ESTIMATION OF CATCHMENT RESPONSE TIME FOR IMPROVED PEAK DISCHARGE ESTIMATION IN SOUTH AFRICA

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PROJECT PROPOSAL

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ABSTRACT

As much as 30% to 75% of the total error in peak discharge estimates at catchment scales can be ascribed to errors in the estimation of catchment response time. The overall objective of this study is to improve peak discharge estimates at a large catchment and/or regional level in South Africa by developing algorithms to estimate the catchment response time, since it has a significant influence on the resulting hydrograph shape and peak discharge. The algorithms will incorporate the most appropriate time variables and catchment storage effects into the regressed empirical time parameter equations. Chapter 1 provides some background on the estimation of catchment response time, followed by a literature review on the influence of variables on catchment response time (Chapter 2) and the nomenclature related to flow types, time variables and time parameters (Chapter 3). Chapter 4 contains a critical synthesis and discussion of the literature review conducted in Chapters 2 and 3 respectively. The research project proposal is included as Chapter 5, which covers the problem statement and purpose, aims, hypothesis, specific objectives and methodology of the study to investigate the problem statement. It is envisaged that this enhanced methodology to express the catchment response time will incorporate the most appropriate time variables and catchment storage effects into the regressed empirical time parameter algorithms to ultimately reduce uncertainty and improve accuracy of estimating the spatial and temporal distribution of runoff.

PREFACE

I, **Ockert Jacobus Gericke** declare that:

(a) The research reported in this project proposal, except where otherwise indicated, is my original work.

(b) This project proposal has not been submitted for any degree or examination at any other university.

(c) This project proposal does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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1. INTRODUCTION

This chapter provides some background on the estimation of catchment response time in terms of the two most frequently used time parameters, *i.e.* the time of concentration (T_C) and lag time (T_L), as well as the problems associated with the use of these time parameters, both at a catchment and regional scale. In conclusion, the layout of this document is summarised.

The estimation of design flood events, *i.e.* floods characterised by a specific magnitude-frequency relationship, at a particular site in a specific region is necessary for the planning, design and operation of civil engineering and related structures (Pegram and Parak, 2004). Both the spatial and temporal distributions of runoff, as well as the critical duration of flood producing rainfall are influenced by the catchment response time. However, due to the large variability in the flood response of catchments to storm rainfall, which is innately variable in its own right, failures of civil engineering and related structures occur regularly in South Africa (Alexander, 2002a). A given runoff volume may or may not represent a flood hazard or result in possible failure of a hydraulic structure, since hazard is reliant on the temporal distribution of runoff (Simas, 1996; McCuen, 2005).

Consequently, most hydrological analyses of rainfall and runoff, especially in ungauged catchments, require catchment response time parameters as primary input, since these parameters serve as indicators of both the catchment storage and the effect thereof on the temporal distribution of runoff. The catchment response time is also directly related to, and influenced by, climatological variables (*e.g.* meteorology and hydrology), catchment geomorphology, catchment variables (*e.g.* land cover, soils and storage), and channel geomorphology (Schmidt and Schulze, 1984; Royappen *et al.*, 2002; McCuen, 2005).

The most frequently used time parameters are the time of concentration (T_C) and lag time (T_L), which are normally defined in terms of the physical catchment characteristics and/or distribution of effective rainfall and direct runoff (USDA NRCS, 2010). The estimation of T_C and T_L can either be empirically or hydraulically-based (McCuen *et al.*, 1984; McCuen, 2005). In the empirical methods, these time parameters are related to the geomorphological and climatological parameters of a catchment using stepwise multiple regression analysis by taking both overland and main watercourse/channel flows into consideration (Kirpich, 1940; Watt and Chow, 1985; Papadakis and Kazan, 1987; Sabol, 1993). The hydraulically-based T_C estimates are limited to the overland flow regime, which is best presented by either the uniform flow theory or basic wave (dynamic and kinematic) mechanics (Heggen, 2003).

In South Africa, the hydraulic T_C estimates for overland flow are based on the Kerby equation, while the empirical United States Bureau of Reclamation (USBR) equation is used to estimate T_C as channel flow in a defined watercourse (SANRAL, 2006). The empirical estimates of T_L used in South Africa are limited to the family of equations developed by the Hydrological Research Unit, HRU (HRU, 1972); the United States Department of Agriculture Natural Resource Conservation Service, USDA NRCS, formerly the USDA Soil Conservation Service, SCS (USDA SCS, 1985) and SCS-SA (Schmidt and Schulze, 1984) equations.

The above-mentioned time parameter estimation methods are commonly used in South Africa, despite the fact that most of them have not been assessed using local data. In terms of the T_C estimates, both the Kerby and USBR methods were developed and calibrated in the United States of America (USA) for catchment areas less than 4 ha and 45 ha respectively. Both the HRU and SCS-SA T_L algorithms were locally developed and verified. However, the use of the HRU methodology is recommended for catchment areas less than 5 000 km², while the SCS-SA methodology is limited to small catchments (up to 30 km²). McCuen (2009), highlighted that, due to differences in the roughness and slope of catchments (overland flow) and main watercourses (channel flow), T_C estimates, such as those based on the USBR equation which considers only the main watercourse characteristics, are underestimated on average by 50%. Subsequently, the resulting peak discharges will be overestimated by between 30% and 50%. Bondelid *et al*. (1982) indicated that as much as 75% of the total error in peak discharge estimates could be ascribed to errors in the estimation of time parameters. In addition, McCuen (2005) highlighted that there is in general, no single time parameter estimation method that is superior to all other methods under the wide variety of climatological, geomorphological and hydrological response characteristics that are encountered in practice.

