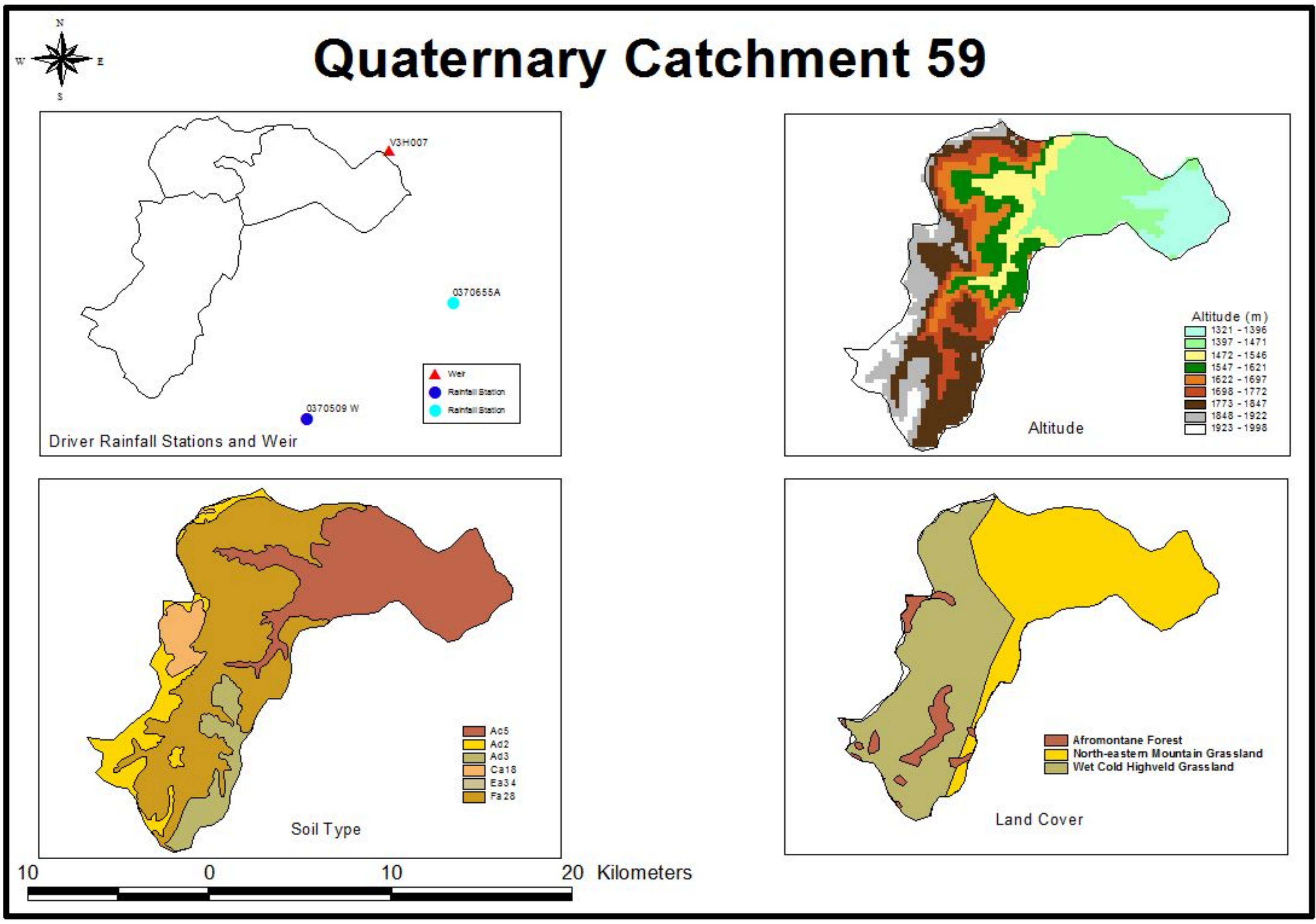

Figure 4.11 Maps of location of rainfall station and flow gauging station, altitudinal range, soil type and land cover for QC 59

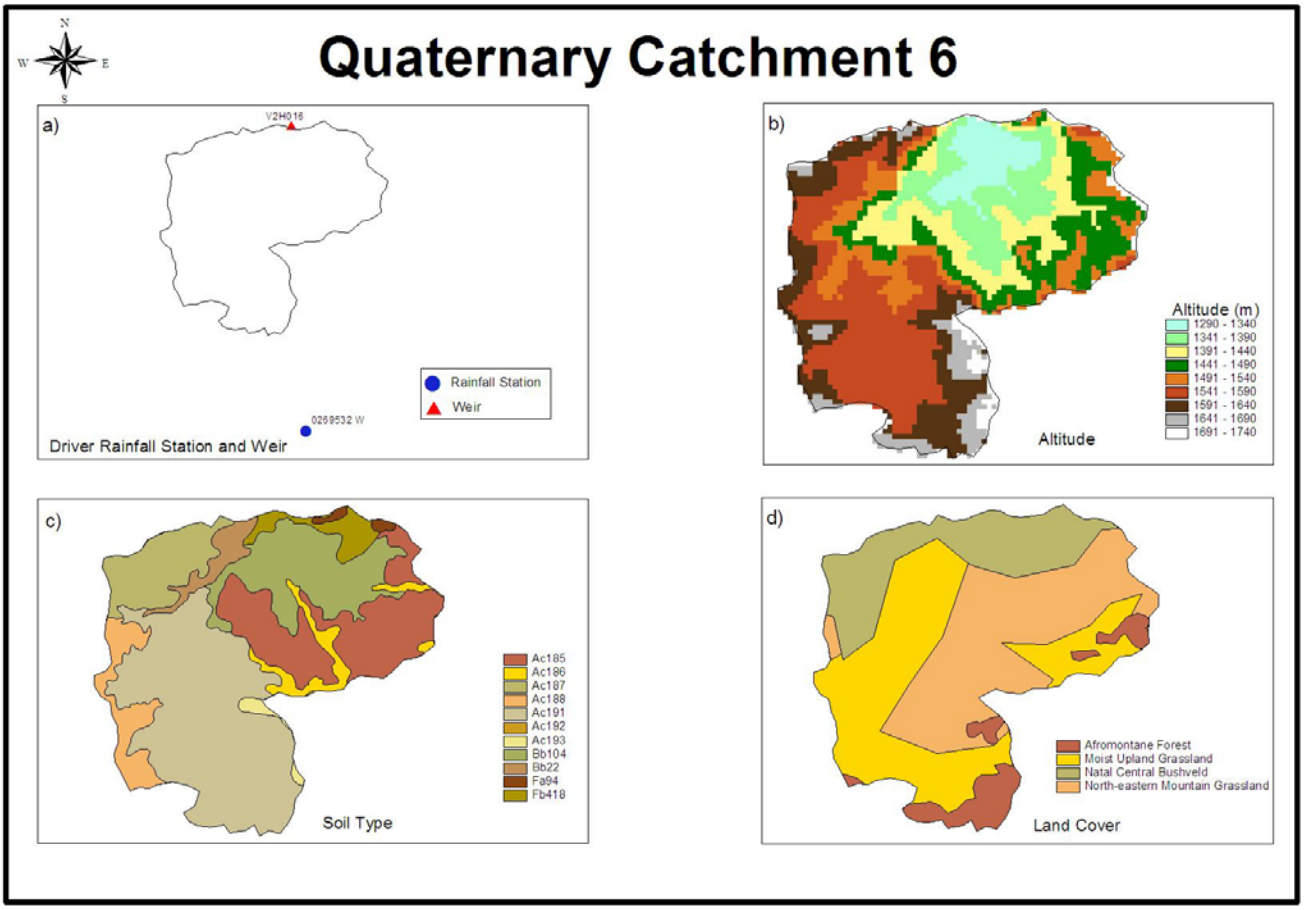

Figure 4.12 Maps of location of rainfall stations and flow gauging station, altitudinal range, soil types and land cover for QC 6

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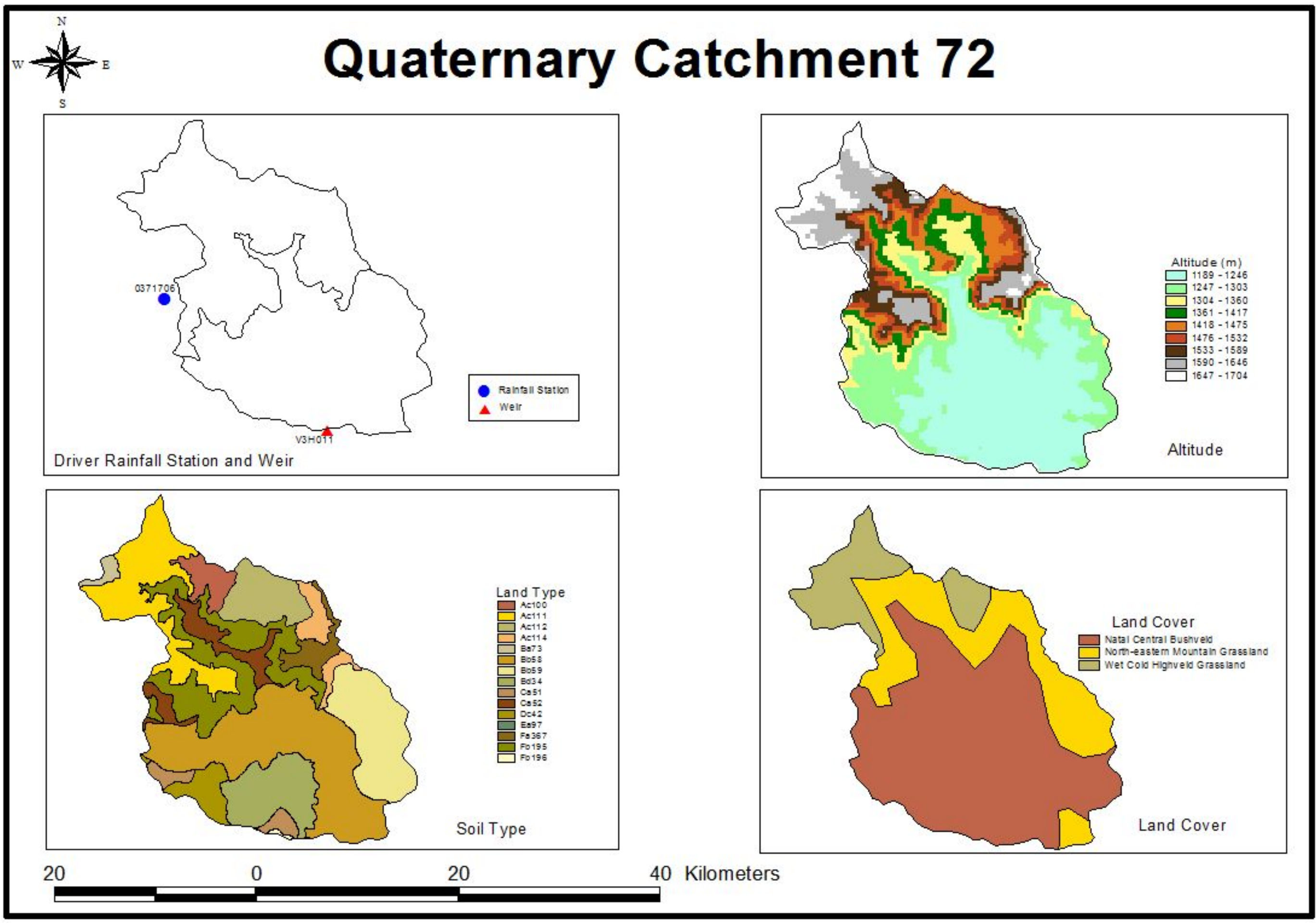

Figure 4.13 Maps of location of rainfall station and flow gauging station, altitudinal range, soil types and land cover for QC 72

