DEVELOPMENT AND ASSESSMENT OF A REFINED PROBABILISTIC RATIONAL METHOD FOR DESIGN FLOOD ESTIMATION IN SOUTH AFRICA

Johannes Pieter Calitz

SEMINAR

Submitted in partial fulfilment of the requirements
for the degree of MSc Eng

School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
Pietermaritzburg
November 2011

ABSTRACT

South Africa currently has no set standard for Design Flood Estimation (DFE). There are however several guides and manuals, which provide designers with several recommended methods. These methods are based on the availability of historical data. Where historical data is available Flood Frequency Analysis (FFA) is the recommended method. FFA can be performed at-site or at a regional scale. However, when the required historical data are unavailable design event models are recommended. These are based on empirical, deterministic or probabilistic approaches. Due to the possible variability and limitations of deterministic methods a probabilistic approach is recommended. In South Africa the Standard Design Flood (SDF) method is one such approach, but requires refinement. This document contains a review of suitable methods for use in the development of a refined probabilistic DFE method for South Africa. It was found that the Rational Method is the most appropriate method, and a methodology is presented.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AMS	Annual Maximum Series
ARF	Areal Reduction Factors
ARI	Average Recurrence Interval
ARR	Australian Rainfall and Runoff
CN	Curve Number
DFE	Design Flood Estimation
DWA	Department of Water Affairs (Formerly DWAF)
DWAF	Department of Water Affairs and Forrestry
EV1	Extreme Value Type I
FFA	Flood Frequency Analysis
GEV	General Extreme Value
GIS	Geographic Information System
GL	Generalised Logistic
HRU	Hydrological Research Unit
LEV1	Log-Extreme Value Type I
LM	L-Moments
LN	Log-Normal
LN2	2 Parameter Log-Normal
LN3	3 Parameter Log-Normal
LP3	Log Pearson Type III
MAP	Mean Annual Precipitation
ML	Maximum Likelihood
MM	Method of Moments
MRM	Modified Rational Method
PDS	Partial Duration Series
PRM	Probabilistic Rational Method
PWM	Probability Weighted Moments
RFFA	Regional Flood Frequency Analysis
RLMA&SI	Regional Linear Moment Algorithm and Scale Invariance
RM	Rational Method
SANRAL	South African Roads Agency Limited

SCS	Soil Conservation Services
SDF	Standard Design Flood
Tc	Time of Concentration
USDA	United States Department of Agriculture

1. INTRODUCTION

Engineers rely on design hydrological information for the design of many hydraulic structures, such as bridges or culverts (Smithers and Schulze, 2003). This information is often estimated at ungauged sites using models to estimate flood frequencies (Schulze *et al.*, 2004). The over- or under-estimation of the design floods could lead to significant loss of resources, loss of lives or over design of a structure, which results in a waste of resources. Table 1.1 provides some statistics of damages caused by recent flooding events in South Africa.

Table 1.1 Social and monetary flood damages of recent flooding events

<table>
<tr><th>Year</th><th>Country</th><th>Region</th><th>Social Impacts</th><th>Estimated Damage</th><th>Source</th></tr>
<tr><td rowspan="3">2011</td><td rowspan="4">South Africa</td><td>Northern Cape</td><td></td><td>R50 Million</td><td rowspan="3">(Shiceka, 2011)</td></tr>
<tr><td>North West</td><td></td><td>R6 Million</td></tr>
<tr><td>KwaZulu-Natal</td><td></td><td>R300 Million</td></tr>
<tr><td>2008</td><td>Western Cape</td><td>20-22 thousand foreign nationals displaced, 2-4 killed and property damage</td><td>R1 Billion</td><td>(Holloway et al., 2010)</td></tr>
</table>

In 1985 it was estimated that the cost of projects involving the estimation of design floods for small to medium sized rural catchments averaged approximately \$250 million per annum in Australia. This was estimated to be the equivalent of \$600 million (approximately R4 billion) in 2009 (Rahman *et al.*, 2009).

Design Flood Estimation (DFE) techniques can be broadly categorised as analysis of streamflow data or rainfall based methods (Smithers and Schulze, 2003). Each of these categories have several techniques available for the estimation of design floods. Streamflow analysis uses statistics of previous floods, whereas rainfall based methods use design rainfall and rainfall-runoff models to estimate the design floods.

The most commonly used streamflow analysis technique is Flood Frequency Analysis (FFA). FFA fits a probability distribution to a set of peak flow events, the most common dataset used is the Annual Maximum Series (AMS) (Smithers and Schulze, 2003). It is however recommended to use Regional Flood Frequency Analysis (RFFA) rather than at-site, as it can be used to more reliably estimate flood peaks at ungauged sites (Smithers and Schulze, 2003).

RFFA has been adopted in both the UK and Australia (Pilgrim, 1989) as the preferred method. FFA is, however, data intensive and when the stringent data requirements are not met rainfall based techniques are used

Rainfall data sets are generally more abundantly available than flow data (Smithers and Schulze, 2003). This can be used as input to continuous simulation models, which produce a sequence of flood events which can be analysed using flood frequency analysis (FFA), otherwise these records can be analysed using FFA and the design rainfall determined. Design event techniques utilise design rainfall for flood determination and are classified as empirical, deterministic or probabilistic methods. Many of these approaches were developed approximately 40 years ago and require updating using data currently available and new approaches (Smithers and Schulze, 2003; Van der Spuy and Rademeyer, 2010).

Deterministic methods assume that using the T-year Average Recurrence Interval (ARI) design rainfall will produce the T-year ARI design flood. This assumption does, however, not hold true as there are several parameters which influence flood producing events, such as antecedent soil moisture, soil and land types (Gericke, 2010). Pilgrim (1989), Ben-Zvi (1989) and Alexander (2002b; a; 2003), to mention a few, have shown how several parameters in design flood estimation are dependent on the ARI of the event in question. Some examples of deterministic methods are the Rational Method (RM) (Mulvaney, 1850; cited by Stephenson, 1981; Shaw, 1994; Thompson, 2007), the Soil Conservation Services method (SCS) (United States. Department of Agriculture. Soil Conservation Service, 1986), the SCS-SA method (Schmidt and Schulze, 1987) and the Unit-Hydrograph method as developed by the Hydrological Research Unit (HRU) (1972). These methods, with the exclusion of the Unit-Hydrograph, are recommended for "smaller" catchments only, but Alexander (2002a) has shown that this is over-conservative in the instance of the RM.

Probabilistic methods, however, derive a link between the T-year design rainfall and the T-year flood. One example is the Probabilistic Rational Method (PRM) used in Australia (Pilgrim, 2001). In South Africa Alexander (2002a) developed the Standard Design Flood (SDF) method, which has been criticised as being over-conservative (Görgens, 2002) and has been recommended for review in several research documents (Smithers and Schulze, 2003; Van Bladeren, 2005; Gericke, 2010). These methods are not limited by catchment sizes and are recommended for large ranges of catchments.

The aim of the proposed study is the refinement, further development and assessment of a (PRM) for South Africa.

Pilgrim (1989) identified four requirements of a DFE model to ensure the selection of the best possible DFE approach. The procedure:

(a) needs to be based on observed flood data,
(b) needs to be simple, lack ambiguity and have familiarity in its application,
(c) should be probabilistic rather than deterministic, and
(d) should incorporate regional differences in hydrological responses.

Since 3 of the 4 above requirements relate to finalised, calibrated models such as the Australian Rainfall and Runoff (ARR) PRM (Pilgrim, 1989) the selection criteria for an appropriate model for this study was limited to point (b) above, i.e. "Needs to be simple, lack ambiguity and have familiarity in application". The remaining criteria will be fulfilled in the following study.

This document contains a literature review of the available DFE methods and the proposed methodology to achieve the aims of the study. Chapter 2 provides the literature review, which includes a review of the DFE methods, dilemma and subjective parameters respectively, and a brief review of FFA and rainfall based methods. The final two chapters (3 and 4) provide reviews of the RM and PRMs as currently used. Chapter 5 contains the discussion and conclusions followed by the proposed methodology in Chapter 6.

2. DESIGN FLOOD ESTIMATION

Design hydrological information is required when designing hydraulic structures such as bridges, dams and culverts. In this chapter the DFE techniques currently in use will be outlined and reviewed. Empirical and Flood envelope techniques are not within the scope of this document.

2.1 Methods

Smithers and Schulze (2003) provide a review of DFE techniques in South Africa, with reference to South African practice. The methods reviewed included FFA, flood envelopes, event based models (e.g. RM, SCS, unit hydrograph) and continuous simulation modelling. Figure 2.1 provides the classification of the techniques as described by Smithers and Schulze (2003).