Therefore, the focus of this study will be on the problems associated with the accurate estimation of the spatial and temporal distribution of runoff by using suitable time parameters to accurately reflect the catchment response time. In essence, existing methods used to estimate catchment response time will be reviewed, after which the relationship between key climatological and geomorphological parameters influencing peak discharge and volume estimations at various catchment levels (*e.g.* small and large) in South Africa will be used to develop regionalised methods. It is anticipated that these methods will result in improved catchment response times that will provide more reliable peak discharge and volume estimates as, to date, this remains a constant challenge in flood hydrology (Cameron *et al.*, 1999).

In Chapters 2 and 3 a comprehensive literature review is presented. Chapter 2 contains a summary of the influence of various variables on the catchment response time, which in turn, has a direct influence on the volume, peak discharge and temporal distribution of runoff from a catchment. Typical variables, such as climatological variables, catchment geomorphology, catchment variables, and channel geomorphology are reviewed. Chapter 3 focuses on how these catchment variables are hydraulically or empirically related to the catchment response time in terms of the response time parameters, T_C and T_L. The applicability and theoretical basis of the various methodological approaches used internationally to estimate these two time parameters are also reviewed, while the relationship between time parameters and methods of regionalisation used in previous studies are discussed.

Chapter 4 contains a critical synthesis and discussion of the literature review conducted in Chapters 2 and 3 respectively. The research project proposal is included as Chapter 5, which covers the problem statement and purpose, aims, hypothesis and specific objectives of the study to investigate the stated problem. Chapter 5 also describes the proposed methodology to be used during this study and a work plan, time schedule, list of required equipment and resources are also included. In conclusion, intellectual property considerations and the expected outcomes, deliverables and contributions to new knowledge are also highlighted.

2. VARIABLES INFLUENCING CATCHMENT RESPONSE TIME

In order to understand the interaction between the different variables influencing the catchment response time and resulting runoff, it is necessary to view all the catchment processes in a conceptual framework, consisting of three parts: (i) the input, (ii) the transfer function, and (iii) the output (McCuen, 2005). Floods are generated in catchment areas in which runoff, resulting from rainfall, drains as streamflow towards a single outlet. Rainfall is the input. The catchment characteristics define the nature of the transfer function, since rainfall losses occur as the catchment experiences a change in storage while it absorbs (infiltration), retains or attenuates (surface depressions) and releases some of the rainfall through subsurface flows, groundwater seepage and evaporation. The effective rainfall exits the catchment as the streamflow output, *i.e.* the direct runoff contributing to flood peaks. However, runoff generation in catchments is highly variable both in time and space, depending not only on the amount and intensity of rainfall, but it is also affected by the different physiographical parameters, or combinations thereof, which describe the catchment characteristics (Beven *et al.*, 1988; Chow *et al.*, 1988; Pilgrim and Cordery, 1993; Alexander, 2001). The different variables which influence the catchment response time and resulting runoff include climatological variables, catchment geomorphology, catchment variables, and channel geomorphology, all of which play significant roles in catchment responses and are therefore be addressed in the rest of Chapter 2.

2.1 Climatological Variables

Climate does not only imply an effect on the spatial and temporal distribution of rainfall, but also implies rainfall intensity, duration and variability, which are all discussed in this section.

The spatial distribution of rainfall can have an influence on the shape of a hydrograph. Rainfall occurring mainly in the upper reaches of a catchment normally results in a longer catchment response time, lower peak discharges and longer hydrograph base lengths. On the other hand, high intensity rainfall falling near the catchment outlet results in a rapid catchment response time and a well defined peak, while the rising and recession hydrograph limbs have steep slopes. The areal reduction factor (ARF), which is the ratio of the maximum point rainfall to the average areal rainfall, can be used as an index of the spatial distribution of rainfall (Van der Spuy and Rademeyer, 2008). The temporal distribution of rainfall in a catchment is important in runoff generation as that rainfall which falls towards the end of a storm will generate more runoff than rainfall with the same intensity at the beginning of a storm. The temporal distribution is significant on small catchments where hydrographs are characterised by a rising limb followed by a relative flat peak, while the recession limb can be either concave or convex as a result of a decreasing or an increasing hyetograph respectively. In large catchments, hydrographs are relatively insensitive to the temporal distribution of rainfall (Alexander, 2001; Van der Spuy and Rademeyer, 2008).

2.2 Catchment Geomorphology

The geomorphological catchment characteristics which are most likely to influence the catchment response time, include area, shape, hydraulic length and average slope.

2.2.1 Catchment area

Wilson (1990) defined catchment area as the total land and water surface area contributing to runoff at a specific point or river cross-section and highlighted that every control point on a river reach has a unique contributing sub-catchment of its own, which increases in size as the control point moves downstream towards the catchment outlet. However, Parak (2003) distinguished between gross, effective and ineffective catchment areas and his definition of gross area is in agreement with that of Wilson's (1990), while the ineffective catchment area is defined as those areas from which runoff cannot reach the catchment outlet, *e.g.* pans and surface depressions. As a result, the effective catchment area is then basically defined as the difference between the gross and ineffective catchment areas. However, in cases where the capacity of the latter storage areas is exceeded and rainfall continues, the inflow equals the outflow, which subsequently contributes to the resulting runoff.

Catchment area is often identified in the literature as probably the single most important geomorphological variable which displays a strong correlation with many flood indices. Catchment areas influence both the time parameters describing the catchment response and the total volume of runoff as a result of catchment-wide rainfall (Ward and Robinson, 1999; Alexander, 2001; McCuen, 2005). In small catchments (< 10 km^2), the relationship between rainfall intensity and the infiltration rate of the soil are dominant, with the peak discharge approximately proportional to the area. In large, hydrologically homogeneous catchments, the quantity and distribution of rainfall relative to the attenuation of the resulting flood hydrograph as it moves towards the outlet is of importance, while the peak discharge tends to be proportionate to the square root of the area (SANRAL, 2006).