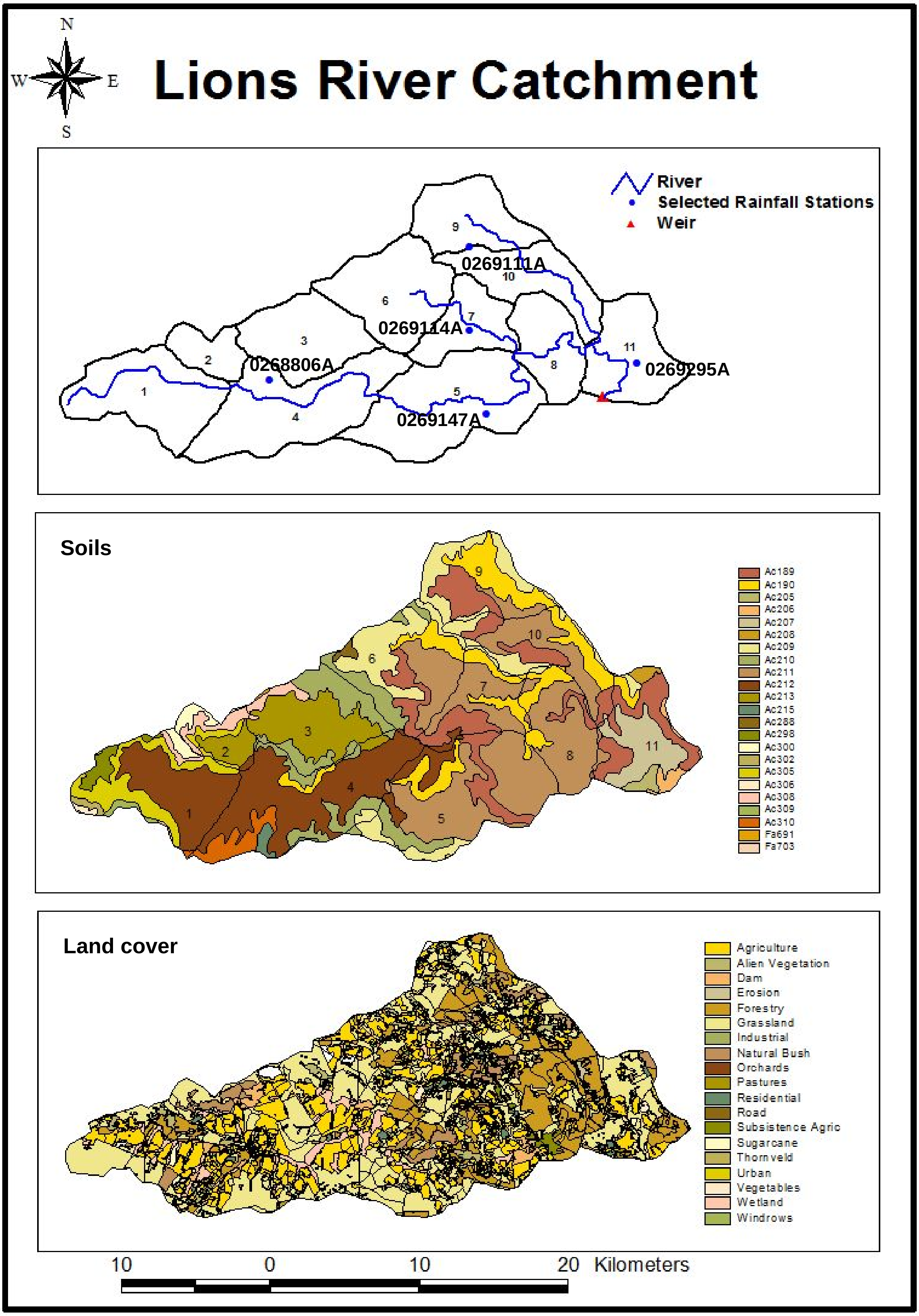

Figure 4.14 Maps of location of rainfall stations and flow gauging station, soil types and land cover for U20B

4.5. Scenarios

The scenarios were set up such that they meet the requirements of Objectives IIa, IIb and IIc of the research study, within the limits of the data available for the selected quaternary catchments. Table 4.2 details the different scenarios simulated.

In order to investigate the impact of scale issues on model performance it was decided to set up scenarios at three different levels of spatial scale *viz*. lumped, sub-catchment and HRU's, as shown in Table 4.2. In lumped mode the whole QC was modelled with a single land cover and soil type. At sub-catchment scale, each QC was divided into smaller physical sub-catchments as outlined by Schulze *et al.* (2005a) and each sub-catchment had a single land cover and soil type. At the HRU scale, each sub-catchment of a QC was divided into four hydrological response units based on the dominant land cover occurring in the QC. For the purpose of this study the four categories selected were thicket and bushveld, cultivated crops, forestry and grassland (TCFG).

To address the objective of investigating the optimum level of soils and land cover information, each scenario incorporated a different degree of soils and land cover information. Modal soils or land cover information refers to the soil type or land cover which occurs most frequently in the selected area. Area weighted soils information was computed by area weighting the soil parameters found in the catchment.

Table 4.2 Levels of scale, soils and land cover information for scenarios

Scenario	**Soils Information**	**Land Cover Information**	**Scale**
Lumped	Modal for whole catchment	Modal for whole catchment	Lumped
MA	Area weighted per sub-catchment	Modal per sub-catchment	Sub-catchments
HA	Area weighted per sub-catchment	Catchment specific HRU	Hydrological response units
HM	Modal per sub-catchment	Catchment specific HRU	Hydrological response units

Objective IIc of this research, investigating the optimum rainfall input in the selected QC's for best model performance, was addressed by setting up scenarios in those QCs which were further delineated into sub-QCs. More than one driver rainfall station was used in some scenarios and appropriately adjusted correction factors were applied such that each sub-catchment had "the" most suitable rainfall station and correction factors.

Scenarios were named according to the different levels of land cover and soils information used. For example, MA implies Modal land cover and Area weighted soil and, HA implies HRU and Area weighted soil. Scenarios addressing the rainfall stations were referred to as "HA1d" where "1d" implies that one driver station was used and while for Scenario "HA2d" two driver stations were used in the simulations.

The *ACRU* input menus for those scenarios which, after going through the modelling exercises produced the best simulations, were then used to simulate peak discharge. The Schmidt-Schulze lag equation was used when this option was invoked.

4.6. Analysis of Observed Data and Design Flood Estimation

The observed rainfall and runoff data used in this study was subjected to detailed analysis prior to its use. This was done to ensure that the simulations are as realistic as possible and that comparisons made between observed data and simulated results were reasonable.

Rainfall data was obtained from the daily rainfall database developed by Lynch (2004). This data has been through several quality checks. Missing data has been infilled using well researched, reliable techniques (Lynch, 2004). The rainfall data for the selected driver rainfall stations used in this study were further interrogated for possible erroneous data and missing data. Only those stations with long records of reliable data were used in the study.

Long records of good quality runoff data are seldom available. Data utilised in this study was obtained from DWAF and subjected to quality checks, including checking for over topping of flow gauging stations or the stage exceeding the upper limits of the rating table for the flow gauging station, outliers and adjustment of the rating tables. The methodology utilised to analyse the runoff data was adopted from Smithers *et al*. (2007). For those flow gauging stations where the rating table has been exceeded, the extension of rating tables was performed according to the methodology described by van Rensburg (2005). According to Smithers *et al*. (2007) a simple log-log extension of the rating table was performed such that the extended rating table could be used to calculate flow rates. Using this approach, the rating table was extended for gauging station V3H011 in QC 59.

In order to identify periods of reliable runoff data which could be used for the verification of simulated results, a methodology developed by Smithers *et al*. (2007) was utilised. Annual runoff : rainfall ratios and percentages of missing runoff data were plotted for comparison purposes. Data from the driver rainfall stations selected for the study were used in these comparisons. Figure 4.14 illustrates the analysis of flow data from the gauging stations used for each of the selected quaternary catchments in the Thukela. From these analyses it was decided that the time periods contained in Table 4.3 will be used for verification purposes for the quaternary catchments in the Thukela. For verification of results in the Lions River catchment, U20B, the whole record from 1960 to 1993 was utilized since the data were of good quality.

Table 4.3 Time periods selected for verification of results in the quaternary catchment in the Thukela Catchment

Quaternary Catchment (QC)	**Flow gauging station**	**Selected Time Period**
QC 6	V2H016	1983 - 1997
QC 59	V3H0007	1958 - 1998
QC 72	V3H011	1960 – 1984 (exclude 1968)

The methodology used to estimate design floods was adopted from Smithers *et al.* (2007). The annual maximum series (AMS) of observed and simulated peak discharge were used in this investigation for the purpose of comparison. According to Smithers *et al.* (2007) the design floods were estimated by fitting probability distributions to the AMS of peak discharges. L-moments were used to fit the distributions to the AMS. The Log Pearson Type III (LP3) distribution was selected for the estimation of design floods (Alexander, 1990). The *ACRU* model input menus were created using the catchment configurations, data and scenarios detailed in this chapter. The model was run for the fifty year period of 1950 to 1999. Results obtained for the investigations performed in this study are illustrated and discussed in the next chapter.

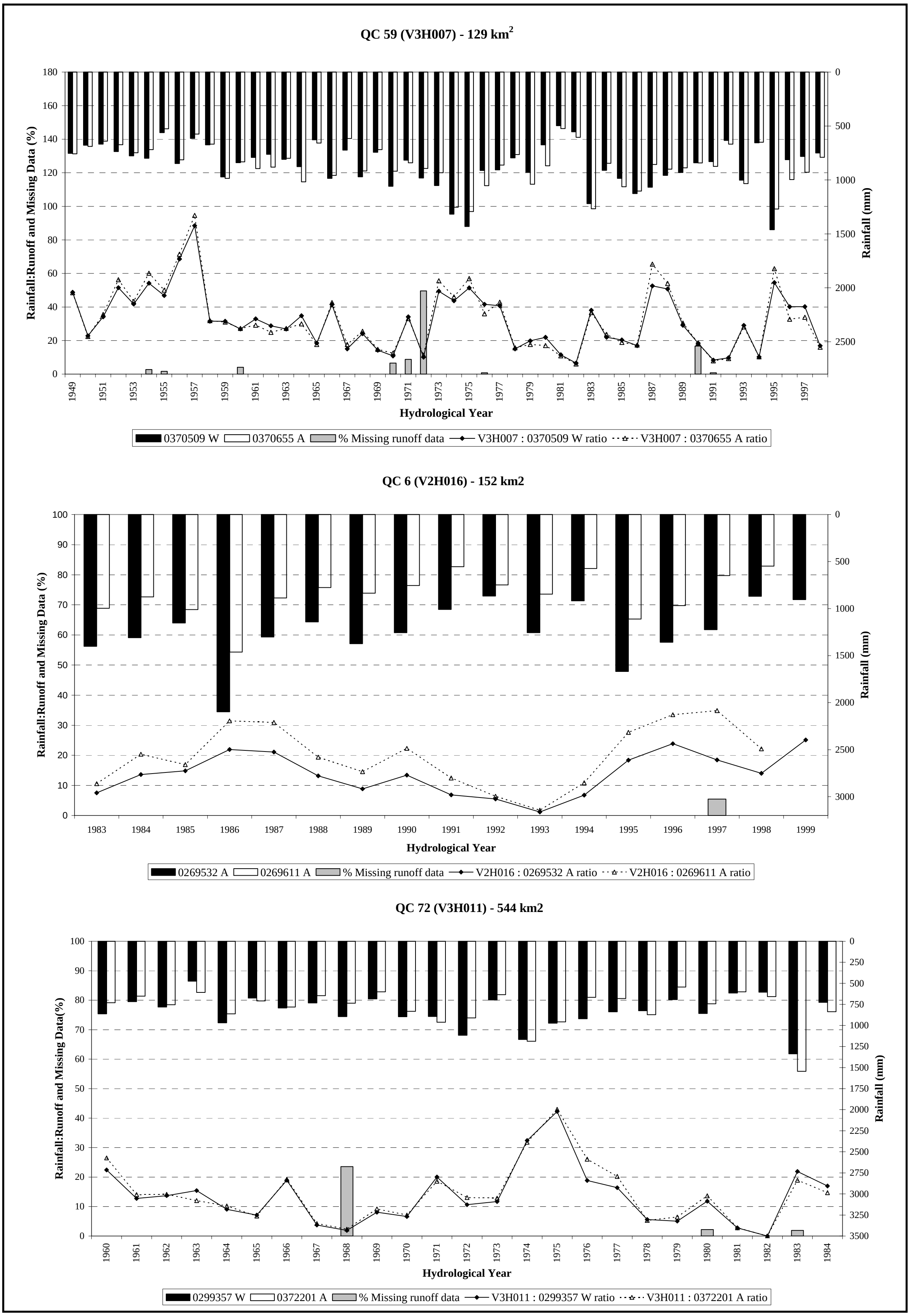

Figure 4.15 Data Analysis for gauging stations V2H016, VH3H007 and V3H011 (after Smithers *et al.,* 2007)

5. RESULTS

The results obtained from the component of this research study for selected Quaternary Catchments 59, 6 and 72 in the Thukela catchment and U20B of the Lions River Catchment are presented and discussed in this chapter.