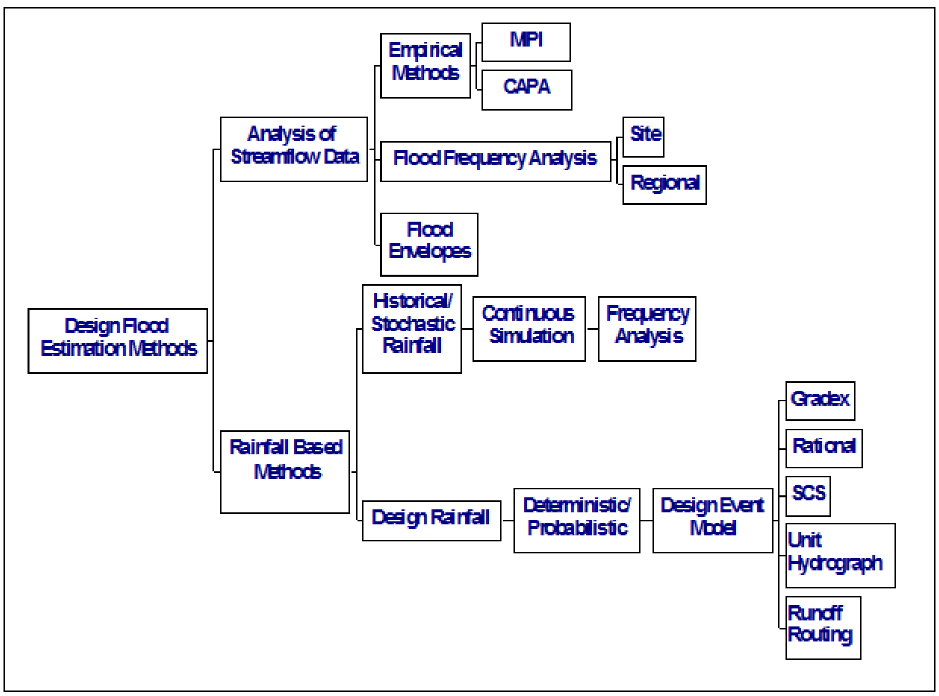


Figure 2.1 Design flood estimation methods (from Smithers and Schulze, 2003)

As shown in Figure 2.1, there are various techniques and models available for DFE. No single method has been identified as the most appropriate method and in many texts and manuals the use of a combination of these are recommended (Pilgrim and Cordery, 1993; Alexander, 2002a; Chadwick *et al.*, 2004; SANRAL, 2006, etc.). When the methods produce vastly different results, this poses the designers with the dilemma of which results to use.

2.2 Design Flood Estimation Using Streamflow Data

When streamflow data is available, FFA is often used to determine the design floods. FFA uses previous experience to estimate future events. At-site analysis uses statistical analysis of previously experienced events to estimate the design floods (Smithers and Schulze, 2003), whereas regional estimation attempts to find regions with similar hydrological responses to combine the past events and produce a Regional Flood Frequency Analysis (RFFA) for that region. RFFA is the preferred approach since it provides a more reliable method of estimating floods at ungauged sites (Smithers and Schulze, 2003). The designers dilemma, data requirements, at-site and regional approaches are briefly reviewed below.

2.2.1 Designer's dilemma

The "Designer's dilemma" was highlighted by Alexander (2002a) who describes the dilemma faced by many engineers when selecting data and techniques. This is illustrated by the example shown in Table 2.1.

Table 2.1. provides estimates of the 2, 50 and 200 year ARI flood event for two rivers (Sand and Breë) using the Log-Pearson Type III (LP3), General Extreme Value (GEV) and the Generalised Logistic (GL) probability distributions. The third "site" is also the Sand River, but includes the use of extended data, which includes extreme events which have occurred. When comparing the variation between the 50 year ARI and 200 year ARI floods for each site, it is evident that estimates can vary quite significantly between sites.

Furthermore when considering the two scenarios shown for the Sand River, the 50 year ARI: 200 year ARI ratio varies significantly at the same site. Not only do the ratios vary significantly, but the magnitudes of the 50 year ARI and 200 year ARI floods are trebled and quadrupled respectively.

Table 2.1 Comparison of the flood magnitude-frequency relationship in two rivers (after Alexander, 2002a)

Site	Distribution	ARI (Years)			50 yr ARI:200 yr ARI
		2	50	200	
Breë River at Ceres	LP3	362	856	1010	1.18
	GEV	357	827	990	1.20
	GL	352	890	1185	1.33
Sand River at Waterpoort 1969 - 1997	LP3	68	938	1517	1.62
	GEV	80	855	1753	2.05
	GL	71	880	2020	2.30
Sand River at Waterpoort 1958 - 2000	LP3	77	3544	9291	2.62
	GEV	115	2491	6743	2.71
	GL	71	2425	7304	3.01

In addition, the probability distribution also provides a variation of the results. The largest variation is shown at the last "site", where the 200 year ARI flood magnitude has a variation of approximately 2500 $m^3.s^{-1}$ dependent on the distribution chosen This variation with distribution was, however, not as significant at the Breë river, where the variation is approximately 200 $m^3.s^{-1}$.

It is therefore clear that the selection of distribution used, selected data and site location will play a crucial role in DFE and poses the designer with the dilemma of which results to use.

2.2.2 Data requirements

FFA requires the availability of long periods of data for accurate estimation of the frequency of long term flood events (i.e. 1:100 year event). It is not recommended for records shorter than 10 years and to estimate events with frequencies greater than twice the record length (Viessman *et al.*, 1989). Van der Spuy and Rademeyer (2010) listed some of the assumptions made when performing FFA:

(a) Each observation is independent and has no effect on the previous or following observation.
(b) The data are free of measurement errors.
(c) The data are identically distributed.

Another crucial assumption is the assumption that the data are stationary (Villarini *et al.*, 2009). Assuming that the data are stationary ignores effects such as climate change and urbanisation. If standard FFA methods are to be used the data therefore needs to undergo stationarity checks.

The data used for FFA can either be Annual Maximum Series (AMS) or a partial duration series (PDS) of peak discharges. The AMS data consists of the maximum recorded peak discharges for each year and it can be assumed that each of these observations is independent, hence fulfilling the above assumption (a) (Van der Spuy and Rademeyer, 2010). PDS datasets do, however, require further analysis to ensure the independence of each observation.

Datasets can contain many different types of errors, ranging from recording errors to hardware malfunction. Errors in the data will cause the FFA estimations to be inaccurate. Van der Spuy and Rademeyer (2010) recommend more in-depth checks when larger hydraulic structures are being designed.

2.2.3 At-site analysis

At-site FFA requires the fitting of a probability distribution to a series of peak events, either graphically or analytically (Basson and Pegram, 1994; Smithers and Schulze, 2000; Alexander, 2002b; Smithers and Schulze, 2003; SANRAL, 2006; Gericke, 2010; Van der Spuy and Rademeyer, 2010). In order to perform FFA the selection of the following aspects need to be considered:

(a) selection of an appropriate probability distribution,
(b) parameter estimation method,
(c) the use of natural or log-transformed data, and
(d) selection of plotting positions.

Smithers and Schulze (2000) highlight the fact that the selection of a probability distribution is particularly important when extrapolating and identifies the following distributions as the most commonly used in South Africa:

(a) GEV
(b) Extreme Value Type 1 (EV1)

(c) Log-Extreme Value Type 1 (LEV1)
(d) 2 and 3 parameter Log-Normal (LN2 and LN3)
(e) LP3

Gericke (2010) proposed that the best distributions for use in South Africa are the LN, LP3 and GEV or a combination of these. To use these methods, the parameters need to be estimated to fit the curves. Some of the methods available for this are the Method of Moments (MM), L-moments (LM), Probability Weighted Moments (PWM) and Maximum Likelihood procedure (ML). The parameter estimation method recommended by SANRAL (2006) is the MM and Alexander (2002b) recommends the use of the LP3 using MM (LP3/MM). Görgens (2007) used both the LP3/MM and GEV/PWM methods.

Log transformed data are often used to smooth the natural data and produce better graphical presentation of the results. The observed data are often plotted to provide a graphical representation of the distribution. The plotting positions recommended by DWA (Van der Spuy and Rademeyer, 2010) and SANRAL (2006) are the Weibull, Blom, Gringorten, Cunane, Beard and Greenwood methods. SANRAL (2006) describe these in further detail.

Beven (2003) identified the following limitations of statistical analysis:
(a) The selection of the seemingly correct distribution curve could be misleading as several curves could be considered acceptable, but produce large variations in the extrapolated design floods.
(b) Most gauging sites do not have robust calibration procedures or long periods of recorded data, which in turn implies that the sample only represents a small sub-set of the floods at the site which may further bias the errors.
(c) The changes in land use or rainfall characteristics are not taken into account.
(d) The statistical distributions will not take into account the changes in runoff generation processes for larger magnitude floods.

Smithers and Schulze (2003) noted that regional estimates often produce more reliable results and recommends further research into the development of a regionalisation technique in South Africa. This is further supported by Viessman *et al.* (1989) who noted that the record lengths are generally too short for at-site analysis and the use of records from hydrologically similar regions produce more accurate results.

2.2.4 Regional analysis

Regionalisation requires the identification of homogeneous flood-producing regions, where the data from several sites can be combined to produce a single, scaled distribution to be applied throughout the region by using site specific scaling factors. The process requires the selection of parameters to identify the different homogeneous regions. Some parameters which have been used are the Mean Annual Precipitation (MAP), Mean Annual Runoff (MAR), catchment area, DWA catchment, soil type, climate type and rainfall type (Pilgrim, 1989; Smithers and Schulze, 2000; Van Bladeren, 2005)

RFFA is the preferred method of analysis as it allows for the combination of shorter records to produce a single regional FFA curve. This allows for easier determination of the most appropriate distribution as well as reducing the extrapolation errors. Once the regionalised realtionships have been determined it enables the estimation of design floods at unguaged sites. Care must be taken to ensure methods are used within their specific geographical and data limits (Smithers and Schulze, 2003).