2.2.2 Catchment shape

Catchment shapes vary greatly and reflect the way in which runoff will be distributed, both in time and space. In wide, fan-shaped catchments the response time will be shorter with higher associated peak discharges as opposed to long, narrow catchments. In circular catchments with a homogeneous slope distribution, the runoff from various parts of the catchment reach the outlet more or less simultaneously, while an elliptical catchment equal in area with its outlet at one end of the major axis, would cause the runoff to be more distributed over time, thus resulting in smaller peak discharges compared to that of a circular catchment (McCuen, 2005). The temporal and spatial distribution of storms, rainfall intensity, density of stream patterns, bifurcation ratio and the critical storm duration are variables which will influence not only the flood peaks, but also the shape of flood hydrographs in different shaped catchments of the same area (Strahler, 1964; Alexander, 2001). Various catchment variables which reflect the catchment shape have been developed. The following are typical variables (Alexander, 2001; Parak, 2003; McCuen, 2005; Jena and Tiwari, 2006):

(a) **Catchment perimeter (*P*):** The distance measured along the catchment boundary;

(b) **Hydraulic length (L_H):** The distance measured along the longest watercourse from the catchment outlet to catchment boundary;

(c) **Centroid distance (L_C):** The distance measured along the main watercourse from the catchment outlet to the point on the main watercourse opposite the centre of area. According to Gericke (2010), the centroid distance is primarily influenced by the size and shape of the catchment, as well as the average catchment slope;

(d) **Shape parameter (F_S):** Normally expressed in terms of the ratio between the catchment area and various catchment length descriptors (Equations 2.1a-2.1c);

(e) **Circularity ratio (R_C):** Normally expressed in terms of the ratio between the catchment area and catchment perimeter (Equations 2.2a-2.2b). The use of these equations is sensitive to anomalous irregularities in the catchment boundary, while the catchment perimeter is also statistically dependent of the catchment area; and

(f) **Elongation ratio (R_E):** Normally expressed in terms of the ratio between the catchment area and the maximum catchment length parallel to the principle drainage line (Equation 2.3). According to Eagleson (1970; cited by Alexander, 2001), there is a strong correlation between the elongation ratio and the average catchment slope varying between unity (gentle slopes) and 0.6 to 0.8 (steep slopes).

$$F_{S1} = \left(L_H L_C\right)^{0.3} \quad (2.1a)$$

$$F_{S2} = \frac{{L_S}^2}{A} \quad (2.1b)$$

$$F_{S3} = \frac{L_M}{\sqrt{A}} \quad (2.1c)$$

$$R_{C1} = \frac{P}{\left(4\pi A\right)^{0.5}} \quad (2.2a)$$

$$R_{C2} = \frac{A}{A_C} \quad (2.2b)$$

$$R_E = \frac{2}{L_M}\left(\frac{A}{\pi}\right)^{0.5} \quad (2.3)$$

where:

A = catchment area [km²],

A_C = area of circle with a perimeter equal to the catchment perimeter [km²],

F_{S1-3} = shape parameters,

L_C = centroid distance [km],

L_H = hydraulic length of catchment [km],

L_M = maximum catchment length parallel to the principle drainage line [km],

L_S = maximum straight-line catchment length (boundary to outlet) [km],

P = catchment perimeter [km],

$R_{C1,2}$ = circularity ratios, and

R_E = elongation ratio.

2.2.3 Catchment hydraulic length

The hydraulic length (L_H), which correlates highly with the main watercourse length, is important in catchment response time parameter estimations (McCuen, 2005). Based on the definition provided in Section 2.2.2 it is clearly evident that the hydraulic length consists of both the main watercourse length and the distance from the start of permanent streams (fingertip tributaries) to the catchment boundary where the maximum volume of water would travel.

2.2.4 Average catchment slope

The correlation between the average catchment and main watercourse slopes is normally good (Alexander, 2001). Slopes, whether gentle or steep, influence the catchment response time and hence the duration of critical rainfall intensity and resulting peak discharges and volumes (Alexander, 2001). The average catchment slope (S) can be determined by using the following methods: (i) Grid method (Equation 2.4; Alexander, 2001), (ii) Empirical method (Equation 2.5; Schulze *et al.*, 1992), and (iii) Neighbourhood method (Equation 2.6; ESRI, 2006). The latter method is also known as the average maximum technique, which is included as a standard functional extension tool in the ArcGIS™ environment. Digital Elevation Models (DEMs) and Geographical Information System (GIS) data are used as the primary input to this method. Typically, in a 3 x 3 search window (grid network with nine cells, C_1 to C_9), eight grid points from the surrounding cells are used to calculate the average slope of the central cell (C_5) using unequal weighting coefficients, which are proportional to the reciprocal of the square of the distance from the kernel centre (Jones, 1998; ESRI, 2006).

$$S_1 = \frac{\Delta H}{\sum_{i=1}^{N} \frac{L_i}{N}} \tag{2.4}$$

$$S_2 = \frac{M \Delta H * 10^{-2}}{A} \tag{2.5}$$

$$S_3 = \sqrt{\left(\frac{\Delta z}{\Delta x}\right)^2 + \left(\frac{\Delta z}{\Delta y}\right)^2} \tag{2.6}$$

where:

S_{1-3} = average catchment slope [m.m^{-1}],

A = catchment area [km²],

$\frac{\Delta z}{\Delta x}$ = rate of change of the slope surface in a horizontal direction from C_5 (centre cell),

$$= \left[\frac{(C_3 + 2C_6 + C_9) - (C_1 + 2C_4 + C_7)}{(N\, x_C)} \right]$$

$\frac{\Delta z}{\Delta y}$ = rate of change of the slope surface in a vertical direction from C_5 (centre cell),

$$= \left[\frac{(C_7 + 2C_8 + C_9) - (C_1 + 2C_2 + C_3)}{(N\, y_C)} \right]$$

$C_{1\text{-}4/\,6\text{-}9}$ = surrounding cells,

C_5 = centre cell,

ΔH = contour interval [m],

L_i = horizontal distance between consecutive contours [m],

M = total length of all contour lines within the catchment [m],

N = number of grid points or cells,

x_C = horizontal cell size, and

y_C = vertical cell size.