Accumulated simulated values for all scenarios and accumulated observed runoff are compared for each selected QC for those periods when non-missing observed data are available and considered to be reliable, as determined from the data analysis undertaken. The accumulated totals as well as the Root Mean Square Error (RMSE) of daily values were calculated for each scenario. In addition, a frequency analysis of daily runoff depths for all scenarios is performed, on simulated and observed values which are greater than zero.

5.1. Simulated Volumes for Quaternary 59

Accumulated streamflows for QC 59 over the period 1958 to 1999 are shown in Figure 5.1. From a visual inspection of Figure 5.1, the accumulated simulated streamflow volumes follow very similar trends with the accumulated observed streamflow volumes indicating that for the given period the *ACRU* model seems to be simulating the streamflows satisfactorily. It is important to note that there are differences between each of the scenarios. Comparing HA1d with HA3d highlights the difference of using more than one driver rainfall station to represent a catchment's rainfall, comparing HA1d with HM1d and HA3d with HM3d shows the differences in modelling with area weighted soils information versus modal soils information. The differences in using a single modal land cover to represent land use in a catchment and HRU's are evident when comparing, for example, scenarios HA3d with MA3d. The results illustrated in Figure 5.1 indicate that from 1974 onwards the lumped scenario results in over-simulation when compared to the observed and therefore using HRU's is more appropriate.

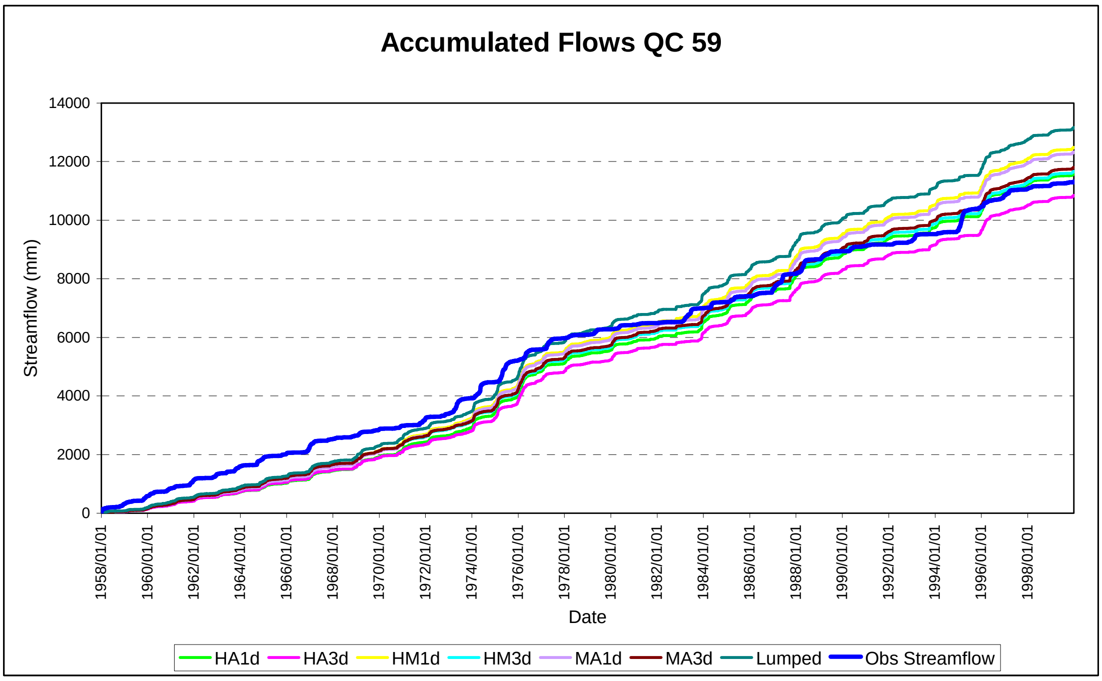

Figure 5.1 Accumulated observed and simulated streamflows for all scenarios in QC 59

It is however difficult to judge from a visual inspection of Figure 5.1, which scenario best represents the observed data. Therefore the accumulated totals and RMSE for the simulated streamflow and observed data for QC 59 are summarised in Table 5.1.

It is evident from the results presented in Table 5.1 that, the total accumulated depth for the lumped scenario is much larger than the accumulated observed depth as well as the accumulated depths for all the other scenarios. This is further emphasised by the largest RMSE of 2.64 mm obtained for the lumped scenario. The results also indicate that those scenarios in which area weighted soils information is used perform better than scenarios which use modal soils information. For example, the RMSE of HA1d is less than that for HM1d, and the RMSE of HA3d is less than the RMSE for HM3d. The effects of using more than one driver rainfall station are evident when comparing scenarios HA1d (RMSE=2.47) with HA3d (RMSE = 2.32) and MA1d (RMSE = 2.48) with MA3d (RMSE = 2.34). The scenarios using more than one driver rainfall station and associated correction factors have smaller error values. Considering both total accumulated flow depths and the RMSE values, the best scenario is HA3d which has a similar accumulated flow depth to the observed and the lowest RMSE = 2.32 mm.

Table 5.1 Total accumulated streamflow depths and the RMSE of the observed and simulated values for QC 59

Scenario	**Spatial Representation**	**Level of Land Cover**	**Level of soils information**	**No of Driver Rainfall Stations**	**Total Accumulated Streamflow (mm)**	**RMSE (mm)**
Observed					11314	
HA1d	12 HRU's	catchment specific	area weighted	1	11586	2.47
HA3d	12 HRU's	catchment specific	area weighted	3	10841	2.32
HM1d	12 HRU's	catchment specific	modal	1	12489	2.59
HM3d	12 HRU's	catchment specific	modal	3	11669	2.42
MA1d	3 Sub-catchments	modal	area weighted	1	12326	2.48
MA3d	3 Sub-catchments	modal	area weighted	3	11802	2.34
Lumped	1 QC	modal	modal	1	13162	2.64

The results of frequency analyses performed on daily observed and simulated runoff depths, for all scenarios is shown in Figure 5.2. The *ACRU* model simulates the observed well even though there is slight under simulation of the larger events.

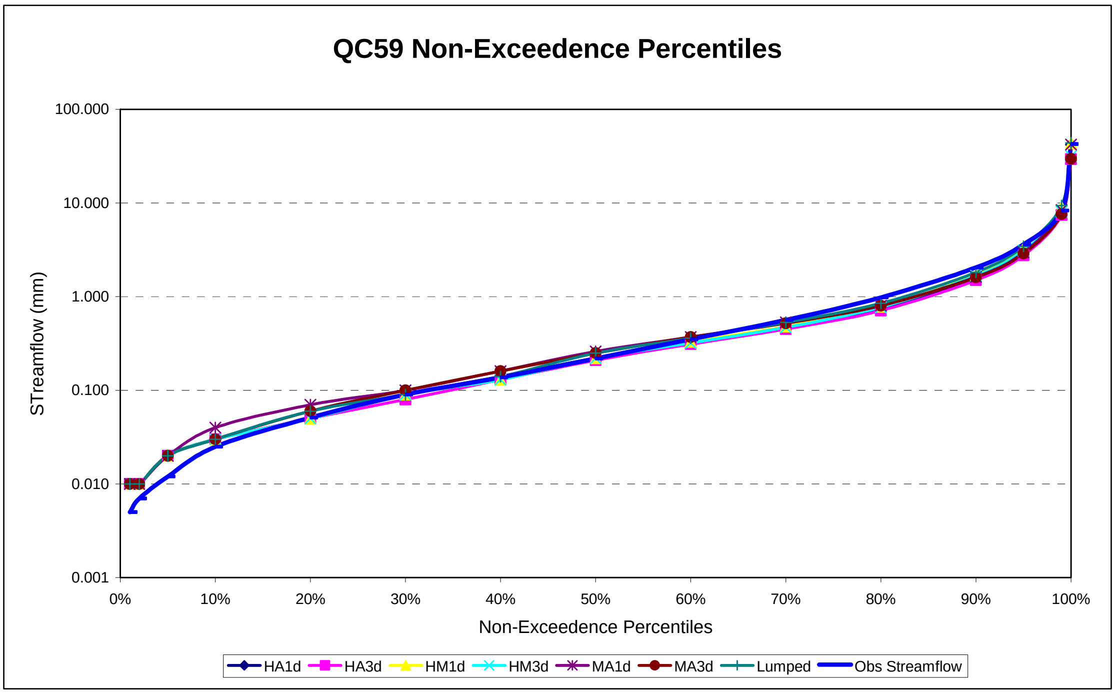

Figure 5.2 Frequency analyses of simulated and observed daily runoff depths for QC59

5.2. Simulated Volumes for Quaternary 6

The accumulated simulated and observed flows in QC6 for the period 1983 to 1998 are shown in Figure 5.3. Only four scenarios were modelled for this QC because it was not divided into sub-catchments by Schulze *et al*. (2005b). It is evident from Figure 5.3 that there is some over-simulation by the *ACRU* model for all scenarios. A detailed look at the driver rainfall station data (0269352A) used in this simulation revealed that when compared to another rainfall station in the area (0269611W) there was a discrepancy between recorded rainfall for some rainfall events. As an example on the 7th and 8th February 1988 Station 0269352A recorded 108 mm and 36 mm respectively whereas Station 0269611W recorded 13.5 mm and 15.5 mm respectively. Similar discrepancies are evident on the 26th and 27th of September 1987 where Station 0269352A has higher recorded rainfall values than those recorded at station 0269611W. It is also evident from Figure 4.15 that for the period 1983 to 1999 the MAP for the two stations differ by an average of about 400 mm of rainfall. The over-simulation of streamflow for this QC by the *ACRU* model, could therefore be attributed to the single driver rainfall station used in the simulation having higher rainfall than the rest of the catchment. All scenarios do, however, follow the same trend as the observed flows. There are also differences between the scenarios modelled. For example, the lumped scenario over-simulates more than all the other scenarios considered.