According to Hosking and Wallis (1997 cited by Chadwick *et al.*, 2004), the basic assumptions of RFFA are that the AMS's at each site are independent of each other, and the scaled data at each site can be described using the same probability distribution. Rao and Srinivas (2008) provide a review of methods used for regionalisation.

The above assumptions form the basis of RFFA. Mansell (2003) and Chadwick *et al.* (2004) provide a description of the RFFA method currently adopted by the UK Flood Estimation Handbook (FEH), which uses a regionalised index flood method.

In South Africa Alexander (2002a) presented a methodology for regionalisation based on the DWA drainage regions and climatic conditions. For the SDF Alexander (2002b) performed a subjective regionalisation. The method used has, however, been criticised by Smithers and Schulze (2003) and Van Bladeren (2005). Other attempts at regionalisation for floods in South Africa have been performed by Kovacs (1988) , Mkhandi (2000), Kjeldsen (2001) and Görgens (2007).

2.3 Design Flood Estimation in the Absence of Streamflow Data

Generally longer records of rainfall data are more widely available than streamflow and thus the estimation of design rainfall values are much easier to achieve (Rahman *et al.*, 1998; Smithers and Schulze, 2003). When FFA is not possible, rainfall based methods are used. The following sections review DFE methods available for use when streamflow data is not available.

2.3.1 Deterministic methods

Deterministic methods use design rainfall to estimate the design floods and they assume that the T-year design rainfall value will produce the T-year design flood. Ben-Zvi (1989), Pilgrim (1989) and Rahman (1998) highlight the fact that this assumption is frequenctly inaccurate as there are several other contributing factors to the design flood.

The most widely used rainfall based method for DFE in small to medium sized catchments is the RM (Hodgkins *et al.*, 2007), which was originally developed by Mulvaney (1850; cited by Stephenson, 1981; Shaw, 1994; Thompson, 2007). Kuichling (1889; cited by Stephenson, 1981) and Lloyd-Davies (1905; cited by Stephenson, 1981), who used the RM in sewer design have, however, also been credited with its development. The model is a deterministic design event model. Several modifications have been made to the RM in attempts to reduce the deterministic nature of the model and even to estimate the design hydrographs. These modifications range from the development of modified runoff coefficient tables (Caltrans, 2006; Kasserchun, 2008) to the development of probabilistic approaches to the use of the RM, such as the PRM (Pilgrim, 1989) and the SDF (Alexander, 2002a). Many texts recommend approximate maximum (15 km^2) and minimum catchment areas when applying the RM (Caltrans, 2006; SANRAL, 2006; Kasserchun, 2008). Pegram (2003) investigated the use of a Modified Rational Method (MRM).

The United States Soil Conservation Services (US-SCS) developed a method known as the SCS method (USDA, 1986). The SCS method was adapted for South African conditions by by Schmidt and Schulze (1987) and is named the SCS-SA method. This incorporated the development of regionalised relationships to take into account the impact of AMC on runoff, the joint association between rainfall and runoff, a lag equation and software for ease of application. The original SCS method does not estimate the hydrograph, but this has been included in the development of the SCS-SA method.

The Unit-Hydrograph (UH) method, unlike the RM and SCS method, estimates the hydrograph of the expected flood. The HRU (1972) as well as SANRAL (2006) describe the use of the UH method for catchment areas up to 5000 km^2. However, it must be noted that only 92 monitoring stations were used in the development for the whole of South Africa.

2.3.2 Probabilistic methods

Pilgrim (1989) and Smithers and Schulze (2003) recommend the use of probabilistic methods rather than deterministic methods for design flood estimation. Probabilistic methods derive relationships that directly link the rainfall and runoff of the same ARI.

Pilgrim (1989) developed the PRM, which has been included in the Australian guide for flood estimation (ARR) and become a widely recognised method for flood estimation in Australia.

In South Africa, the Standard Design Flood (SDF) method was developed by Alexander (2002a), but Görgens (2002) found that when estimating the 50 year floods the SDF estimates were equivalent to approximately 210 % of the LP3 FFA estimates. In the development, Alexander (2002a) does state that the factors derived, which could cause the over-estimation, are within the uncertainty levels. Smithers and Schulze (2003) expressed the need to assess the SDF method and provide further refinement. Gericke (2010) reviewed the SDF method and found that the SDF over-estimated design floods by up to 230 % in the Department of Water Affairs (DWA) C5 secondary drainage region. Van Bladeren (2005) proposed modifications to the SDF method, but in the C5 region these only provided improvements in 26% of the catchments assessed. Gericke (2010) also performed a calibration of the SDF method. The calibrated SDF (Gericke, 2010) provided the most accurate results in the majority of the study area and is described in further detail in Section 4.3. The calibrated SDF/probability distribution ratios ranged between 0.85 and 1.15, which is a major improvement on the standard SDF results. This highlights the need for a review of the SDF or a new approach to the implementation of the PRM in South Africa.

2.4 Catchment Parameters Used In Design Flood Estimation

Nearly all DFE methods require various catchment parameters to estimate the design floods. RFFA requires the determination of catchment with similar hydrological responses, which generally uses catchment parameters. Rainfall based methods often use catchment parameters to determine runoff coefficients and empirical methods incorporate the parameters. The estimation of some of these parameters are subjective and influence the results from these models. These parameters are briefly reviewed below.

2.4.1 Catchment slope (S)

The catchment slope refers to the average slope of the catchment and is often measured along the watercourse. There are several methods used for the estimation of catchment slope. The following 5 methods have been identified in literature (Gericke, 2010):

(a) 10-85: This method uses the change in elevation between the points 10% and 85% along the watercourse divided by the distance between these points.

(b) Equal area: A graphical method, whereby the average slope is estimated by balancing the area above and below the slope line.

(c) Grid/Areal Slope: This is a simple graphical method, whereby a large number of slope measurements at different points in a catchment are determined, and the final slope is the arithmetic average.

(d) Taylor-Schwarz (1952): This method uses the longest watercourse as an index to the sum of the distances between contours along the watercourse divided by the square root of the slopes between the contours.

(e) GIS techniques: Advances in GIS software allows users to estimate catchment slopes using various methods in GIS. These methods can involve highly detailed Digital Elevation Models (DEMs) and perform calculations at high speeds.

Rahman *et al.* (2009) deemed the 10-85 method as adequate and the simplest method to use, whereas the Taylor-Schwarz method is recommended by DWA (Van der Spuy and Rademeyer, 2010) due to it having a more scientific basis. Maidment *et al.* (2000) describe the processes involved in using GIS to estimate slopes. The four GIS methods used were the average terrain slope, average flow-path slope, average travel-distance slope and global slope. These methods produced varied results when compared to manually estimated slopes, with the global technique producing the most similar results. This was attributed to similar estimation methods. It was noted that all of the above methods can be considered viable.

2.4.2 Time of concentration

The time of concentration (*Tc*) refers to the time required for the entire catchment to be contributing to the flow at the catchment outlet. It has also been described as the time required for the most hydrologically remote area of a catchment to contribute to the catchment outfall (Young *et al.*, 2009). The *Tc* is a crucial element of rainfall based deterministic methods as it assumes that the peak flow occurs at the time when the storm duration equals *Tc* (Thompson, 2007). Hence the duration of design precipitation is estimated using *Tc*. Pilgrim (1989) also used the *Tc* to describe the expected regional variability.

Tc is often related to the slope and catchment length. This is evident in *Tc* estimation methods, such as the SCS (SANRAL, 2006), Kerby-Hathaway (Van der Spuy and Rademeyer, 2010) and Bransby Williams (Alexander, 2002a).

Another method for estimating *Tc*, is the use of a Lag time (L_T). L_T refers to the time interval between the centre of mass of the excess rainfall to the peak of the respective hydrograph. The SCS method uses the SCS lag equation, shown in equation 2.1 below:

$$L_T = \frac{l^{0.8}(S'+25.4)^{0.7}}{7069y^{0.5}} \tag{2.1}$$

where

L_T = lag time (h)

l = hydraulic length of catchment (m),

y = average catchment slope (%), and

$S' = \frac{25400}{CN-II} - 254$

with

CN-II = antecedent moisture condition retardance factor.

The Schmidt-Schulze lag equation (Schmidt and Schulze, 1984) was developed for use in South Africa with the SCS-SA method. A L_T also needs to be converted to *Tc* (Schulze *et al.*, 2004). This is achieved using Equation 2.2.

$$T_c = 0.6\ L_T \tag{2.2}$$

where

T_c = time of concentration (h), and

L_T = lag time (h).

Although the methods listed above are recommended for use in design manuals (SANRAL, 2006), they have not been updated/reviewed since development or assessed for use in South Africa.

In Australia, Pilgrim and McDermott (1982; cited by Pilgrim, 1989) and Flavell (1983; cited by Pilgrim, 1989) developed *Tc* estimation methods using observed floods for the New South Wales (NSW) region and south west of Western Australia (WA). These methods are area specific, which relate the *Tc* to the catchment area alone. This eliminated all subjective parameters often used in the estimation of *Tc*. Pilgrim (1989) noted that in a country such as Australia, one method to determine *Tc* throughout the entire country would not be adequate and that each region would require different methods or information to reproduce the design floods. Pilgrim (1989) also notes that the estimation of *Tc* is not crucial for calibrated models, only the need to reproduce the results achieved in the calibration process, as these results will be directly linked to the estimated design floods.