2.3 Catchment Variables

Catchment variables that influence catchment response times include land cover, soil characteristics, and storage and reservoirs.

2.3.1 Land cover

Changes in land use can have local, regional and global hydrological consequences. On a global scale, afforestation, deforestation, agricultural intensification, wetland drainage and urbanisation are considered to be the significant changes in land use, both in terms of spatial extent and hydrological impact on annual and seasonal flows, floods, erosion and water quality (Calder, 1993; Ward and Robinson, 1999).

At a catchment level, the nature and spatial distribution of main land-use groups can also significantly affect runoff characteristics such as volume, peak and temporal distribution. Rural catchments are mainly characterised by pervious land uses, while impervious areas normally dominate in urban catchments. Studies have reported that urbanisation can result in increases in flood peaks ranging from 20 to 50%, and high-density industrial urbanisation can result in increases of 100% (SANRAL, 2006). Ward and Robinson (1999) confirmed that urbanisation increased flood peaks in northern Virginia, USA, by between 200 and 800% and between 100 and 300% in Texas, USA. However, this is only the case when no attenuation of flood peaks and runoff occur by means of obstructions (walls and fences), ponds, recreational areas, parks and open spaces.

Hood *et al.* (2007) compared the catchment response time characteristics in terms of T_L in catchments with low impact residential development and traditional residential development respectively. It was established that low impact development resulted in lower peak discharge depths, runoff coefficients and runoff volume, while the lag times and runoff threshold values increased in comparison to traditional residential development.

The influence of natural vegetation on discharges and volumes depends on the climatic region in which a particular catchment is situated. In humid regions, the effect of vegetal cover does not vary significantly between seasons, while vegetal cover in semi-arid regions can vary appreciably both seasonally and annually, thereby introducing more variability in the magnitude, timing and distribution of runoff (Alexander, 2001).

2.3.2 Soil characteristics

Soil texture and structure influence the vertical and lateral movement of water through the soil profile, *i.e.* the infiltration and percolation capacity which, in turn, affect the volume of direct or surface runoff (McCuen, 2005). The antecedent soil moisture status of a catchment is acknowledged as the most important determinant of the conversion of rainfall to runoff and provides an indication of the soil's initial infiltration rate. Soils are initially dry or more permeable with a resulting higher rate of infiltration, which decreases over a period due to saturation, with most of the effective rainfall and associated direct runoff being produced after saturation. Any changes in the antecedent soil moisture status will result in significant changes in peak discharges and volumes (Alexander, 2001).

2.3.3 Storage and reservoirs

Storage in a catchment occurs as detention storage, *e.g.* storage in overland flow (influenced by surface roughness), main watercourse flow, pans, lakes and marshes, and storage affects the attenuation and translation of flood peaks. Reservoirs act as surface water stores which can intercept and attenuate large volumes of runoff with hydrographs attenuated and translated (lagged) by the storage (SANRAL, 2006).

2.4 Channel Geomorphology

The most important geomorphological channel characteristics which are most likely to influence the catchment response time are the main watercourse length and average slope, main watercourse cross-sections and roughness, and drainage density.

2.4.1 Main watercourse length and average slope

The main watercourse length (L_{CH}) is defined as the distance measured along the main channel from the catchment outlet to the start of the channel (fingertip tributary) near the catchment boundary. This distance can be measured relatively accurately on topographical maps, although the use of standard functions in the ArcGIS™ environment is recommended (Gericke, 2010). The average main watercourse slope can be determined by using the following methods: (i) Equal-area method (Equation 2.7), (ii) 10-85 method (Equation 2.8), and (iii) Taylor-Schwarz method (Equation 2.9) (Alexander, 2001; McCuen, 2005; Van der Spuy and Rademeyer, 2008).

$$S_{CH1} = \frac{(H_T - H_B)}{L_{CH}} \tag{2.7}$$

$$S_{CH2} = \frac{(H_{0.85L_{CH}} - H_{0.10L_{CH}})}{(0.75L_{CH})} \tag{2.8}$$

$$S_{CH3} = \left(\frac{L_{CH}}{\sum_{i=1}^{N} \frac{L_i}{\sqrt{S_i}}} \right)^2 \tag{2.9}$$

where:

S_{CH1-3} = average main watercourse slope [m.m^{-1}],

$A_i = \left(\frac{H_i + H_{i+1}}{2} - H_B \right) L_i$ [m²],

$H_T = \frac{\left(\sum_{i=1}^{N} A_i * 2 \right)}{L_{CH}} + H_B$ [m],

H_B = height at catchment outlet [m],

H_i = specific contour interval height [m],

$H_{0.85L}$ = height of main watercourse at length $0.85L_{CH}$ [m],

$H_{0.10L}$ = height of main watercourse at length $0.10L_{CH}$ [m],

L_{CH} = length of main watercourse [m],

L_i = distance between two consecutive contours [m], and

S_i = slope between two consecutive contours [$m.m^{-1}$].

2.4.2 Main watercourse cross-sections and roughness

The main watercourse cross-sections and roughness, as well as the catchment roughness characteristics, are important in hydrological analyses and hydraulic design. Cross-sectional characteristics of importance are the area, wetted perimeter, longitudinal slope and roughness. Channel instability, erosion and developmental processes continually change the geometry of cross-sections and must therefore be accounted for in any discharge-head relationship. Surface roughness affects the velocity and hence the temporal and spatial distribution of runoff, whether overland or channel flows are concerned. In the case of overland flow, an increase in surface roughness will result in flow retardation and subsequently higher potential infiltration rates. An increased roughness in channels will result in lower velocities, deeper flow depths and higher associated flood levels and a possible reduction in erosion or sediment transport (McCuen, 2005).