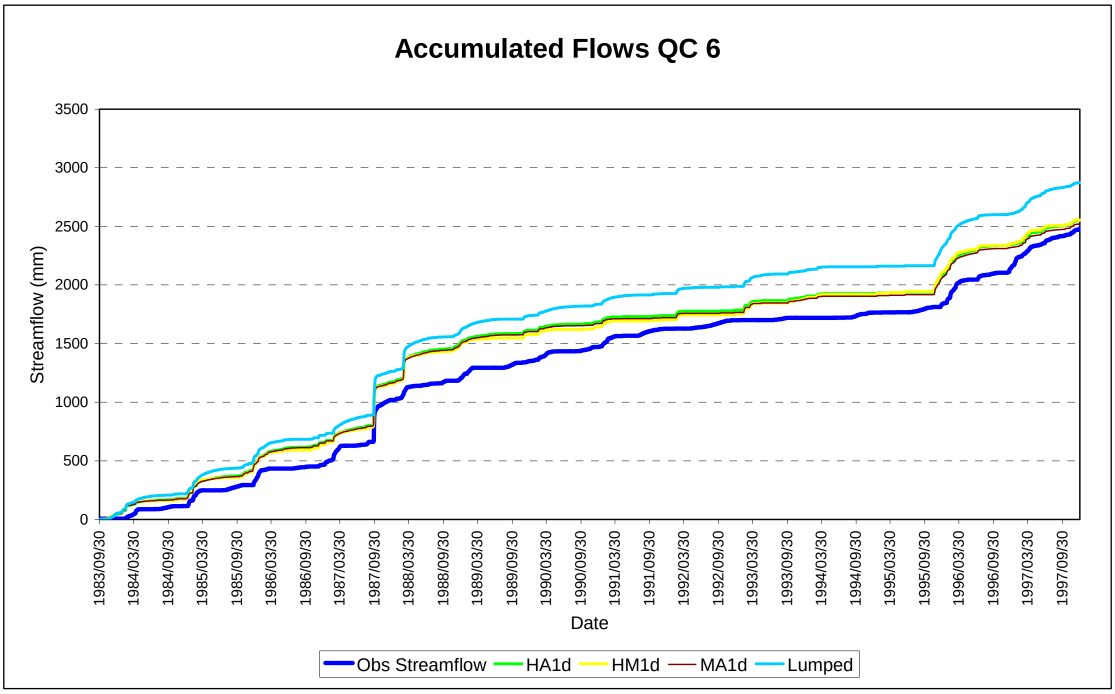

Figure 5.3 Accumulated observer and simulated flows for QC 6 for all scenarios

The trends are reflected in Table 5.2 which summarises the accumulated totals as well as the RSME values, for all scenarios for QC 6. There is a very small difference in accumulated totals when comparing scenarios HA1d and HM1d, however, the RMSE shows that HM1d has a larger error value implying that in QC 6 the use of area weighted soils yield better results. The results for scenarios HA1d and MA1d are very similar and this is reflected in the results from the frequency analyses shown in Figure 5.4 and in the total accumulated streamflows and RMSE contained in Table 5.2. This could be due to the fact that QC 6 is relatively homogenous and it was not divided into sub-catchments. Both scenarios HA1d and MA1d simulated the observed well in terms of total accumulated streamflow depths and low RMSE values.

Table 5.2 Total accumulated streamflow depths and the RMSE of the observed and simulated values for QC 6

Scenario	**Spatial Representation**	**Level of Land Cover**	**Level of soils information**	**No. of Driver Rainfall Stations**	**Total Accumulated Streamflow**	**RMSE**
Observed					2484	
HA1d	4 HRU’s	Catchment specific	Area weighted	1	2551	1.73
HM1d	4 HRU’s	Catchment specific	modal	1	2555	1.78
MA1d	1 QC	modal	Area weighted	1	2521	1.73
Lumped	1 QC	modal	modal	1	2873	1.73

The results of frequency analyses of observed and simulated daily runoff depths for QC 6 are presented in Figure 5.4. The model slightly over-simulates the larger events which again could be attributed to the driver rainfall station used in the simulation. There are larger differences for the smaller events which could be due to erroneous observed low flow measurements or that the low flows are not simulated adequately by the *ACRU* model.

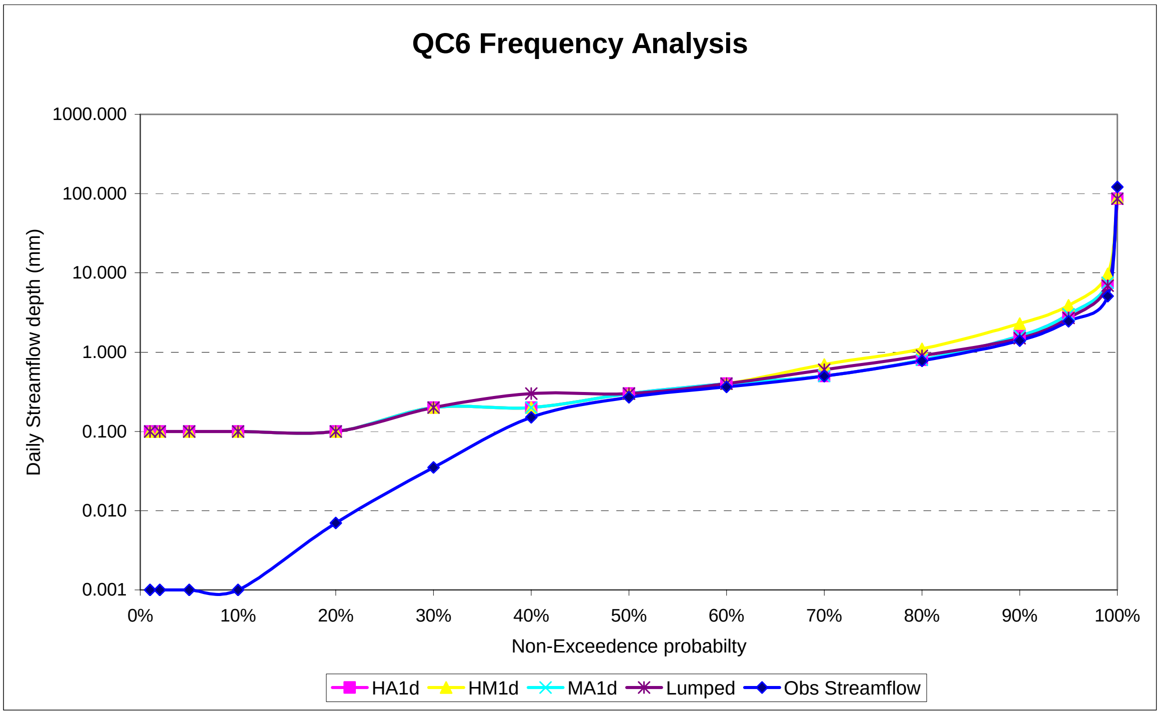

Figure 5.4 Frequency analyses of simulated and observed daily runoff depths for QC 6

5.3. Simulated Volumes for Quaternary 72

The accumulated simulated and observed streamflow depths for all scenarios for QC 72 are presented in Figure 5.5 and, the accumulated totals of streamflow depths for simulated and observed values as well as the RMSE for all scenarios are presented in Table 5.3. These results indicate that the lumped scenario and scenario MA1d are very similar and both over-simulate the observed runoff depth. These two scenarios have the largest accumulated total streamflow depths and RMSE values. It is also evident that the *ACRU* model over-simulated flows up until 1975 and from 1976 onwards the simulated flows for most scenarios was slightly under-simulated. This could be attributed to land use changes in the catchment. For 1983-1984 the observed and simulated flows compare very well.

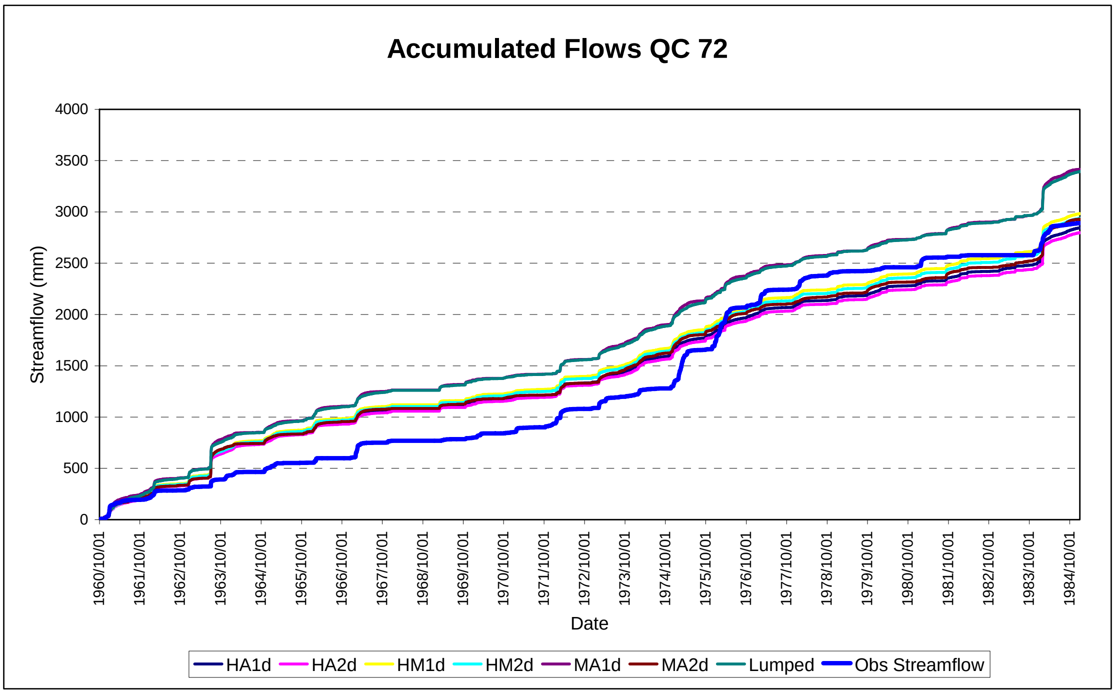

Figure 5.5 Accumulated simulated and observed flows for QC 72 for all scenarios

As expected, the driver rainfall stations made little difference to the simulations since the RMSE values (Table 5.3) for both HA1d and HA2d and HM1d and HM2d are similar. This is because only one rainfall station was actually used but two different sets of correction factors were applied. Simulations obtained using area weighted soils information performed better than simulations using modal soils information, in terms of accumulated totals and RMSE values. Comparing total accumulated streamflow depths and the RMSE values for scenarios HA1d and MA1d illustrates that modelling as HRU's results in improved simulations. The best results were obtained for Scenario HA1d which had the lowest RMSE of 7.68 mm and the accumulated total streamflow depth closest to observed total. The results of frequency analyses of the observed and simulated streamfow depths for all scenarios in QC 72 are shown in Figure 5.6 It is evident from this illustration that the simulated streamflow volumes using the *ACRU* model generally followed the trends in the observed streamflow volume well, but the larger events were slightly under-simulated. Differences in the scenarios are evident in Figure 5.6.

Table 5.3 Total accumulated streamflow depths and the RMSE of the observed and simulated values for QC 72

Scenario	Spatial Representation	Level of Land Cover	Level of soils information	No. of Driver Rainfall Stations	Total Accumulated Streamflow (mm)	RMSE (mm)
Observed					2891	
HA1d	8 HRU's	catchment specific	area weighted	1	2845	7.68
HA2d	8 HRU's	catchment specific	area weighted	2	2797	7.68
HM1d	8 HRU's	catchment specific	modal	1	2982	7.69
HM2d	8 HRU's	catchment specific	modal	2	2937	7.69
MA1d	2 sub-catchments	modal	area weighted	1	3415	7.71
MA2d	2 sub-catchments	modal	area weighted	2	2929	7.70
Lumped	1 QC	modal	modal	1	3393	7.71

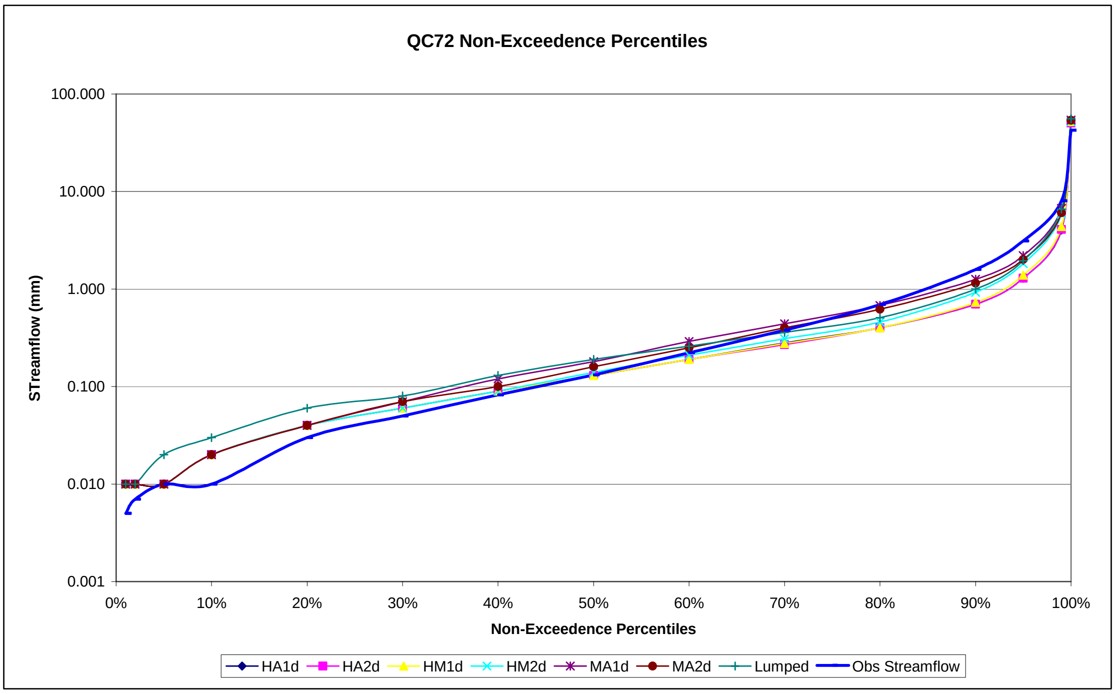

Figure 5.6 Frequency analyses of simulated and observed daily runoff depths for QC 72

5.4. Simulated Volumes for Quaternary U20B

The accumulated simulated and observed flows for QC U20B for the period 1960 to 1993 are shown in. From Figure 5.7 it is evident that accumulated flows for the lumped scenario are much higher than the accumulated observed flows as well as for all the other scenarios. When configured as a lumped catchment, the *ACRU* model over-simulates in QC U20B. It is also evident that the simulated flows are closer to the observed flows when this catchment is discretised into sub-catchments. There is a clear indication from a visual inspection of Figure 5.7, that there are differences in accumulated flows between the scenarios modelled. For scenarios HA1d, HM1d and MA1d where only one driver rainfall station was used, the results showed under-simulation by the model. Scenarios HA5d, MA5d and HM5d result in a slight over-simulation by the model but follow the same trends as the observed data. Visually, scenario HA5d seems to simulate the observed flows the best.