2.4.3 Design rainfall

For rainfall based methods, the estimation of the design rainfall is required. All design event models use design rainfall intensity (*I*) for a storm with a duration equal to *Tc* (SANRAL, 2006).

There are various databases and methods currently available in South Africa for the estimation of the design rainfall. Alexander (2003) and SANRAL (2006) recommend the use of TR102 (Adamson, 1981), which has been described by Smithers and Schulze (2003) as being outdated as it was developed 30 years ago. TR102 is a compilation of the South African Weather Service (SAWS) data up to 1981, which had FFA performed on the data. The data set consists of approximately 2500 stations and provides design rainfalls for events ranging from 1-7days. In DFE design rainfall is often required for shorter time periods and can be estimated using empirical equations such as the modified Hershfield equation.

Smithers (2000) developed a Regional Linear Moment Algorithm and Scale Invariance (RLMA&SI) method to estimate a minute by minute grid of short (≤24hr) and long term (1-7day) design rainfalls for South Africa. This involved the regionalisation of the data, by means of dividing the country into relatively homogenous rainfall regions. Two studies were completed before the development of the RLMA&SI, which focused on the long and short duration rainfalls.

The short and long term grids vary, due to differing regions and the number of stations used, using 412 and 11 200 stations respectively. 32% (+- 3600 stations) of the stations used in the long term grid estimation had records in excess of 25 years. However only 23% (+- 100 stations) of the stations used in the short term grid exceed record lengths of 20 years. This method used the most up to date data available at the time and has been updated for the eThekwini region (Smithers, 2002) and the Cape Town region (Smithers, 2010). The rainfall grid consists of a database and methodology to estimate design rainfall for durations ranging from 5 minutes to 7 days and for the 2 to 200 year ARI's. Gericke (2010) used the Smithers (2000) RLMA&SI technique for his study.

Both of the methods described above use a point based rainfall system. The RLMA&SI uses a regional approach and TR102 is based on analysis of at-site data. When dealing with larger catchments, a multitude of these points could be within the catchment. This poses designers with the problem of which design rainfall value use, or how to get an accurate average estimate. Gericke (2010) identifies three methods for the averaging of rainfall within a catchment:

(a) Arithmetic: The arithmetic average of the rainfalls experienced within the catchment, i.e. Average Rainfall = Sum of all Rainfalls / Number of stations or points considered.

(b) Thiesen polygons: A catchment is sub-divided between the points or stations located within it equidistantly and an area weighted average is used.

(c) Rainfall contours (isohyets): Similar to the Thiesen polygons the catchment is subdivided into regions based on rainfalls experienced at points or stations, but instead of using equidistant divisions the rainfall values are used to produce isohyets, which can then be averaged across the catchment.

These calculations can be performed using computer based GIS tools, but can also be performed manually. It must also be noted that since the Smithers (2003) minute by minute grid is a point rainfall database derived using a regional approach, the averaging thereof is not recommended (Gericke, 2010).

When considering larger catchments the variation of the precipitation across the catchment also affects the design rainfall. In these instances manuals such as the Roads Drainage Manual (SANRAL, 2006) recommend the use of Areal Reduction Factors (ARF). These factors reduce the point design rainfall to take into account the variation of rainfall across the catchment.

2.4.4 Runoff estimation

Runoff is estimated using various methods. In general the runoff is considered to be a function of the rainfall experienced within the catchment. Mulvaney (1850; cited by Thompson, 2007) proposed the use of a runoff coefficient (C) that is the ratio of total runoff depth to total precipitation depth. This relationship is shown in Equation 2.3.

$$C = \frac{R}{P} \tag{2.3}$$

where

C = runoff coefficient,

R = total runoff depth (mm), and

P = total precipitation depth (mm).

This was the relationship adapted for the RM. Mulvaney (1850) used catchments in Ireland to calibrate values of C and assumed that C did not vary for different storm events. There are several tables of C values available for use in design manuals (Caltrans, 2006; SANRAL, 2006; Kasserchun, 2008). These tables link the land use and catchment slopes to the estimated C values. The development of the Probabilistic Rational Method (PRM) both locally (Alexander, 2002a) and internationally (Ben-Zvi, 1989; Pilgrim, 1989) introduced the use of the C value to link the T-year ARI design rainfall to the T-year ARI design flood event.

The US-SCS (1986) developed the SCS method, which uses the SCS Curve Number (*CN*) as a runoff predictor. Similar to the RM there are CN tables in various text books, which can be used to estimate the runoff for various land use types (e.g. give examples). The curve number is not applied as simplistically as the RM's runoff coefficient. US-SCS (1986) provided Equation 2.4 to estimate peak discharge for the SCS method.

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{2.4}$$

where

Q = runoff (mm),

P = rainfall (mm),

S = potential maximum storage after runoff begins (mm), and

I_a = initial abstraction (mm),

S is a function of the curve number and is show in Equation 2.5 for SI units.

$$S = 25.4(\frac{1000}{CN} - 10) \tag{2.5}$$

The original proposed methodologies of the above methods assume that the C and CN are constant for each ARI. This has been proven to be an incorrect assumption and has been taken into consideration in many design handbooks and current texts (Pilgrim, 1989; Alexander, 2003; Schulze et al., 2004; Van der Spuy and Rademeyer, 2010).

Schmidt and Schulze (1987) adapted the SCS method for use in South Africa (SCS-SA). The *CN* tables were extended to take into account the diverse nature of South African soils and included the estimation of *CN* adjustments to take into account typical Antecedent Moisture Conditions (AMC) prior to large events. This was achieved adjusting the initial *CN* based on the analysis of the soil moisture simulated by the *ACRU* continuous model to determine the typical soil moisture conditions prior to large storms. In addition, a frequency analysis of the the peak discharge simulated by the *ACRU* model was performed to consider the joint probability of rainfall and runoof and thus the rainfall and runoff ARIs were linked for ARI up to 20 years (Schmidt and Schulze, 1987).

2.5 Conclusion

It is evident that there are a large number of methods and variables to consider when estimating the design floods, each of which have a varying effect on the final estimates.

Caution must therefore be taken when estimating the variables and a consistent methodology needs to be developed. The most appropriate method is the RM, since it has been used in various studies, is still widely used and is simple in its application.

3. REVIEW OF THE RATIONAL METHOD

The RM is still widely used despite having been developed over 150 years ago (Thompson, 2007). This chapter contains a review of the history and the use thereof in the South African context.

3.1 Background

The RM, originally developed by Mulvaney (1851; cited by Stephenson, 1981; Shaw, 1994; Thompson, 2007), is a deterministic method, which relies on subjective input. It is simple in its application and is widely recognised in the industry, where it is often used as a "check" (Pegram and Parak, 2004). The RM formula as shown in the eThekwini design manual (Kasserchun, 2008) is shown in Equation 3.1.

$$Q = U_F C I A R_F \tag{3.1}$$

where

Q = peak flow ($m^3.s^{-1}$),

C = runoff coefficient,

I = rainfall intensity ($mm.hr^{-1}$),

A = catchment area (m^2),

U_F = unit factor (1/3.6 or 0.278 for SI units), and

R_F = reduction factor.

The unit factor takes into account the use of either SI units or US customary units and the reduction factor was introduced at a later stage and is not used universally. The remaining parameters are explained in further detail in the following chapters.

When using the RM method there are 5 assumptions to be aware of (Haarhoff and Cassa, 2009):

(a) the rainfall intensity is considered to be constant throughout the rainfall event,

(b) the rainfall is distributed evenly across the entire catchment,

(c) the maximum flow occurs at the time when the entire catchment is contributing to the flow, i.e. when the duration of the rainfall event equals the time of concentration (*Tc*),

(d) the runoff coefficient does not change for different ARI or rainfall durations, and

(e) the ARI of the design rainfall is equal to the ARI of the design flood.

The applicability of these assumptions are often criticised and are discussed in the sections below.

3.2 Runoff Coefficient

The runoff coefficient (*C*) in the RM is described by Thompson (2007) as the ratio of total depth of runoff to the total depth of precipitation and, in its traditional use, varies between zero and one. This does not change the fact that it is one of the parameters which causes the biggest variations in design floods estimated using the RM (Smithers and Schulze, 2003). Parak (2007) identified that *C* is the least precisely defined parameter in the model.

There are several different sets of *C* estimation tables available for use both locally (SANRAL, 2006; Kasserchun, 2008; Van der Spuy and Rademeyer, 2010) and internationally (Caltrans, 2006). Use of the tables is the simplest form of using the RM. However the results are highly user dependant (Pilgrim and Cordery, 1993). Wilson (1990) noted that urbanisation increases *C* as the impervious surfaces, which were previously vegetated, result in a larger percentage of the rainfall forming runoff.