2.4.3 Drainage density

Drainage density (*D*), which is defined as the ratio of the total length of watercourses within a catchment to the catchment area, can have a marked effect on the discharge. In well drained catchments a larger proportion of the rainfall (effective rainfall) will contribute to direct runoff, while the catchment response time will be comparatively short resulting in steeper rising hydrographs, than in catchments characterised by many surface depressions, marsh ground and minor lakes (Strahler, 1964; McCuen, 2005).

Chapter 3 which follows will address the nomenclature related to flow types, time variables and time parameters respectively.

3. CLASSIFICATION OF FLOWS, TIME VARIABLES AND PARAMETERS

In Chapter 3 the focus is on how the influence of the catchment variables discussed in Chapter 2 are either hydraulically or empirically related to the catchment response time in terms of the response time parameters: T_C and T_L. Since these time parameters are associated with specific flow regimes and time variables acting as transfer functions, the classification of the different flow types is discussed first. In the sections to follow, the conceptual and computational definitions of all the time variables and parameters are highlighted, after which the applicability and theoretical basis of the various methodological approaches used internationally to estimate time parameters are reviewed. In conclusion, the relationship between the various time parameters and regionalisation of the time parameters are discussed.

3.1 Classification of Flows

Rainfall that reaches the earth's surface on a catchment can be separated into three time dependent functions: (i) initial abstractions (I_A), (ii) the loss function, and (iii) the effective or excess rainfall. I_A is that part of the rainfall that occurs prior to the commencement of direct runoff and collectively refers to insignificant losses such as interception, evaporation during rainfall, depression storage and the initial/base-index infiltration. In South Africa, Schmidt and Schulze (1984; 1987) found empirically that I_A can be approximated by 15% of the potential maximum soil water retention (S_R), but recommended 10% for design purposes (based on fieldwork). The loss function refers to the portion of rainfall that occurs after the start of direct runoff, but does not appear as direct runoff, due to medium to long term interception, depression, infiltration and soil storages (McCuen, 2005). Effective rainfall is the component of the rainfall which is neither retained on the land surface, nor infiltrated into the soil and which becomes direct runoff under the assumption of Hortonian overland flow. In other words, the volume of effective rainfall equals the volume of direct runoff (Chow *et al.*, 1988).

The net amount of water that contributes to total runoff can follow a combination of different flow paths to reach the catchment outlet and may include the following:

(a) **Surface flow:** This occurs either as a result of rainfall restricted to watercourse and open water surface areas, overland flow, main watercourse/channel flow and/or as a combination thereof. Overland flow occurs either as Hortonian or saturated overland flow. Hortonian overland flow is produced when the rainfall intensity exceeds the infiltrability of soil until saturation is reached, while saturated overland flow is produced by rainfall on already saturated areas near main watercourses and valleys (Royappen *et al.*, 2002). In the case of sheet overland flow the flow depths are of the same order of magnitude as the surface resistance (roughness parameters). At some point in the upper reaches of a catchment, sheet flow will transition to shallow concentrated flow characterised by well-defined gullies and flow depths exceeding the flow resistance heights. The transition point between sheet and concentrated flow is characterised by the presence of continuous surface depression stores collecting sheet flow from radial directions (Ward and Robinson, 1999; Seybert, 2006).

The commencement of channel or main watercourse flow in a catchment is typically defined at a point where a regular, well-defined channel exists with either perennial or intermittent flow. The travel time for flow in defined watercourses or channels can be hydraulically estimated by making use of either Manning's or Chézy's equations based on average velocities and channel slopes or by using site-specific or regionalised empirical estimates of the travel time (Seybert, 2006).

(b) **Subsurface and lateral flow:** This is defined as the sum of throughflow, transmissive return flows and interflow (rapid lateral flow). Throughflow is generated by the rapid infiltration of rainfall into soil, which results in an increased soil moisture status and associated hydraulic conductivity. Transmissive return flows occur when the water table rises into more transmissive layers with a lateral flux of water due to rapid subsurface flows (Pilgrim and Cordery, 1993; Ward and Robinson, 1999; Royappen *et al.*, 2002).

Interflow (rapid lateral flow) can occur through pipes and macropores, or along an interface between soil horizons. According to Hickson (2000; cited by Royappen *et al.*, 2002), interflow through pipes, macropores and surface cracks can account for up to 90% of water flowing into the soil. Both pipes and macropores have a direct influence on the distribution and storage of infiltrated water in the soil profile.

(c) **Baseflow:** Baseflow can be defined as sustained base runoff and consists of groundwater movement and delayed throughflow. In essence, baseflow is that portion of infiltrated water that reaches the saturation zone at the water table and then percolates laterally through saturated aquifers to be discharged into a main watercourse at seepages or springs (Royappen *et al.*, 2002). Both graphical and recursive filtering methods have been proposed to separate direct runoff and baseflow. The selection or preference for any method will depend on the type and amount of observed data available versus required accuracy of the design problem and time constraints. Arnold *et al.* (1995), highlighted that the graphical methods often fail to accurately describe water movement over time in a catchment for the multitude of rainfall events and antecedent soil moisture conditions that can occur. According to Tan *et al.* (2009), the use of graphical methods must be restricted to single-peaked and isolated hydrographs.

The flow types (a) to (c) were considered explicitly to highlight and describe the direct influence thereof on the time parameters used to express the catchment response time.

3.2 Classification of Time Variables and Parameters

In this section a distinction will be made between time variables and time parameters.

3.2.1 Time variables

Time variables can be estimated from the spatial and temporal distributions of rainfall hyetographs and total runoff hydrographs. In order to estimate these time variables, hydrograph analyses based on the separation of: (i) total runoff hydrographs into direct runoff and baseflow, (ii) rainfall hyetographs into initial abstraction, losses and effective rainfall, and (iii) the identification of the transfer function (*c.f.* Chapter 2) are required. A convolution process is used to transform the effective rainfall into direct runoff through a synthetic transfer function based on the principle of linear super-positioning, *e.g.* multiplication, translation and addition (Chow *et al.*, 1988; McCuen, 2005).