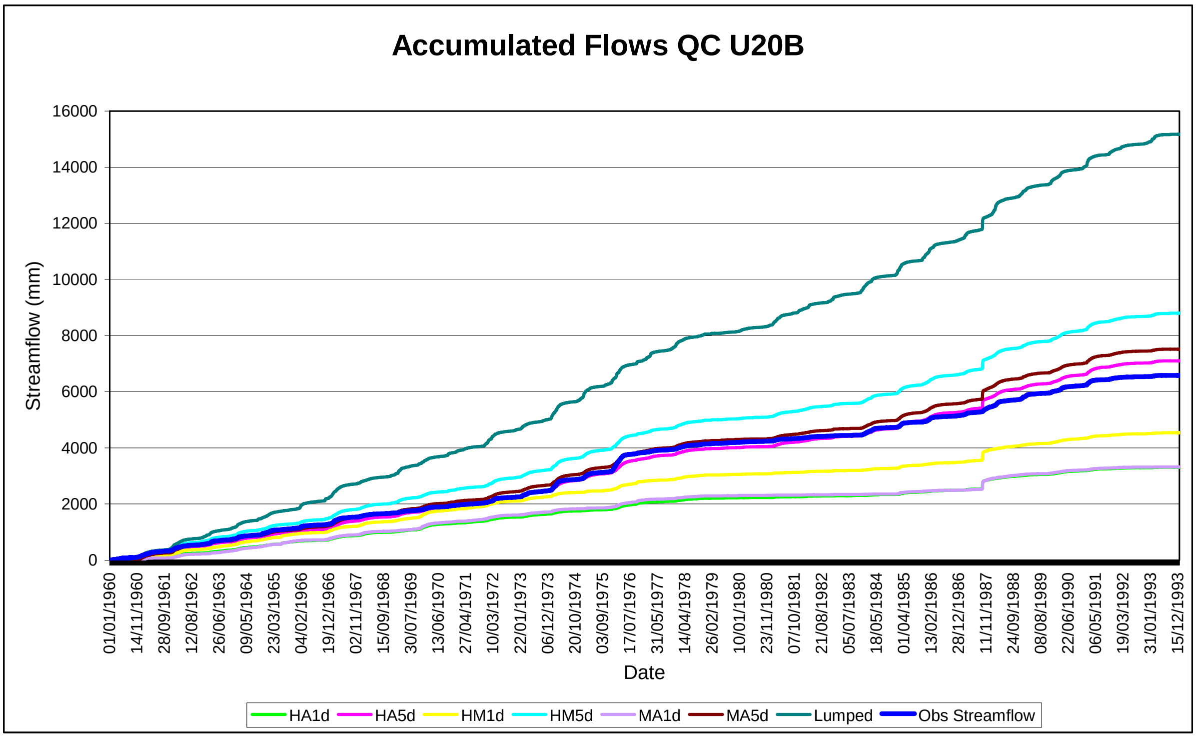

Figure 5.7 Accumulated flows for QC U20B for all scenarios

The accumulated totals of streamflow depths for simulated and observed values as well as the RMSE for all scenarios simulated in QC U20B are presented in Table 5.4. These results indicate the difference in using one driver rainfall station in comparison to utilizing five. In those scenarios where one driver station is used (HA1d, HM1d and MA1d), the model consistently under-simulates the observed flows and the RMSE values are larger. Again these results indicate that the use of five rainfall stations better represented the rainfall in the catchment and therefore improved the simulations. Simulations obtained using area weighted soils information performed better than simulations using modal soils information, in terms of accumulated totals and RMSE values. This is evident when comparing scenarios HA5d (RMSE = 0.5) and HM5d (RMSE = 0.62) from Table 5.4. A comparison of scenarios HA5d and MA5d indicates that the use of HRU's results in simulated flows with a smaller error and accumulated totals closer to that of the observed data. The best scenario is HA5d which has the smallest RMSE of 0.5 and accumulated flow closest to that of the observed.The results of frequency analyses of observed and simulated daily runoff depths for QC U20B are presented in Figure 5.7. The model slightly over-simulates the larger events however results for scenarios MA5d and Ha5d follow trends of the observed quite well. There are some discrepancies in the smaller events which again can be attributed to the way in which the model simulates low flows.

Table 5.4 Total accumulated streamflow depths and the RMSE of the observed and simulated values for QC U20B

Scenario	**Spatial Representation**	**Level of Land Cover**	**Level of soils information**	**No. of Driver Rainfall Stations**	**Total Accumulated Streamflow (mm)**	**RMSE (mm)**
Observed					6588	
HA1d	44 HRU’s	catchment specific	area weighted	1	3313	0.8
HA5d	44 HRU’s	catchment specific	area weighted	5	7105	0.5
HM1d	44 HRU’s	catchment specific	modal	1	4536	0.83
HM5d	44 HRU’s	catchment specific	modal	5	8796	0.62
MA1d	11 sub-catchments	modal	area weighted	1	3327	0.82
MA5d	11 sub-catchments	modal	area weighted	5	7519	0.51
Lumped	1 QC	modal	modal	1	15170	1.65

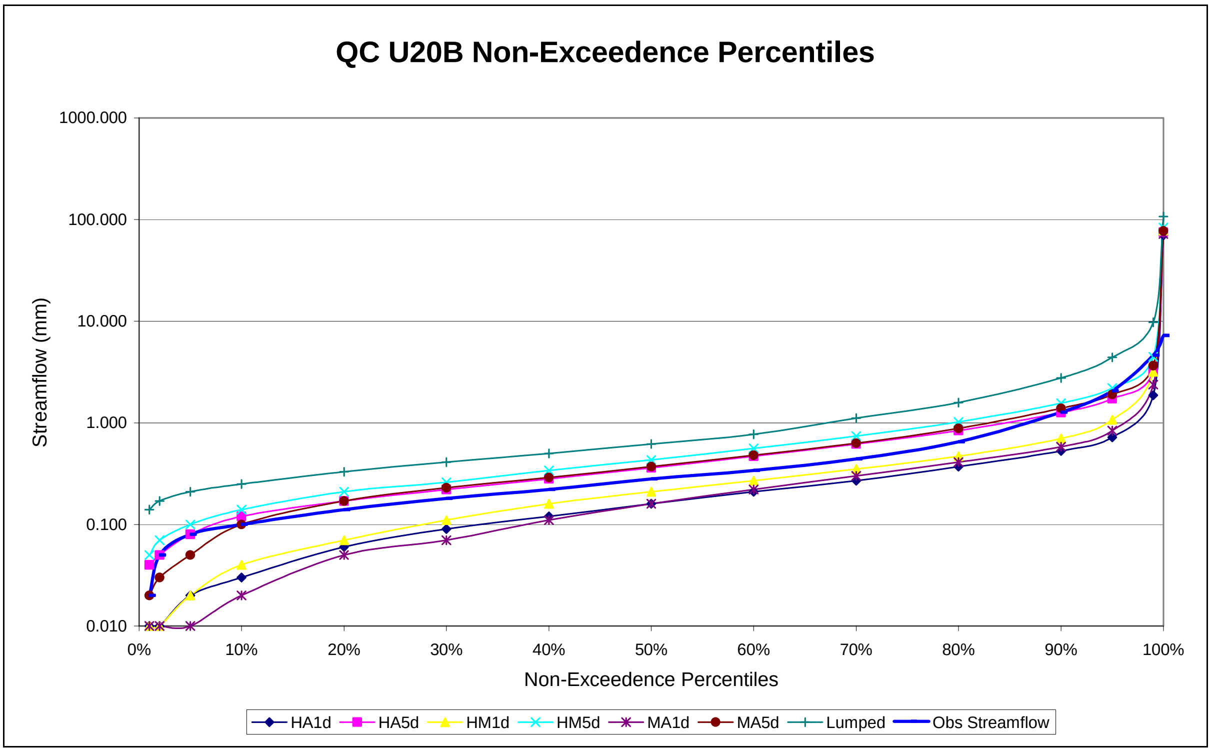

Figure 5.8 Frequency analyses of simulated and observed daily runoff depths for QC U20B

The scenarios which resulted in the "best" results in all four of the selected catchments are presented in Table 5.5. It is evident from the results presented that in all four quaternary catchments those scenarios in which QC's are divided into HRU's using area weighted soils information simulated the observed data the best. It is also clearly evident that the use of more than one driver rainfall station more adequately represents rainfall in the catchment and therefore gives more realistic results.

Table 5.5 Summary of "Best" scenario results for selected catchments

Quaternary Catchment	**Area (km^2)**	**Best Scenario**
59	129	HA3d
6	152	HA/MA
72	544	HA1d
U20B	353	HA5d

The findings obtained in this study concur with preliminary investigations done by (Chetty *et al.*, 2003) where catchment discretisation, appropriate levels of soil and land cover information as well as the use of more than a single driver rainfall station per QC was investigated in the 353 km^2 Lions River catchment. In order to estimate design floods using a continuous simulation modelling approach, the scenarios which simulated the best runoff volumes, as indicated in Table 5.5, were used to simulate peak discharge. The results are reported in the next section.

5.5. Simulated Peak Discharge for Quaternary 59

A frequency analysis of simulated and observed peak discharge for QC 59 is illustrated in Figure 5.9. This graph shows that the *ACRU* model simulated peaks with slight over-simulation for the smaller events but the larger events seem to be slightly under-simulated. Figure 5.10 illustrates that the design floods computed from the simulated peak discharges have lower values than the observed recurrence interval floods especially for the higher return period events.