An important factor, which is widely overlooked, is the variation of the runoff coefficient as the average recurrence interval varies. As the rainfall intensity and volume increase the effect of the internal storage of catchments decrease, which leads to an increase in the runoff coefficient (Van der Spuy and Rademeyer, 2010). The SCS-SA method (Schmidt and Schulze, 1987) does take this into account by means of accounting for the AMC. Other methods that takes these effects into account are the RMs as proposed by the eThekwini Engineering Unit Design Manual (Kasserchun, 2008) and the DWA (Van der Spuy and Rademeyer, 2010). The eThekwini approach is to reduce the estimated design peaks, using the 100 year ARI storm as a basis. This thereby assumes the runoff production does not increase with ARI, but rather reduces from the 100 year ARI event. This factor is applied by simply applying the factor to the peak runoff. Table 3.1 provides the eThekwini factors.

Table 3.1: eThekwini ARI reduction factors

Probability of exceedance	100	50	20	10	5	2
ARI reduction factor	1.00	0.83	0.67	0.6	0.55	0.5

The DWA however assumes the opposite, i.e. the runoff coefficient is reduced for decrease in ARI. The DWA simply describes this factor as an "experience factor" (Van der Spuy and Rademeyer, 2010). This is applied using Equation 3.2 and Table 3.2 provides the range of *fr*.

$$C_1 = fr\ (C_Y + C_p + C_v) \tag{3.2}$$

where

fr = experience factor,

C_1 = rural runoff coefficient,

C_Y = steepness runoff coefficient,

C_p = permeability runoff coefficient, and

C_v = vegetation runoff coefficient.

Table 3.2: DWA experience factor (after Van der Spuy and Rademeyer, 2010)

Probability of exceedance	50	20	10	5	2	1	0.5
fr	0.32	0.50	0.61	0.71	0.83	0.92	1.00

3.3 Limitations

The Rational method does not estimate the flood volume, and only estimates the peak discharge (Haarhoff and Cassa, 2009). Cordery and Pilgrim (2000) noted that since the RM does not incorporate temporary storage or the effect of non-uniform rainfall intensity, its use is limited to urban and small rural catchments There has been some advancement in the development of new runoff coefficient tables and ARI factors, as is evident from the design manuals and texts available, but these do not adequately compensate for the variation of results between different users, regional differences, AMC, MAP, soils, etc. Furthermore, the assumption that the y-year ARI rainfall will produce the y-year ARI flood is not valid. Hence the development of a probabilistic method is recommended.

4. PROBABILISTIC RATIONAL METHOD

Two of the prominent PRM developments are the Australian PRM developed by Pilgrim (1989) and the SDF method in South Africa developed by Alexander (2002a). These methods are reviewed below.

4.1 Development

To develop the PRM the relationship between the runoff coefficient C_y and the remaining parameters needs to be defined for the Y-year ARI. This was achieved by using the following format of the RM, shown in Equation 4.1:

$$Q_y \quad = U_F C_y I_{(Tc,y)} A \tag{4.1}$$

where

Q_y = peak flow for ARI y,

C_y = runoff coefficient for return period y,

$I_{(Tc,y)}$ = rainfall intensity, which is a function of Tc and ARI y, and

U_F and A hold the same values as described in Equation 3.1.

By simple manipulation of Equation 4.1 it can be shown that the runoff coefficient C_y can be estimated using Equation 4.2.

$$C_y = Q_y / U_F A I_{(Tc,y)} \tag{4.2}$$

This relationship forms the basis of the PRM and is used for calibrating the model (Pilgrim, 1989). Pilgrim (1989) provides a visual representation of the above relationship, which is displayed in Figure 4.1.

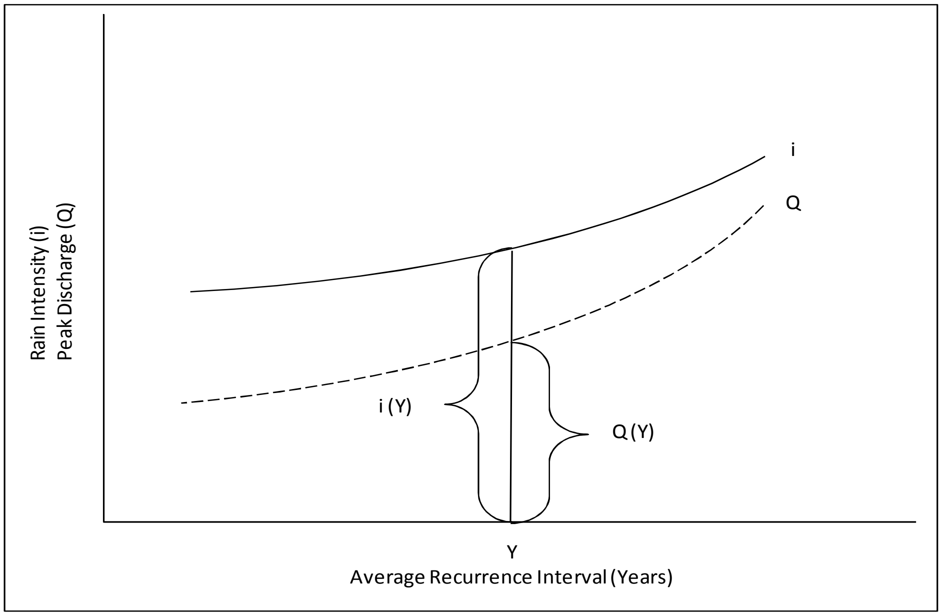


Figure 4.1 Frequency curves of rainfall and runoff for derivation of probabilistic runoff coefficients (from Pilgrim, 1989)

4.2 Australian Guidelines

Pilgrim (1989) describes how the ARR is considered "authoritative by all involved professionally with flood estimation and by the courts". In ARR the PRM, developed by Pilgrim (1989) for Australia, is recommended as the most appropriate method to use in 5 of the 9 identified regions in Australia (Pilgrim, 2001).

4.2.1 Rainfall

The PRM uses ARF curves developed for the USA, but are deemed viable for use in Australia. This was due to the fact that there has not been sufficient research into this topic for Australia (Pilgrim, 2001).

4.2.2 Regionalisation

The PRM follows Australian state boundaries to a large extent as the drainage basins and the flow data had been analysed by the different State Authorities (Pilgrim, 1989). Pilgrim (2001) does, however, express the desire to expand the analysis across these boundaries when the required data is available.

Three techniques were used for regionalisation in the development of the PRM (Pilgrim, 1989):

(a) A dimensionless flood frequency curve, with actual discharges, which is related through a reference discharge and regressions. It is described as being similar to the Index Flood Method (Dalrymple, 1950; 1960; cited by Pilgrim, 1989).
(b) A flood frequency curve similar to (a), but using frequency factors instead of actual discharges.
(c) Multiple regressions for each ARI, using the US Geological Survey (1986; cited by Pilgrim, 1989) approach.

Method (b) was used in the case where there was very little data in the western region of New South Wales (NSW) and involved the field estimates of bankfull flows. It was noted that the accuracy for this region will be lower (Pilgrim, 1989).

For eastern NSW a map of C_{10} contours, taking into consideration the MAP isohyets, short duration design rainfall intensities, topography, soil type and gauging reliability, were found to be an appropriate representation. In the Victoria region, C_{10} values were mapped with state wide frequency factors, and C_Y values applied across the regions of South Australia and the Northern Territory. For Western Australia the catchment variables of area, stream length, percentage clearing and elevation from outlet to stream source were significant in different relationships. However, a maximum of two of these variables were involved in the application of the PRM for these regions.

4.2.3 Regional variability

To estimate *Tc* the PRM uses equations derived by Pilgrim and McDermott (1982; cited by Pilgrim, 1989) for the New South Wales region and Flavell (1983; cited by Pilgrim, 1989) for the south west of Western Australia (WA). The equations are in the format shown in Equation 4.3, where V_1 and V_2 are regional constants:

$$Tc = V_1 A^{V_2} \tag{4.3}$$

These equations were used because they were derived using data from the different regions, hence fulfilling some of Pilgrim's (1989) requirements for DFE. Table 4.1 provides the regional constants for the different regions in Australia as found in ARR (Pilgrim, 2001).

Table 4.1: Regional constants used to estimate *Tc*

Region	V_1	V_2
South West of WA	2.31	0.54
Southern Australia	0.5	0.65
Eastern NSW, Victoria, WA	0.76	0.38
WA	0.56	0.38

In regions where these equations based on past data are not available, Pilgrim (2001) recommends the use of the Bransby-Williams formula.

4.3 Standard Design Flood Method

The Standard Design Flood (SDF) method was developed by Alexander (2002a) using 152 representative flow stations and subjective regionalisation based on extreme rainfall events. A series of maps were produced, which provide the required model parameters for different regions within South Africa. Currently the SANRAL Drainage Manual (2006) recommends the use of the SDF method in conjunction with other methods for DFE.

4.3.1 Rainfall

Alexander (2002a) states that the rainfall used in the development of the SDF method was not an important factor as the method links the design rainfalls to the design floods in the study. It is also crucial to use the same design rainfall in the calculation process thereafter. Alexander (2003) recommends the use of an ARF when using the SDF method.

Rainfall intensity was estimated using the modified Hershfield equation (Alexander, 2003) for durations up to six hours. For durations exceeding six hours, but less than 24 hours, the interpolation between the six hour Hershfield result and the 1-day TR102 (Adamson, 1981) values are recommended. Gericke (2010) describes the Hershfield equation as being inadequate, especially when relying on questionable parameters such as the number of days on which thunder was heard.