The effective rainfall hyetographs can be estimated from rainfall hyetographs in one of two different ways, depending on whether observed streamflow data are available or not. In cases where both observed rainfall and streamflow data are available, index methods such as the: (i) Phi-index method (phi-index equals the average rainfall intensity above which the effective rainfall depth equals the direct runoff depth), and (ii) constant-percentage method (losses are proportional to the rainfall intensity and the effective rainfall equals the direct runoff depth) can be used (McCuen, 2005). However, in ungauged catchments, the separation of rainfall losses must be based on infiltration methods, which account for infiltration and other losses separately. The SCS runoff curve number method is internationally the most widely used (Chow *et al.*, 1988).

In the literature, various researchers (McCuen *et al*., 1984; Schmidt and Schulze, 1984; Simas, 1996; McCuen, 2005; Jena and Tiwari, 2006; Hood *et al*., 2007; Fang *et al*., 2008; McCuen, 2009) have used the differences between the pair values of time variables to define two distinctive time parameters: T_C and T_L. Apart from these two time parameters, other time parameters such as the time to peak (T_P) and hydrograph time base (T_B) are also frequently used. In general, time variables obtained from hyetographs include the peak rainfall intensity, the centroid of effective rainfall and the end time of the rainfall. Hydrograph-based time variables generally include peak discharges of observed surface runoff, the centroid of direct runoff and the inflection point on the recession limb of a hydrograph (McCuen, 2009).

3.2.2 Time parameters

Most hydrological flood-related designs require at least one time parameter as input, whether T_C or T_L is concerned. In the previous section it was highlighted that time parameters are based on the difference between two time variables, each respectively obtained from a hyetograph and hydrograph. In practice, these time parameters have multiple conceptual and/or computational definitions, and T_L is sometimes expressed in terms of T_C. In the following sections the conceptual and computational definitions of T_C and T_L will be highlighted, while the various hydraulic and empirical estimation methods currently in use and their interdependency, as well as any previous attempts to regionalise these time parameters will be reviewed. A total of five hydraulic and 44 empirical time parameter (T_C, T_L and T_P) estimation methods were found in the literature and evaluated accordingly. Based on the outcome of this evaluation, only 15 (7 T_C and 8 T_L) methods are included in Sections 3.3 and 3.4. As far as possible, an effort was made to present all the equations in Système International d'Unités (SI Units); otherwise the format (units) of the equations as published by the original authors, was retained. Therefore, some of the equations listed in Sections 3.3 and 3.4 may have different units.

3.3 Time of Concentration

Multiple definitions are used in the literature to define T_C. The most commonly used conceptual, physically-based definition of T_C is defined as the time required for runoff, as a result of effective rainfall with a uniform spatial and temporal distribution, to contribute to the peak discharge or, in other words, the time required for a water particle to travel from the catchment boundary along the longest watercourse to the catchment outlet (Kirpich, 1940; McCuen *et al*., 1984; McCuen, 2005; SANRAL, 2006; USDA NRCS, 2010). From this conceptual definition, the computational definition of T_C is thus the distance travelled along the principal flow path (which is divided into segments of reasonably uniform hydraulic characteristics) divided by the mean flow velocity in each of the segments (McCuen, 2009). The current common practice is to divide the principal flow path into segments of overland flow (sheet and/or shallow concentrated flow) and main watercourse or channel flow. The travel times in the various segments are computed separately and added. However, Aron *et al.* (1991) identified this procedure as hydraulically incorrect, since the flow velocity in any reach depends on the flow rates entering that particular reach from upstream reaches, while the transition points between sheet and concentrated flow are arbitrarily allocated. In order to overcome this problem, Aron *et al.* (1991) proposed the use of a fractional concept, which assumes swale flow over the entire catchment expressed as a function of the drainage area, while the stream drainage system repeat itself successively into smaller and smaller geometrically similar segments. These fractional dimensions were used as a measure of geometric similarity and combined with other catchment shape parameters, the rational method and kinematic wave theory to express the T_C.

The second conceptual definition of T_C relates to the temporal distribution of rainfall and runoff, where T_C is defined as the duration between the start of effective rainfall and the resulting peak discharge (*c.f.* Figure 3.1). The specific computations used to represent T_C

based on time variables from hyetographs and hydrographs will be discussed in the next section to establish how the different interpretations of observed rainfall: runoff distribution definitions agree with the conceptual T_C definitions in the afore-mentioned paragraphs.

3.3.1 Time of concentration estimated from observed data

Numerous computational definitions have been proposed for estimating T_C from observed rainfall and runoff data. The following methods as illustrated in Figure 3.1 are occasionally used to estimate T_C from observed hyetographs and hydrographs (McCuen, 2009):

(a) The time from the end of effective rainfall to the inflection point on the recession limb of the total runoff hydrograph (end of direct runoff);

(b) The time from the centroid of effective rainfall to the peak discharge of total runoff;

(c) The time from the maximum rainfall intensity to the peak discharge; or

(d) The time from the start of the total runoff (rising limb of hydrograph) to the peak discharge of total runoff.