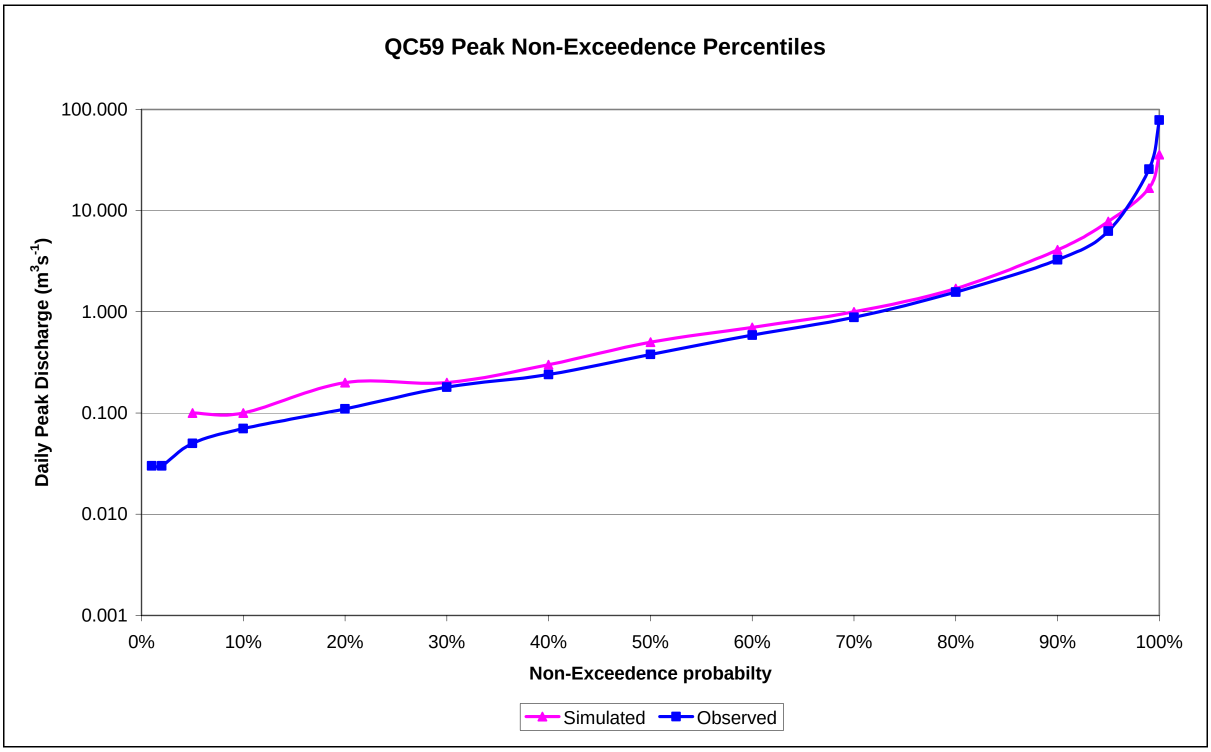

Figure 5.9 Frequency analyses of simulated and observed daily peaks for QC 59

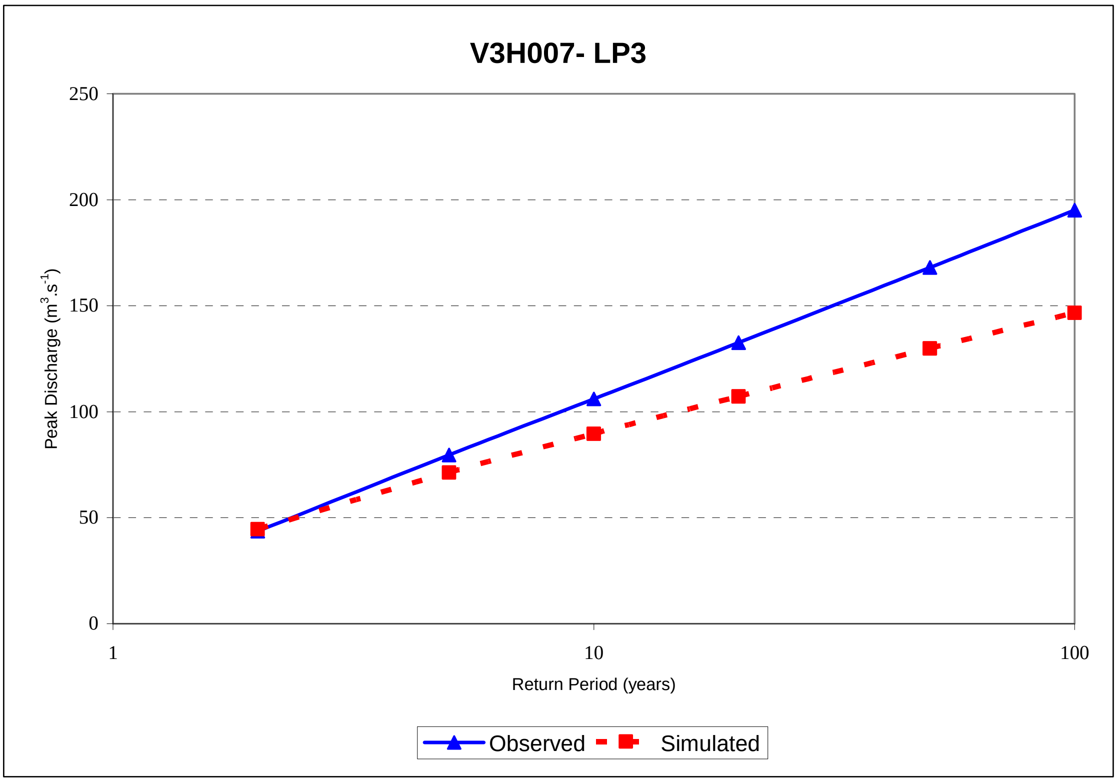

Figure 5.10 Design peak discharges computed from simulated and observed values for V3H007 (QC 59)

5.6. Simulated Peak Discharge for Quaternary 6

A frequency analysis of simulated and observed daily peak discharge for QC 6 is presented in Figure 5.11. This graph shows that the *ACRU* model under-simulates the peaks but there is some over-simulation in the larger events. Figure 5.12 illustrates that there is over-simulation of design floods when compared with the observed design floods especially for the larger return period events. This could be attributed to the driver rainfall station which was used to represent the rainfall of the catchment having a higher MAP when compared to another nearby rainfall station hence larger simulated volumes resulting in higher peaks.

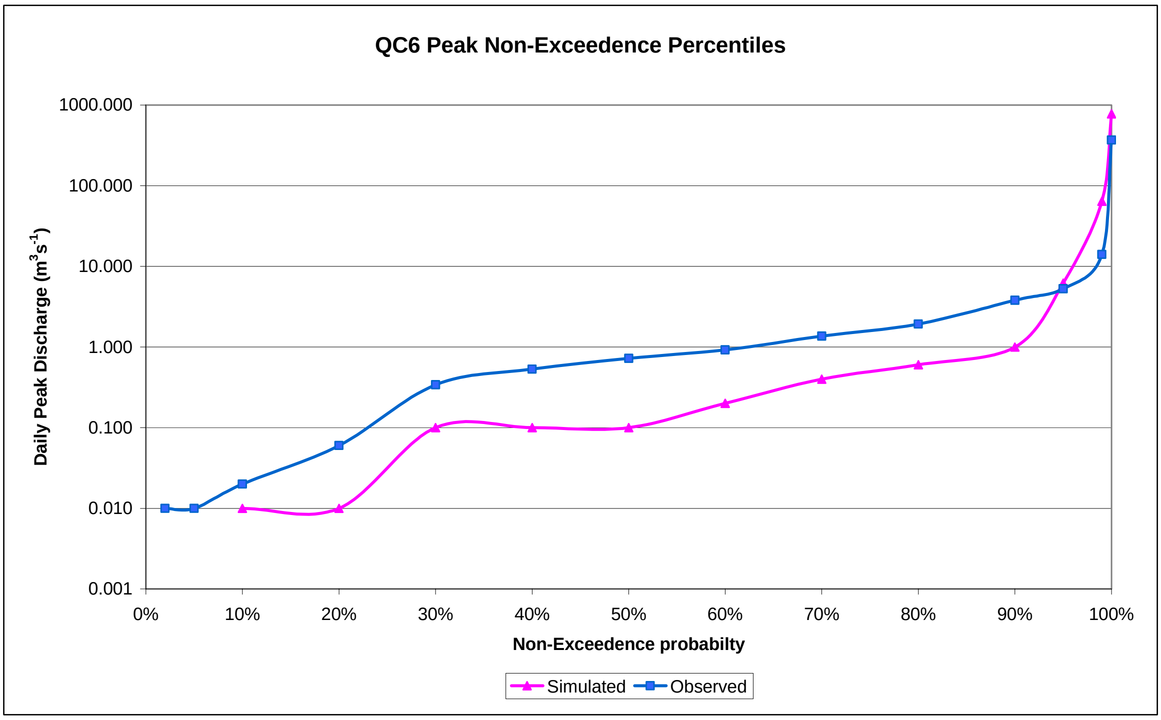

Figure 5.11 Frequency analyses of simulated and observed daily peaks for QC 6

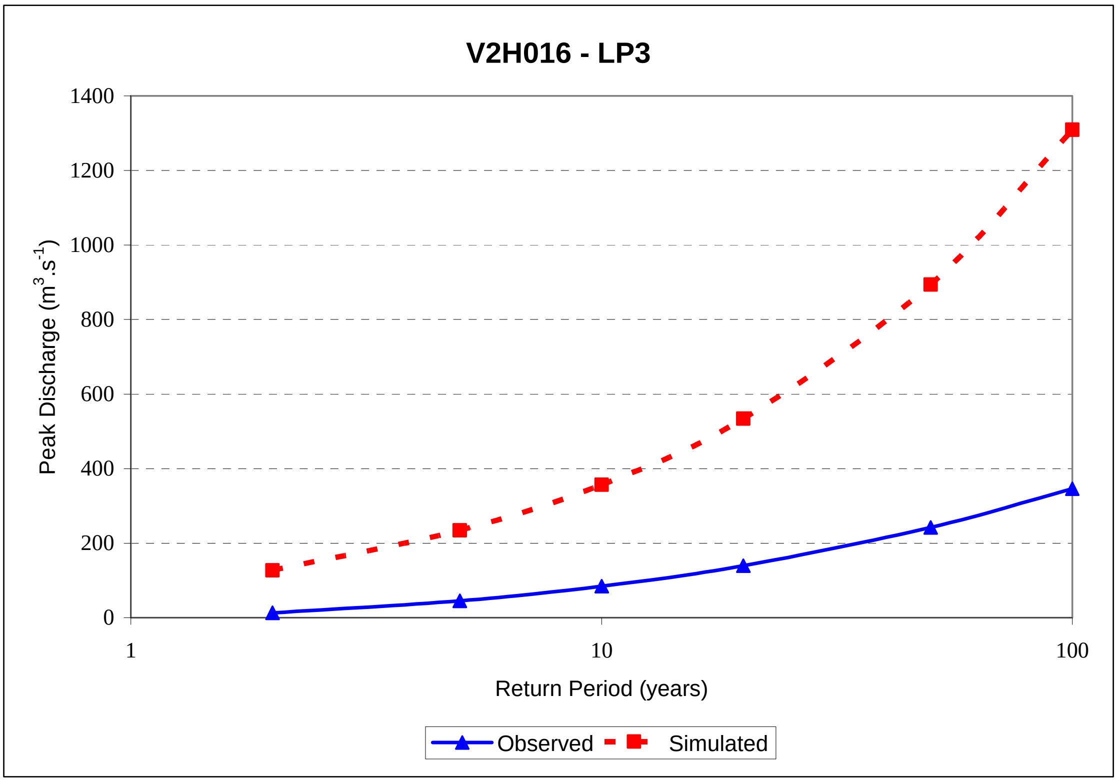

Figure 5.12 Design floods for simulated and observed values for V2H016 (QC 6)

5.7. Simulated Peak Discharge for Quaternary 72

Figure 5.13 and Figure 5.14 illustrate the frequency analysis of peak discharge and, simulated and observed design floods for QC 72 respectively. Both these figures indicate under-simulation for smaller events and over-simulation for larger events. Poor results obtained in this catchment could be attributed to the poor quality of observed data that was available. Only one rainfall station was used in this catchment. This poor spatial representation of rainfall which drives a rainfall-runoff model like *ACRU* also affects the design flood estimates which rely on streamflow volumes to estimate peak discharge. Irrigation was also not accounted for in these simulations and this activity could impact the results.