4.3.2 Data adjustments

Alexander (2002b) challenged the current use of extreme events in the estimation of design flood events. He raised concerns over the events that seem to occur more frequently than estimated when excluding these events from the calculations. Statistically these events could seem as extreme outliers and are often excluded from the analysis. Alexander (2002b) instead included these events into his statistical analysis as well as increasing the extreme low outliers to coincide with the lower ranges of a LN probability distribution.

4.3.3 Calibration

The SDF is a calibrated Rational Method for South Africa, which relies on the relationship between the estimated runoff coefficients for the 2 and 100-year ARI (C_2 and C_{100}). The calibration procedure was performed using design floods estimated using frequency analysis of flow data sets, and fitting a LP3 distribution curve to this data based on MM estimators (Alexander, 2002b; a). This analysis provided Alexander (2002a) with the estimated design floods for various catchments within South Africa.

4.3.4 Regionalisation

Gericke (2010) highlights the significance of the identification of representative, homogenous regions for the development of the SDF method. The SDF method uses a total of 29 drainage basins, which are based on the DWA drainage regions. These regions were also used as the basis the HRU surface water resources studies (Middleton *et al.*, 1981; Midgley *et al.*, 1994). The SDF regions are referred to as the SDF basins to avoid confusion between the SAWS precipitation districts and the DWA drainage regions (Alexander, 2002a; Gericke, 2010). Some of the drainage basins have been sub-divided further to take into account climatic differences in the regions. Van Bladeren (2005), however, expressed the need to further divide these regions. Gericke (2010) performed an analysis of the SDF method in the C5 DWA region at the DWA quaternary scale. This study produced more accurate results than both the original SDF methodology (Alexander, 2003) and the Van Bladeren (2005) modifications.

Alexander (2002a) used subjective adjustments to regionalise the calibrated *C*-values, these were also modified subjectively to be more conservative.

4.3.5 Regional variability

For each SDF basin Alexander (2002a) identified at least one representative flow and rain gauging station. Alexander (2003) provides the methodology for flood estimation using the SDF method. The recommended Tc estimation technique is the SCS lag equation, throughout the entire South Africa.

4.4 Comparison

To highlight the differences between the SDF method and PRM the following requirements as stated by Pilgrim (1989) are again brought to the attention of the reader. These can be found in Chapter 1 (Page 3)

In both instances the models are based on the observed flood data available at the time. It must, however, be noted that the methodology adapted by the SDF method did not follow standard procedures in practice. This is evident by the inclusion of high outliers and increase of low outliers, which would normally remain unchanged.

Both models use the same equation to estimate the design flood, which is simply the original rational method with ARI dependent variables.

4.5 Limitations

The SDF method has already taken into account a safety factor for each region, which eliminates the need for the engineer to adjust the results from the model. The designer is still encouraged to use his experience and other models in conjunction with the SDF to confirm the accuracy of the results (Alexander, 2002a; Van Bladeren, 2005).

Unlike the original RM, Alexander (2002) states that the SDF method is valid for catchments ranging from 10 to 40 000 km^2.

Van Bladeren (2005) identified that the SDF method over-estimated design floods in 11 of the basins, under-estimated the results in 5 basins and only had reasonable results in 8 of the basins. Gericke (2010), on the other hand concentrated on a smaller region, the DWA C5 region, where he identified that the SDF over-estimated results by up to 230%.

4.5.1 Recommended refinement

Smithers and Schulze (2003) recommend further investigation and refinement of the following aspects of the SDF:

(a) the use of outdated rainfall data (TR102),
(b) the subjective adjustments made to the runoff coefficient, and
(c) the method of regionalisation.

5. DISCUSSION AND CONCLUSIONS

Since there has been limited research into DFE in South Africa after the early 1970's, there is a need to update and developed new methods for DFE. The methods currently in use do not adequately comply with Pilgrim's (1989) requirements for the selection of an appropriate DFE method. To fulfil these requirements, a probabilistic method needs to be developed and is recommended by several studies.

Although the RM in its original and modified form is still widely used in industry, it has been recognised that the method produces widely varied results, which can be attributed to the subjective nature of some of the parameters. This limits the recommended catchment area for use.

The development of a probabilistic method derives the runoff coefficient utilises selected catchment parameters to link the y-year ARI rainfall event to the y-year ARI flood event, thus eliminating the need for runoff coefficient tables. The regionalisation would also identify hydrologically similar regions and apply the factors specific to each region, thereby taking into account the regional variation of the events. Internationally, the PRM approach has been successfully used in Australia and been included in the ARR, which is considered an authoritative text. This was achieved by the use of several regional parameters such as the T_c, rainfall characteristics and calibrated C values.

In South Africa the SDF method, which is also a PRM adaptation, has been shown to be inadequate in several regions in several studies, which confirms the need for the refinement, improvement or development of a new PRM for South Africa. The method was criticised for its over-estimation of design floods, regionalisation, recognition of regional variations and statistical analysis methods.

The regionalisation used in the development of the SDF method is described by Alexander (2002a) as being subjective, implying that this was based on Alexander's experience. These modifications can therefore vary between different developers and a more reliable method of regionalisation is required. As shown in Section 2.2.4, there are several methods available for the regionalisation of data. The success of RFFA is evident from the success of the Australian PRM (Pilgrim, 1989). A more statistical approach would therefore be recommended.

Due to the RM being widely used in industry, is simple to apply and its success as a probabilistic method internationally, it is the most appropriate method to apply for the study.

To conclude, the following needs to be considered for the development of a PRM in South Africa:

(a) streamflow data needs to be collected and assessed,
(b) catchment parameter estimation methods need to be selected, which would take into account regional variation as well as being reproducible,
(c) the RM needs to be calibrated at sites where appropriate data is available,
(d) the calibration needs to be regionalised, using a statistical method such as the index flood method, and
(e) the performance of the updated method needs to be assessed.

6. PROJECT PROPOSAL

This chapter will provide the methodologies selected for use from the literature review and provide a proposed work plan for the study.

6.1 Aims and Objectives

The aim of the project is to develop/refine a regionalised, probabilistic approach to the application of the RM of design flood estimation for South Africa. The first part of the study will concentrate on a single water management area as delineated by the DWA, to refine the methodology.

The objectives of the project include the following:

(a) To calibrate the Rational Method using observed data.
(b) To regionalise the application of the calibration results.
(c) To assess the performance of the refined probabilistic application of the Rational Method at ungauged sites.

The assessment of the SDF method is excluded from the scope of this study due to the existence of many references to short-comings and calls to review the method.

6.2 Proposed Methodology

The following sections will provide the proposed methodology to achieve the above stated aims and objectives.

6.2.1 Streamflow data collection and checking

Primary flow data will be obtained from reliable sources within South Africa, such as the DWA. This data will then be assessed in terms of both length and quality. In order to provide accurate results longer sets of data are required. Hence selecting a minimum record length could reduce the number of stations to use. The second criterion is the quality of the data. Data sets can have many quality errors ranging from user errors to technical errors. Some examples are the incorrect capture of data and hardware malfunction. The data will be tested for the following errors/criteria, followed by possible solutions:

(a) Records shorter than 10 years: Exclusion of site for at-site FFA.

(b) Negative/null records: Exclusion of erroneous data.

(c) "Over-topping": Possible extension of the rating tables, otherwise exclusion of erroneous data.

(d) Extreme outliers: A comparison analysis will be performed to assess the effect and possible exclusion.

6.2.2 Parameter estimation

Before being able to calibrate the model the methods for estimation of the following parameters need to be confirmed:

(a) Time of concentration: The final estimation method is still to be identified.

(b) Catchment slope: The catchment slope will be estimated using the 10-85 method.

(c) Design rainfall: A comparison test will be done between the use of arithmetic, Thiessen polygons, isohyets and the selection of an appropriate grid point from the Smithers and Schulze (2003) minute by minute grid. These results can be mapped using GIS to indicate the variation across regions.

6.2.3 Calibration of Rational Method at gauged sites

The frequency analysis will provide the design flood peaks to be used for the calibration of the RM at gauged sites. Calibration will be achieved by performing FFA on gauging weirs identified in Section 6.2.1 above. The selection of a probability distribution will depend on the best fit distribution and the the RM will be calibrated at the selected sites. The above methodology will provide a series of FFA curves and calibrated *C* values for gauged sites within South Africa.

6.2.4 Regionalisation of calibrations for application at ungauged sites

In order to regionalise the calibration performed in Section 3.2.3., catchments with similar hydrological responses will need to be identified. The initial delineation will attempt to link the Smithers (2000) rainfall clusters used for the development of the rainfall grid and the spatial distribution of the calibrated C values as well as the catchment area and MAP as recommended by Van Bladeren (2005). The entire process will follow the steps recommended by Roa and Srinivas (2008):

(a) attribute selection;
(b) feature preparation;
(c) formation of clusters;
(d) identifying initial regions;
(e) testing for homogeneity;
(f) adjustment of heterogeneous regions; and
(g) fitting suitable probability distribution using Goodness-of-fit (GOF) tests.

The regionalisation process will produce maps of the catchment regions and/or C value contours.