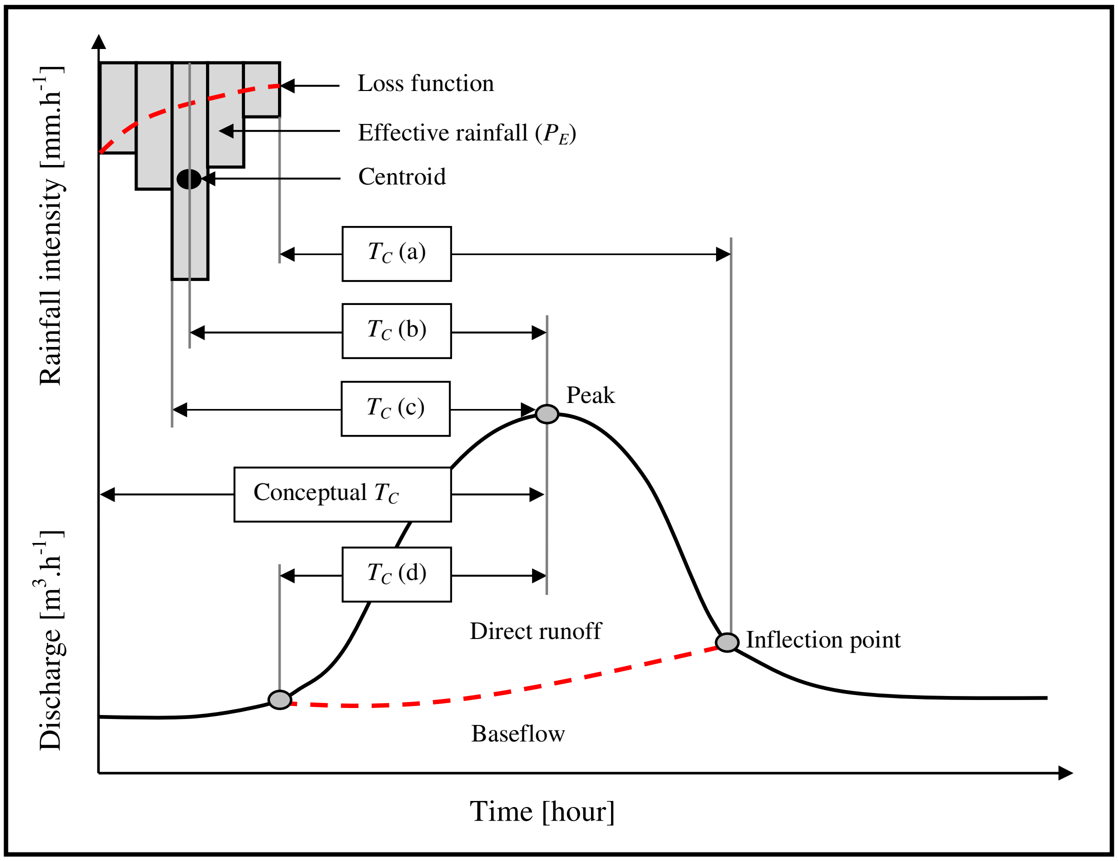

Figure 3.1 Schematic relationship between different T_C definitions (after McCuen, 2009)

In South Africa, the South African National Roads Agency Limited (SANRAL) recommends the use of method (a), but in essence all these methods are dependent on the conceptual definition of T_C introduced in the previous section. It is also important to note that all these methods listed in (a) to (d) are based on random time variables with an associated probability distribution or degree of uncertainty. The "centroid values" denote "average values" and are therefore considered likely to be more stable time variables representative of the catchment response, especially in larger catchments or where flood volumes are central to the design. In contrast to large catchments, the time variables related to peak rainfall intensities and peak discharges are considered to provide the best estimate of the catchment response in smaller catchments where the exact occurrence of the maximum peak discharge is of more importance. McCuen (2009) analysed 41 hyetograph-hydrograph storm event data sets from 20 catchment areas ranging from 1 to 60 ha in the USA. The results were indicative that the T_C based on the conceptual definition and principal flow path characteristics significantly underestimated the temporal distribution of runoff and needs to be increased by 56% in order to reflect the timing of runoff from the entire catchment, while the T_C based on method (b) proved to be the most accurate and was therefore recommended.

3.3.2 Hydraulic estimation methods

The hydraulically-based T_C estimates are limited to overland flow, which is ultimately derivable from the uniform flow theory and basic wave mechanics, *e.g.* the kinematic wave (Henderson and Wooding, 1964; Morgali and Linsley, 1965; Woolhiser and Liggett, 1967), dynamic wave (Su and Fang, 2004) and kinematic Darcy-Weisbach (Wong and Chen, 1997) approximations.

The focus of this study is on larger catchments in which main watercourse, *i.e.* channel flow dominates. Therefore, only a selection of the overland flow methods commonly used in South Africa to estimate T_C as shallow concentrated flow in the upper reaches of a catchment, are included and briefly discussed.

3.3.2.1 Mixed sheet and concentrated overland flow

The characteristics of the transition point between sheet and concentrated overland flow were discussed in Section 3.1. Kerby's method is commonly used to estimate T_C both as mixed sheet and/or shallow concentrated overland flow in the upper reaches of a catchment. This method (Equation 3.1) was developed by Kerby (1959; cited by Seybert, 2006) and is based on the drainage design charts developed by Hathaway (1945; cited by Seybert, 2006). Therefore, it is sometimes referred to as the Kerby-Hathaway method. The South African Drainage Manual (SANRAL, 2006) also recommends the use of Equation 3.1 for overland flow in South Africa. McCuen *et al.* (1984) highlighted that this method was developed and calibrated for USA catchments with areas less than 4 ha, average slopes less than 1% and roughness parameters (Manning's *n*-values) varying between 0.02 and 0.8. In addition, the length of the flow path is a straight-line distance from the most distant point on the catchment boundary to the start of a fingertip tributary (well-defined watercourse) and is measured parallel to the slope. The flow path length must also be limited to ± 300 m.

$$T_{Co} = 1.4394\left(\frac{nL_O}{\sqrt{S_O}}\right)^{0.467} \tag{3.1}$$

where:

T_{Co} = overland time of concentration [minutes],

L_O = length of overland flow path [m],

n = Manning's roughness parameter for overland flow, and

S_O = average overland slope [$m.m^{-1}$].