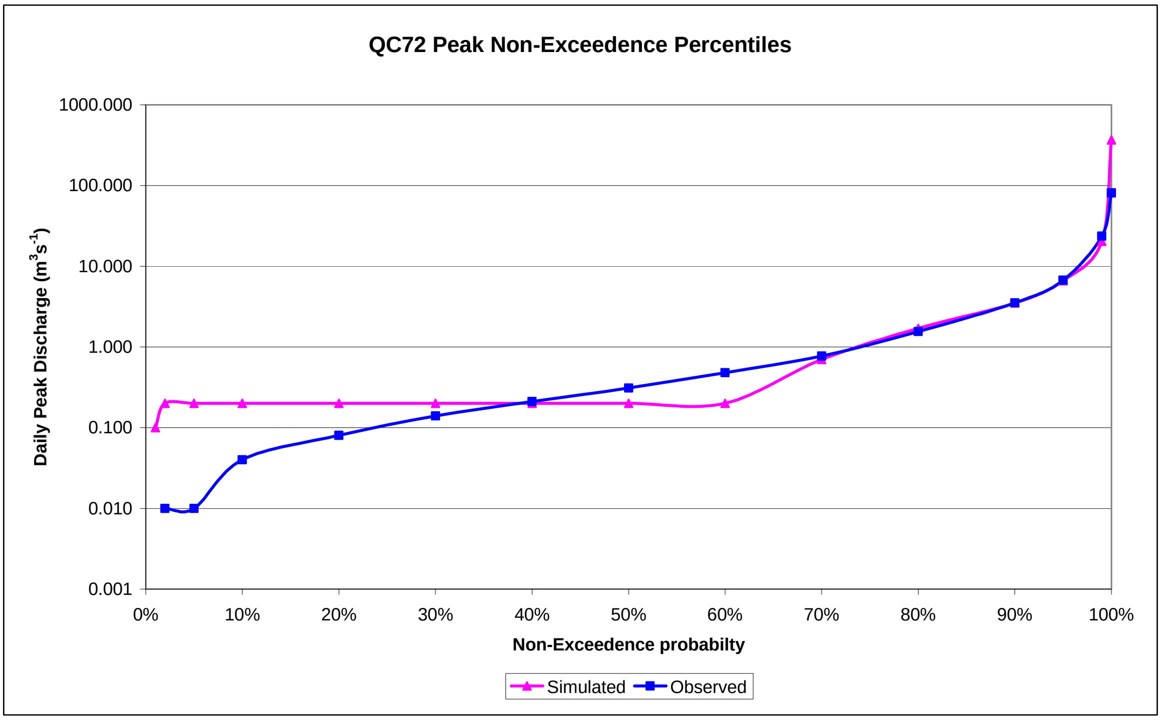

Figure 5.13 Frequency analyses of simulated and observed daily peaks for QC 72

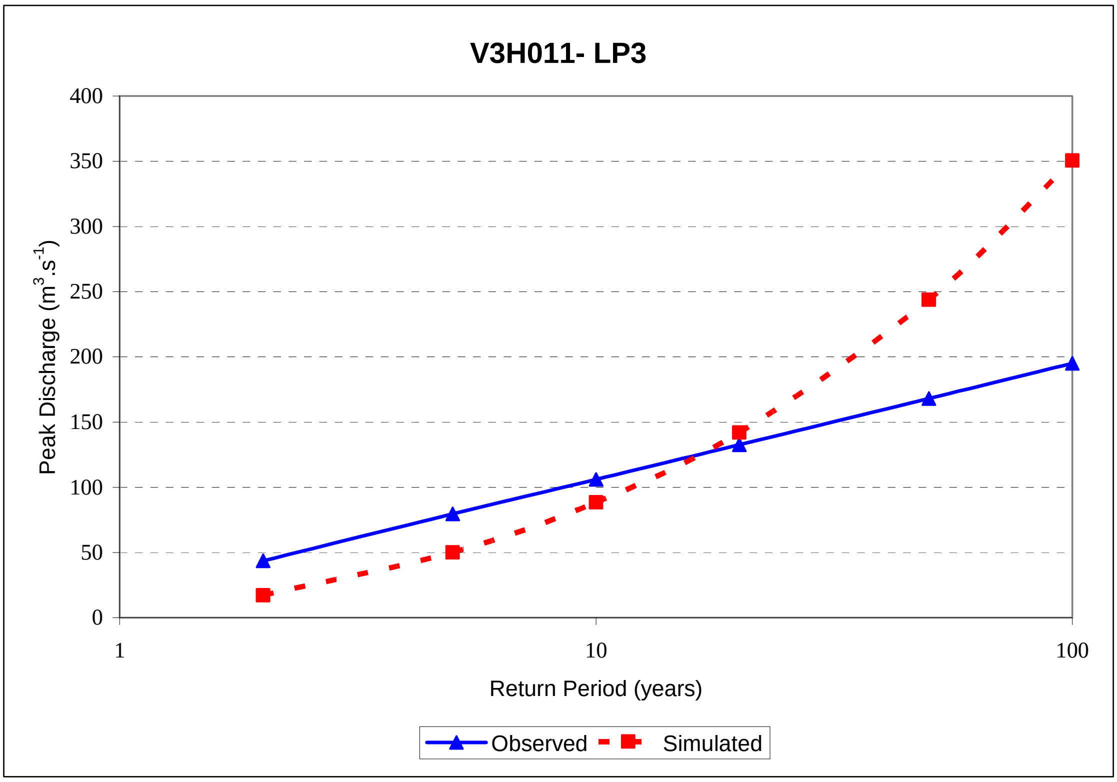

Figure 5.14 Design floods for simulated and observed values for V3H011 (QC 72)

5.8. Simulated Peak Discharge for Quaternary U20B

Figure 5.15 illustrates the frequency analysis of simulated and observed daily peaks for QC U20B in the Lions River catchment. The model over-simulates the peaks except for the very big events. The design floods shown in Figure 5.16 are slightly over-simulated but follow the trend of the observed design floods very well. This could be attributed to the long continuous record of good quality rainfall and runoff data available for this area.

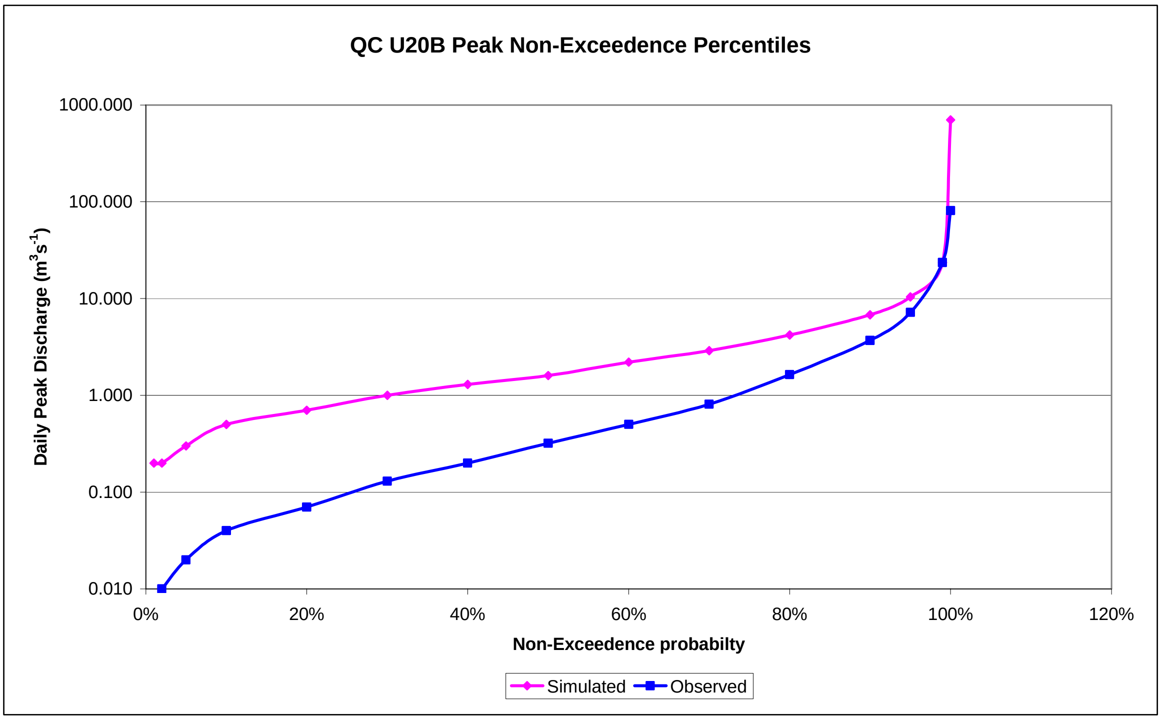

Figure 5.15 Frequency analyses of simulated and observed daily peaks for QC U20B

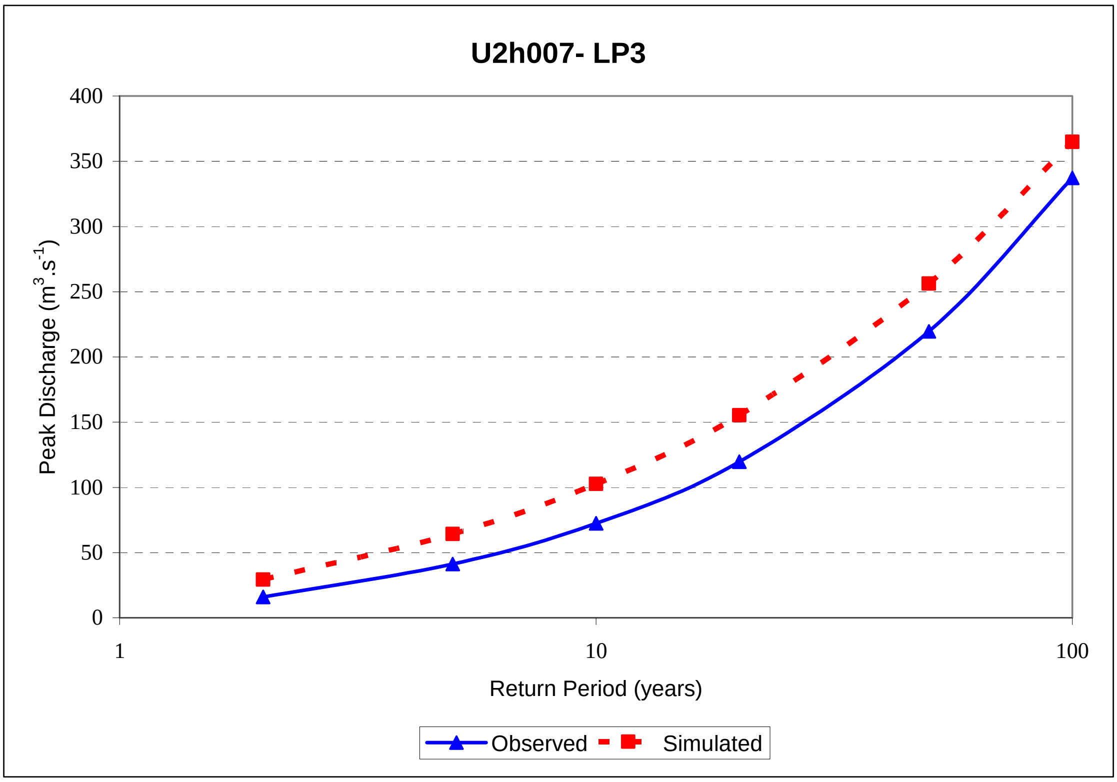

Figure 5.16 Design floods for simulated and observed values for U2H007 (QC U20B)

Table 5.6 contains the observed and simulated total accumulated streamflow depths and design flood peaks at the 1:50 year and 1:100 year recurrence intervals, for the four selected quaternary catchments. From the tabulated information, it is evident that for QC 6, there was an over-estimation of the design streamflow depths by approximately 4% and 20 % at the 1:50 and 1:100 year recurrence intervals respectively. This over-estimation of simulated streamflow depths could be attributed to the driver rainfall station used to represent the rainfall over that catchment having a higher MAP when compared to a nearby station. However, the design peaks for QC 6 are over-estimated by 269% and 278% at the 1:50 year and 1:100 year recurrence intervals respectively. The over-prediction of the design peaks could partially be related to the over-estimation of streamflow depth. The over simulated streamflow volumes were used in the estimation of peak discharge where, and therefore could have contributed to the over-simulation of peak discharges. However such large over-simulation also indicate that there is a significant problem in the estimation of peak discharge in this catchment. This could be related to inaccurate representation of catchment lag by the lag equation used in the study. In addition, the Schmidt-Schulze lag equation used to estimate catchment lag in this study uses MAP as a surrogate for climate and it has already been established that the rainfall station used had a higher MAP than the surrounding stations.