6.2.5 Assessment of performance of updated and refined method

A number of selected stations from the collected data will be "hidden" in the design flood estimation/regionalisation process and be used to verify the performance of the newly proposed probabilistic method. This will be achieved by comparing the FFA results to the PRM-SA results.

This will provide a series of graphs indicating the fit of FFA versus the PRM-SA results.

6.3 Resources

The resources required are listed below:

(a) MS Office software.
(b) Streamflow data from the Department of Water Affairs.
(c) Hydrological data from UKZN (Smithers and Schulze Rainfall Grid).

(d) GIS – UKZN licence.
(e) Statistical package – UKZN licence.

6.4 Project Plan

Please see Appendix A for a proposed working plan in the form of a gantt chart.

7. REFERENCES

Adamson, P. T. 1981. *Southern African storm rainfall*. Department of Environment Affairs. Pretoria, South Africa.

Alexander, W. J. R. 2002a. The Standard Design Flood - Theory and practice, http://www.up.ac.za/academic/civil/divisions/water/upflood.html, pp 12.

Alexander, W. J. R. 2002b. Statistical analysis of extreme floods, http://www.up.ac.za/academic/civil/divisions/water/upflood.html, pp 16.

Alexander, W. J. R. 2003. User Manual: The Standard Design Flood - a new design philosophy, http://www.up.ac.za/academic/civil/divisions/water/upflood.html, pp 22.

Basson, M. S. and Pegram, G. G. S. 1994. *Probabalistic management of water resource and hydropower systems*. Water Resources Publications. Highlands Ranch, Colo., USA.

Ben-Zvi, A. 1989. Toward a new Rational Method. *Journal of Hydraulic Engineering* 115 (9): 1241-1255.

Beven, K. J. 2003. *Rainfall-runoff modelling : the primer*. Wiley. Chichester, London, England.

Caltrans. 2006. Chapter 810: Hydrology. In: *Highway Design Manual*, California Department of Transport, California, USA.

Chadwick, A., Morfett, J. and Borthwick, M. 2004. *Hydraulics in civil and environmental engineering*. Spon. London, England.

Dalrymple, T. 1950. *Regional Flood Frequency*. Report No. 11-B. Highway Res. Board Res., USA.

Dalrymple, T. 1960. *Manual of hydrology: Part 3 Flood flow techniques. Flood frequency analyses.* Report No. 1543-A. US Geol. Survey Water Supply, USA.

Flavell, D. J. 1983. The Rational Method applied to small rural catchments in south west of Western Australia. In: ed.^eds. *Transactions, Institute of Engineers Australia*, Australia.

Gericke, O. J. 2010. Evaluation of the SDF method using a customised design flood estimation tool. Unpublished MScEng Thesis, Department of Civil Engineering, Stellenbosch University, Stellenbosch, RSA.

Görgens, A. H. M. 2002. Design flood hydrology. In: ed. Basson, G., *Design and rehabilitation of dams*, 460-524. Institute for Water and Environmental Engineering, Department of Civil Engineering, University of Stellenbosch, South Africa.

Görgens, A. H. M. 2007. *Modernised South African design flood practice in the context of dam safety*. Report No. 1420/2/07. Water Research Commission, Gezina, South Africa.

Haarhoff, J. and Cassa, A. M. 2009. *Introduction to flood hydrology*. Juta. Cape Town, South Africa.

Hodgkins, G. A., Hebson, C., Lombard, P. J. and Mann, A. 2007. *Comparison of peak-flow estimation methods for small drainage basins in Maine*. Report No. 2007–5170. U.S. Geological Survey, Maine, USA.

Holloway, A., Fortune, G. and Chasi, V. 2010. *Risk and development annual review: Western Cape*. Report No. University of Cape Town, Cape Town, South Africa.

HRU. 1972. *Design flood determination in South Africa*. University of the Witwatersrand, Department of Civil Engineering. Johannesburg, South Africa.

Kasserchun, R. 2008. *Design manual: Guidelines for the design of stormwater drainage and stormwater management systems*. Report No. Coastal Stormwater and Catchment Management Department, eThekwini Municipality, Durban, South Africa.

Kjeldsen, T. R., Smithers, J. C. and Schulze, R. E. 2001. Flood frequency analysis at ungauged sites in the KwaZulu-Natal province, South Africa. *Water SA* 27 (3).

Kovács, Z. P. 1988. *Regional maximum flood peaks in southern Africa*. Department of Water Affairs. Pretoria, South Africa.

Kuichling, E. 1889. The relationship between the rainfall and the discharge of sewers in populous areas. In: ed.^eds. *Transactions, ASCE*, 16.

Lloyd-Davies, R. E. 1906. The Elimination of Stormwater from Sewage Systems. In: ed.^eds. *Proceedings, Institute of Civil Engineers (GB)*, 7.

Maidment, D., Djokic, D. and ESRI. 2000. *Hydrologic and hydraulic modeling support with geographic information systems*. Environmental Systems Research Institute. Redlands, Calif., USA.

Mansell, M. G. 2003. *Rural and urban hydrology*. Thomas Telford. London, England.

McDermott, G. E. and Pilgrim, D. H. 1982. *Design flood estimation for small catchments in New South Wales*. Dept of Natl Development and Energy. Canberra, Australia.

Middleton, B. J., Pitman, W. V., Midgley, D. C. and University of the Witwatersrand. HRU. 1981. *Surface water resources of South Africa : volume II : Drainage region C : the Vaal basin*. University of the Witwatersrand. Hydrological Research Unit. Johannesburg, South Africa.

Midgley, D. C., Pitman, W. V. and Middleton, B. J. 1994. *Surface water resources of South Africa 1990*. Water Research Commission. Pretoria, South Africa.

Mkhandi, S. H., Kachroo, R. K. and Gunsdeksrs, A. G. 2000. Flood Frequency Analysis for Southern Africa: II. Identification of regional distributions. *Hydrological Sciences Journal* 45 (3): 449-464.

Mulvaney, T. J. 1850. On the use of self-registering rain and flood gauges in making observations on the relationship of rainfall and runoff and of flood discharges in a given catchment. In: ed.^eds. *Transactions, Institute of Civil Engineers (Ireland)*, 10.

Parak, M. 2007. Flood estimation for roads, bridges and dams. Unpublished MScEng Thesis, Department of Civil Engineering, University of KwaZulu-Natal, Durban, RSA.

Pegram, G. G. S. 2003. Rainfall, rational formula and regional maximum flood - Some scaling links. *Australian Journal of Water Resources* 7 (1): 29-39.

Pegram, G. G. S. and Parak, M. 2004. A review of the Regional Maximum Flood and Rational Formula using geomorphological information and observed floods. *Water SA* 30 (3): 16.

Pilgrim, D. H. 1989. Regional methods for estimation of design floods for small to medium sized drainage basins in Australia. In: ed.^eds. *Baltimore Symposium*, 14. Baltimore, USA.

Pilgrim, D. H. 2001. *Australian rainfall and runoff : a guide to flood estimation*. Institution of Engineers. Barton, A.C.T., Australia.

Pilgrim, D. H. and Cordery, I. 1993. Chapter 9: Flood Runoff. In: ed. Maidment, D. R., *Handbook of Hydrology*, McGraw-Hill, New York, USA.

Rahman, A., Haddad, K., Kuczera, G. and Weinmann, E. 2009. *Australian Rainfall and Runoff revision project 5: Regional flood methods (Stage 1)*. Report No. P5/SI/003. University of Western Sydney, Sydney, Australia.

Rahman, A., Hoang, T. M. T., Weinmann, E. and Laurenson, E. M. 1998. *Joint Probability Approaches to Design Flood Estimation: A Review*. Report No. Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Victoria, Australia.

Rao, A. R. and Srinivas, V. V. 2008. *Regionalization of watersheds : an approach based on cluster analysis*. Springer Science+Business Media B.V. Dordrecht, Netherlands.

SANRAL. 2006. *Drainage manual*. South African National Roads Agency Limited ;. Pretoria, South Africa.

Schmidt, E. J. and Schulze, R. E. 1984. *Improved estimates of peak flow rates using modified SCS lag equations*. University of Natal. Pietermaritzburg, South Africa.

Schmidt, E. J. and Schulze, R. E. 1987. *Flood volume and peak discharge from small catchments in Southern Africa, based on the SCS technique*. Water Research Commission. Pretoria, South Africa.

Schulze, R. E., Schmidt, E. J. and Smithers, J. C. 2004. *Visual SCS-SA user manual : PC-based SCS design flood estimates for small catchments in southern Africa*. University of KwaZulu-Natal. Pietermaritzburg, South Africa.

Shaw, E. M. 1994. *Hydrology in practice*. Chapman & Hall. London, England.

Shiceka, S. 2011. Media statement on the decalaratio of a national disaster as a reult of flooding and other natural disasters in the country. affairs, M. f. c. g. a. t., Pretoria, South Africa.

Smithers, J. C. 2002. *The estimation of design rainfall for Durban Unicity*. Report No. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, South Africa.

Smithers, J. C. 2010. *The Estimation of Design Rainfall for Cape Town Metro Area*. Report No. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Smithers, J. C. and Schulze, R. E. 2000. *Development and evaluation of techniques for estimating short duration design rainfall in South Africa*. Water Research Commission. Pretoria, South Africa.

Smithers, J. C. and Schulze, R. E. 2003. *Design rainfall and flood estimation in South Africa*. Water Research Commission. Gezina, South Africa.

Stephenson, D. 1981. *Stormwater hydrology and drainage*. Elsevier Scientific. Amsterdam, Netherlands.

Thompson, D. B. 2007. *The Rational Method*. Report No. R. O. Anderson Engineering, Minden, Nevada, USA.

United States. Department of Agriculture. Soil Conservation Service. 1986. *Urban hydrology for small watersheds*. Soil Conservation Service. Washington, D.C.

USDA. 1986. *Urban hydrology for small watersheds*. Soil Conservation Service. Washington, D.C., USA.

Van Bladeren, D. 2005. *Verification of the proposed Standard Design Flood (SDF)*. Report No. 344512/1. SRK Consulting (Pty) Ltd, Pretoria, South Africa.

Van der Spuy, D. and Rademeyer, P. F. (2010). Flood frequency estimation methods as applied in the Department of Water Affairs. Pretoria, South Africa, Department of Water Affairs.

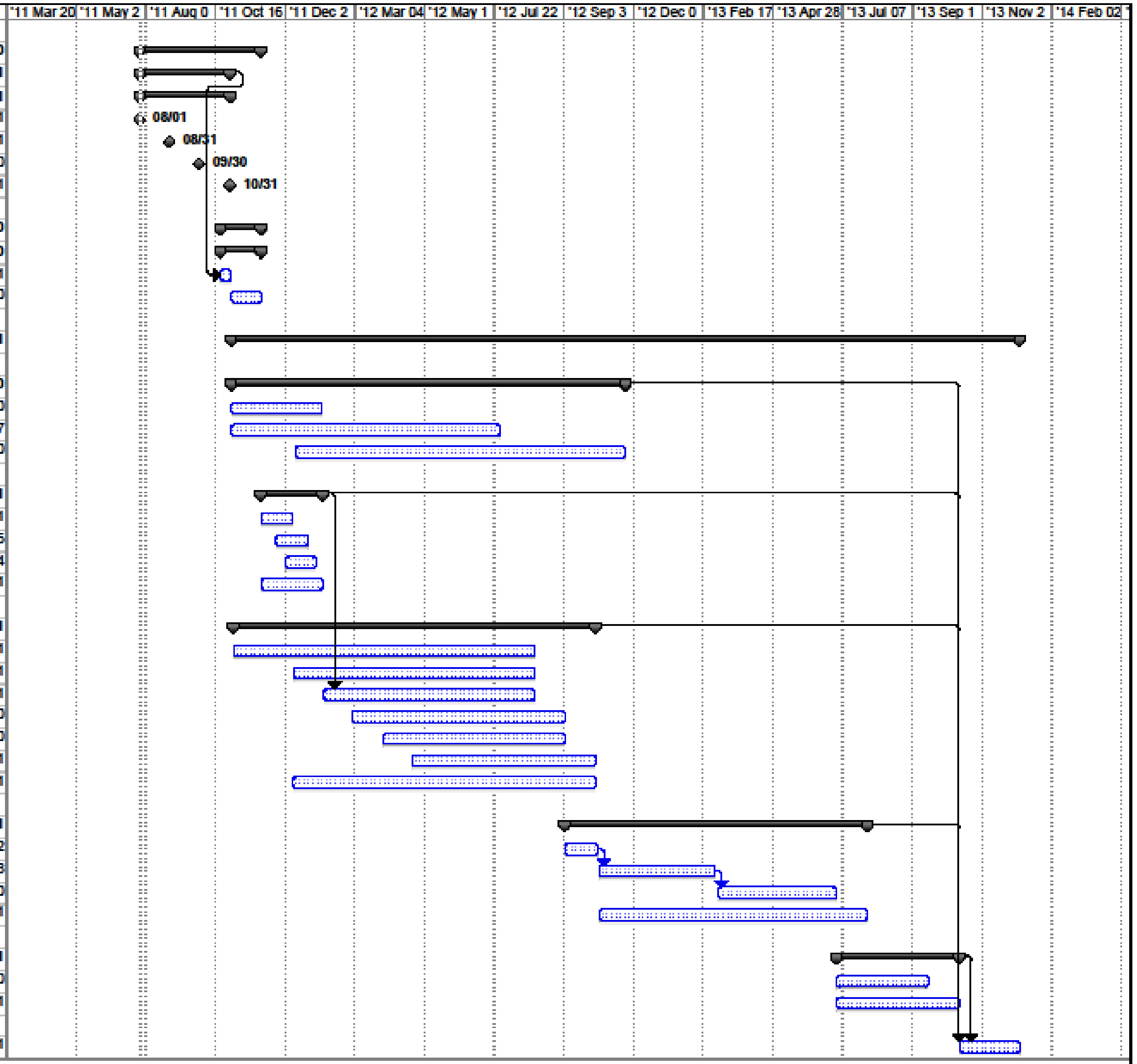
Viessman, W., Lewis, G. L. and Knapp, J. W. 1989. *Introduction to hydrology*. Harper & Row. Cambridge, USA.

Wilson, E. M. 1990. *Engineering hydrology*. Macmillan. Basingstoke, England.

Young, C. B., McEnroe, B. M. and Rome, A. 2009. Empirical determination of Rational Method runoff coefficients. *ASCE Journal of Hydrologic Engineering* 14 (12): 1061-1067.

APPENDIX A – PROPOSED WORKING PLAN

ID	Task Name	Duration	Start	Finish
1				
2	**Presentation**	**89 days?**	**Mon 11/08/01**	**Wed 11/11/30**
3	**Literature Review**	**66 days**	**Mon 11/08/01**	**Mon 11/10/31**
4	**Deadlines**	**66 days**	**Mon 11/08/01**	**Mon 11/10/31**
5	1st Draft Due	0 days	Mon 11/08/01	Mon 11/08/01
6	Final Document Due	0 days	Wed 11/08/31	Wed 11/08/31
7	Receive Corrections	0 days	Fri 11/09/30	Fri 11/09/30
8	Provide Corrected Version	0 days	Mon 11/10/31	Mon 11/10/31
9				
10	**Presentation**	**29 days?**	**Fri 11/10/21**	**Wed 11/11/30**
11	**Deadlines**	**29 days?**	**Fri 11/10/21**	**Wed 11/11/30**
12	Present to SRK	7 days	Fri 11/10/21	Mon 11/10/31
13	Presentation	22 days?	Tue 11/11/01	Wed 11/11/30
14				
15	**Project Plan**	**571 days?**	**Tue 11/11/01**	**Tue 13/12/31**
16				
17	**Streamflow data collection and checking**	**288 days?**	**Tue 11/11/01**	**Fri 12/11/30**
18	Data Collection	67 days?	Tue 11/11/01	Mon 12/01/30
19	Data Checking	197 days?	Tue 11/11/01	Fri 12/07/27
20	Reporting	241 days?	Wed 12/01/04	Fri 12/11/30
21				
22	**Design rainfall estimation**	**46 days?**	**Thu 11/12/01**	**Tue 12/01/31**
23	Performing calculations as per methodology	23 days?	Thu 11/12/01	Sun 12/01/01
24	Comparing estimated averages	24 days?	Fri 11/12/16	Mon 12/01/16
25	Map Production	24 days?	Mon 11/12/26	Tue 12/01/24
26	Reporting	46 days?	Thu 11/12/01	Tue 12/01/31
27				
28	**Calibration of Rational Method at gauged sites**	**264 days?**	**Thu 11/11/03**	**Wed 12/10/31**
29	Identification of Appropriate sites/gauging stations	220 days?	Thu 11/11/03	Fri 12/08/31
30	Flood Frequency Analysis	176 days?	Tue 12/01/03	Fri 12/08/31
31	Flood Estimation at sites using the original Rational Method	153 days?	Thu 12/02/02	Fri 12/08/31
32	Comparison of FFA and RM results	154 days?	Thu 12/03/01	Sun 12/09/30
33	At-site Calibration	131 days?	Mon 12/04/02	Sun 12/09/30
34	Map Production	133 days?	Tue 12/05/01	Wed 12/10/31
35	Reporting	221 days?	Mon 12/01/02	Wed 12/10/31
36				
37	**Regionalisation of Calibration**	**219 days?**	**Mon 12/10/01**	**Wed 13/07/31**
38	Identifying of regionalisation parameters	25 days?	Mon 12/10/01	Fri 12/11/02
39	Identifying Regions	84 days?	Mon 12/11/05	Thu 13/02/28
40	Regionalisation	86 days?	Mon 13/03/04	Sun 13/06/30
41	Reporting	194 days?	Mon 12/11/05	Wed 13/07/31
42				
43	**Refined Method Assessment**	**89 days?**	**Mon 13/07/01**	**Thu 13/10/31**
44	Comparison of FFA estimations to PRM-SA estimates	66 days?	Mon 13/07/01	Mon 13/09/30
45	Reporting	89 days?	Mon 13/07/01	Thu 13/10/31
46				
47	Compilation of final document	43 days?	Fri 13/11/01	Tue 13/12/31



Project: 205502158_MSc_Planning
Date: Tue 11/08/02

Task		Progress		Summary		External Tasks	
Split		Milestone		Project Summary		External MileTask	

Split