In QC 59 design stormflow depths were under-predicted by approimately 31% and 34%. The design flood peaks were also under-predicted by approximately 23% and 25% for the 1:50 year and 1:100 year recurrence intervals respectively.

In QC 72 design stormflow depths were under-estimated by 8% and 4% at the1:50 year and 1:100 year recurrence intervals respectively. However, the over estimation of the design peaks by 44% and 79% at the1:50 year and 1:100 year recurrence intervals respectively could be attributed to the poor simulation of daily peak discharges. QC 72 was the largest catchment used in the study. It is postulated that the catchment lag could have been a major factor resulting in the over-estimation of design floods. The estimated lag could have been too short and hence the resultant peaks too high. The Schmidt –Schulze equation is not suited for use in very large catchments since it was developed on research based in small catchments less than 3 km^2 whereas QC 72 is a 544 km^2 catchment. Parameters used in the estimation of lag such as the 30-minute intensity may no longer hold true on large catchments. Lag is also sensitive to the slope of a catchment and larger catchments generally imply gentler slopes where stormflow response may no longer be as rapid as expected on smaller catchments.

In QC U20B design streamflow depths were over-predicted with percentage differences between simulated and observed of 12% and 16 % at the 1:50 and 1:100 year recurrence intervals respectively. There is a corresponding over estimation of design peaks between 8% and 16 % difference at the 1:50 and 1:100 year recurrence intervals respectively. The results presented in Table 5.6 indicate overall that there are problems associated with the estimates of design flood peaks using the *ACRU* model as configured in this study. QC 59 and QC U20B are the only catchments which yield reasonable results.

Table 5.6 Observed and simulated design floods at the 1:50 year and 1:100 year recurrence interval for quaternary catchments 59, 6, 72 and U20B

Quaternary Catchment	**59 ($129km^2$)**		**6 ($152km^2$)**		**72 ($544km^2$)**		**U20B ($353km^2$)**	
Recurrence Interval (years)	**50**	**100**	**50**	**100**	**50**	**100**	**50**	**100**
Design Stormflow Depths Observed (mm)	29	33	97	164	14	16	11	12
Design Stormflow Depths Simulated (mm)	42	50	93	136	16	17	9	10
Percentage Difference in Stormflow Depths (%)	-31	-34	4	20	-8	-4	12	16
Recurrence Interval (years)	**50**	**100**	**50**	**100**	**50**	**100**	**50**	**100**
Design Peaks - Observed ($m^3.s^{-1}$)	129	146	242	350	168	195	220	337
Design Peaks - Simulated ($m^3.s^{-1}$)	168	195	894	1309	243	350	256	364
Percentage Difference in Peaks (%)	-23	-25	+269	+278	+45	+79	+16	+8

6. DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

This dissertation comprised three objectives as outlined in Chapter 1 of this document. Objective I, *viz*. review the literature on different approaches for design flood estimation and exploration of the potential for the use of a continuous simulation modelling approach to design flood estimation, is addressed in Chapters 2 and 3. A discussion of this review and conclusions drawn, are reported in Section 6.1. Objectives IIa, IIb, IIc and Objective III, dealing with scale issues for configuring the *ACRU* model and comparing simulated and observed design flood estimates using a continuous simulation model, are addressed in the case studies detailed in Chapter 4. Results are reported in Chapter 5 and a discussion of the results and conclusions are reported in Section 6.2. Recommendations from this research are reported in Section 6.3.

6.1. Techniques for Design Flood Estimation

Design flood estimation is a necessary step in the planning and design of hydraulic structures subject to flood risk. According to Cameron *et al*. (1999) "the choice of an acceptable and cost-effective engineering or management solution is fundamentally dependent upon having reliable estimates of flood frequency in terms of both peak flows and volumes of water. This remains a challenge in hydrology" (Cameron *et al.*, 1999). Several techniques are available to estimate design floods. The main approaches are methods based on the analysis of the streamflow data and rainfall-runoff based methods.

Methods based on the analysis of streamflow data include empirical formulae, maximum flood envelopes and flood frequency analysis which includes either at-site or regional approaches. Methods based on the analysis of floods bypass explicit consideration of the underlying processes and resort to statistical analyses or fitting empirical models to observed data. The large natural variability of floods means that large data sets are required and these are seldom available. Empirical formulae are found to generally be conservative and, according to Cordery and Pilgrim (2000), if these methods are not calibrated from the catchment in question, their use can be hazardous and should be avoided.

If long records of good quality streamflow data are available, at-site flood frequency analyses are used for design flood estimation. Since adequate observed streamflow data is seldom available, regional approaches to flood frequency analysis are utilised where data from several sites in a region are used to estimate the frequency distribution at each site in question. Research shows that regional approaches are reliable and robust. A review of the literature advocates the use of regional frequency analysis because a "well conducted regional frequency analysis will yield quantile estimates accurate enough to be useful in many realistic applications" (Hosking and Wallis, 1997).

Rainfall based methods are used when there is limited or no streamflow data available but longer rainfall records are available. Rainfall-runoff based methods include design event models, joint probabilities approaches and continuous simulation modelling. Design event models have several limitations and make simplifying assumptions. The most important assumption being that the frequency of the estimated flood has the same frequency as the input rainfall.

The continuous simulation modelling approach to design flood estimation is seen to hold a great deal of potential. The advantages of this approach are that it overcomes some of the limitations of the design event models, antecedent moisture conditions are accounted for, concepts are more physically based than with other methods, the effects of complex hydrological systems and river engineered systems can be and, a complete hydrograph is obtained, not only peak discharge. These advantages need to be weighed against the challenges of input data preparation, assigning values to model parameters and choosing the appropriate time scale and spatial resolution at which should take place.

It can be concluded that the widely used existing techniques for design flood estimation have several limitations and since there is a need for improved design estimates, further research into techniques for design flood estimation is required. According to Cordery and Pilgrim (2000), "the problems with research into design flood estimation need redress if the state-of-the-art of design flood estimation is to make significant progress". The continuous simulation modelling approach is seen to hold great potential for the future of design flood estimation. Several of the research studies reviewed in this study have reported realistic, acceptable results using continuous simulation modelling. Techniques for design flood estimation currently utilised in South Africa are based on methods developed in the 1970's. The potential that continuous simulation modelling holds, together with the available computing power, longer rainfall and streamflow records, land use and soils databases which are available for the whole country, Geographical Information Systems (GIS) it is envisaged that using a continuous simulation modelling approach can produce a powerful tool to estimate design floods for South Africa.

6.2. Design Flood Estimation in the Thukela and Lions River Catchments Using a Continuous Simulation Approach

Conclusions drawn from assessing scale issues in configuring the ACRU model are reported in Section 6.2.1. Conclusions drawn from comparisons of simulated and observed design flood estimates using continuous simulation modelling are reported in Sections 6.2.2.

6.2.1. Assessing scale issues for the configuration of the *ACRU* model

A continuous simulation modelling approach aims at preserving the physical relationships between variables and a critical question which needs to be addressed is the "level" of representation that will preserve the "physical chain" of the hydrological processes, both in terms of scale of representation and level of description for the modelling process (Martina, 2004). The primary objectives of this component of this study was to investigate the appropriate scale at which a continuous simulation model should be configured for the selected catchments and the spatial aggregation levels of soil and land cover information required to give optimum results.

The *ACRU* model was selected as the continuous simulation model and the investigation focused on determining the optimal level of catchment discretisation and input information assimilation for the *ACRU* model configuration. Relatively un-impacted upstream catchments with sufficient and reliable data were selected. Three QC's were selected with catchment areas ranging from 129 to 544 km^2 in the Thukela Catchment. This range of catchment areas was deemed adequate since the majority of QC's within the Thukela catchment have catchment areas less than 500 km^2. It was therefore assumed that the results obtained for the selected QC's will be valid for all QC's in the Thukela catchment. The 353 km^2 Lions River quaternary catchment was also included in the investigations since no suitable QC with this range of area was found in the Thukela catchment.

Conclusions drawn from the study using the *ACRU* model in the selected areas can be summarized as follows:

- The selected quaternary catchments as lumped entities consistently resulted in large over-simulation of streamflows. Discretising catchments into sub-catchment produced more realistic simulations. Form the results obtained in this study, it is concluded that quaternary catchments in the Thukela and Lions River catchment should be discretised to the HRU level since the best simulations were obtained using HRU's.
- All scenarios using area weighted soils information yielded more realistic simulated streamflow volumes, when compared to the use of modal soils information. It is therefore more appropriate to use area weighted soils information for the continuous simulation model.
- Simulated volumes were improved when land cover was represented by HRU's than when a single modal land cover was used to represent the land cover in whole quaternary catchment.
- Modelling using more than one driver rainfall station per sub-QC with appropriate precipitation correction factors yielded better results than, modelling using a single driver rainfall station for QC59 and U20B. This is highlighted in QC 72 and QC 6 where simulated streamflows were over-predicted since only one driver rainfall station was used. There were not many reliable representative rainfall stations in the area for QC 72 and the single rainfall station used could not reflect the spatial variations in rainfall within the catchment. In QC 6 the selected driver rainfall station with a longer rainfall record had a higher MAP than another station within the catchment with shorter records and a distance away. The model therefore over-predicted streamflow volumes, since the selected station could not account for the spatial variability of rainfall within this lumped catchment. In general the results indicate that the better the spatial variations in rainfall are represented by more raingauges, the more realistic the simulations are when compared to observed flows.

6.2.2. Comparisons of observed and simulated design flood estimates

The "best" simulations of volume for each of the selected QC's were subsequently used to estimate design peak discharges and these were compared against values computed from the observed flood data. It can be concluded from the analysis of the results that the *ACRU* model configured at the HRU scale with area weighted soils information and several suitable driver rainfall stations yielded reasonably realistic design flood peak estimates for QC U20B and QC 59 of the selected quaternary catchments. Analyses at the 1:50 year and 1:100 year recurrence intervals indicated that QC 6 produced large over-predictions when compared to the observed. Design floods for Q C72 were over-predicted by almost 70% for the 1:100 year recurrence interval. The over and under-prediction in design floods points to problems associated with various aspects of estimating the peak discharge in the *ACRU* model. Specifically, it is postulated that the the lag equation used in the study had a large impact the estimation of peak discharge.

6.3. Recommendations from the Study

The recommendations from these results are:

- The optimum level of catchment discretisation in the Thukela catchment should include sub-quaternary catchments for use in a continuous simulation model. This level of discretisation may be considered for all QC's in southern Africa for modelling purposes.
- Catchments should be modelled using HRU's with area weighted soils information and, where possible, more than one driver rainfall station for the catchments which constitute a QC. Therefore, efforts need to be put in place to further develop the quaternary catchments database into a more refined database at a sub-QC scale with appropriate area weighted soils information and up-to date land cover information to facilitate the selection of HRU's.
- Driver rainfall station selection for a refined database needs to be done very carefully and where possible the use of more than one station in relatively heterogeneous catchments should be attempted since the spatial representation of rainfall for continuous simulation modelling is very important.

- The *ACRU* model only adequately simulated design floods for one of the selected catchments. Research needs to be channeled into assessing the performance of the model in other catchments for design flood estimation purposes. The problems associated with the estimation of design floods is linked to the calculation of daily peak discharges which is dependent on the simulation of runoff volume, the estimation of catchment lag and the temporal distribution of rainfall. These aspects which affect the timing and magnitude of peak flows require further investigation in order to adequately predict design peak discharges.
- The impacts of flood routing were not accounted for in this study since external catchments were selected. Flood routing in a hydrological study will impact the attenuation and lagging of hydrographs flowing through internal catchments. Thus for internal catchments, adequate representation and application of flood routing will yield more realistic peak flows.
- Operational catchments have several land use activities which can alter the streamflow in a catchment. It is important to adequately represent the land use of a catchment and the subsequent changes over time, to account for resultant hydrological impacts of these activities.
- The quality of data used in a rainfall-runoff modelling is very important for realistic simulations and for verification purposes. It is recommended that all data be carefully analysed before use in such studies.
- Frequency analyses of volumes simulated by the *ACRU* model simulations indicated problems in the low flow ranges. This needs attention and future research since these low flows are important for environmental considerations and in drought estimation.

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