3.3.2.2 Concentrated overland flow and channel flow

The NRCS velocity method is commonly used to estimate T_C both as shallow concentrated overland and/or channel flow. This method is based on a constant velocity of Newtonian mechanics (travel time equals distance travelled) and is commonly used for concentrated overland flow estimates where the flow path geometry, surface roughness and slope are relatively constant (Seybert, 2006). Either Equation 3.2a or 3.2b can be used to express T_C for concentrated overland or channel flow. In the case of main watercourse/channel flow, this method is referred to as the NRCS segmental method, which divides the flow path into segments of reasonably uniform hydraulic characteristics. Separate travel time calculations are performed for each segment based on either Equations 3.2a or 3.2b, while the total T_C is expressed as Equation 3.2c (after USDA NRCS, 2010):

$$T_{Co,\ ch(i)} = 0.0167\left(\frac{nL_{O,CH}}{R^{0.667}\sqrt{S_{O,CH}}}\right) \qquad (3.2a)$$

$$T_{Co,\ ch(i)} = 0.0167\left(\frac{L_{O,CH}}{18\log\left(\frac{12R}{k_s}\right)\sqrt{RS_{O,CH}}}\right) \qquad (3.2b)$$

$$T_{Co,\ ch} = \sum_{i=1}^{N} T_{Ci} \qquad (3.2c)$$

where:

$T_{Co,\ ch}$ = overland/channel flow time of concentration [minutes],

$T_{Co,ch(i)}$ = overland/channel flow time of concentration of segment *i* [minutes],

k_s = Chézy's roughness parameter [m],

$L_{O,CH}$ = length of flow path, either overland or channel flow [m],

n = Manning's roughness parameter,

R = hydraulic radius which equals the flow depth [m], and

$S_{O,CH}$ = average overland or channel slope [m.m^{-1}].

3.3.3 Empirical estimation methods

The empirically-based T_C estimates are derived from observed meteorological and hydrological data and usually consider the whole catchment, not the sum of sequentially computed reach/segment behaviours. Stepwise multiple regression analyses are normally used to analyse the relationship between the response time and geomorphological, hydrological and meteorological parameters of a catchment.

3.3.3.1 Mixed sheet and concentrated overland flow

The empirical SCS method is commonly used to estimate T_C as mixed sheet and/or concentrated overland flow in the upper reaches of a catchment. The SCS (later NRCS) developed this method (Equation 3.3) in 1975 for homogeneous, agricultural catchment areas up to 8 km² with mixed overland flow conditions dominating. The calibration of Equation 3.3 was based on method (c) (*c.f.* Section 3.3.1) and a T_C: T_L proportionality ratio of 1.417 (McCuen, 2009). However, McCuen *et al.* (1984) proved that Equation 3.3 provides accurate T_C estimates for catchment areas up to 16 km².

$$T_{Co} = \frac{L_O^{0.8}\left[\frac{25400}{CN} - 228.6\right]^{0.7}}{706.9\,S^{0.5}} \quad (3.3)$$

where:

T_{Co} = time of concentration [minutes],

CN = runoff curve number,

L_O = length of overland flow path [m], and

S = average catchment slope [m.m^{-1}].

3.3.3.2 Main watercourse/channel flow

The following empirical methods are commonly used to estimate T_C as channel flow in defined watercourses:

(a) **Bransby-Williams method:** This method was developed by Williams (1922; cited by Li and Chibber, 2008) and is expressed as Equation 3.4. The use of this method must be limited to rural catchment areas less than ±130 km² (Fang *et al.*, 2005; Li and Chibber, 2008), while the Australian Department of Natural Resources and Water (ADNRW, 2007), highlighted that initial overland flow travel time is already incorporated into Equation 3.4, therefore an overland flow or standard inlet time should not be added.

$$T_{Cch} = 0.2426\left(\frac{L_{CH}}{A^{0.1}S_{CH}^{\ 0.2}}\right) \quad (3.4)$$

where:

T_{Cch} = channel flow time of concentration [hours],

A = catchment area [km²],

L_{CH} = length of main watercourse/channel [km], and

S_{CH} = average main watercourse slope [m.m^{-1}].

(b) **Kirpich method:** Kirpich (1940) calibrated two empirical equations to estimate T_C in small, agricultural catchments in Pennsylvania and Tennessee, USA. The catchment areas ranged from 0.4 to 45.3 ha, with average catchment slopes between 3% and 10%. In this method (Equation 3.5), the estimated T_C values should be multiplied by 0.4 (overland flow) and 0.2 (channel flow) respectively where the flow paths in a catchment are lined with concrete/asphalt.

$$T_{Cch} = 0.0633\left(\frac{L_{CH}{}^{2}}{S_{CH}}\right)^{0.385} \tag{3.5}$$

where:

T_{Cch} = channel flow time of concentration [hours],

L_{CH} = length of longest watercourse [km], and

S_{CH} = average main watercourse slope [m.m^{-1}].

Although this method is proposed to estimate T_C in main watercourses as channel flow, McCuen *et al.* (1984) highlighted that the coefficients used in Equation 3.5 probably reflect significant portions of overland flow travel time, especially if the relatively small catchment areas used during the calibration are taken into consideration. In addition, these coefficients are empirically-based to represent regional effects, which would make it inappropriate to use outside the catchments used for calibration. McCuen *et al.* (1984) also showed that Equation 3.5 had a tendency to underestimate T_C values in 75% of the urbanised catchment areas smaller than 8 km², while in 25% of the catchments (8 km² < A ≤ 16 km²) with substantial channel flow, it had the smallest bias. Pilgrim and Cordery (1993) also confirmed that the latter was also evident from studies conducted in Australia.

(c) **Johnstone-Cross method:** This method was developed by Johnstone and Cross (1949; cited by Fang *et al.*, 2008) to estimate T_C in the Scioto and Sandusky River catchments (Ohio Basin), ranging from 65 km² to 4 206 km². Equation 3.6 is primarily a function of the main watercourse length and average slope.

$$T_C = 0.0543\left(\frac{L_{CH}}{S_{CH}}\right)^{0.5} \tag{3.6}$$

where:

T_{Cch} = channel flow time of concentration [hours],

L_{CH} = length of longest watercourse [km], and

S_{CH} = average main watercourse slope [m.m^{-1}].

(d) **USBR method:** Equation 3.7 was proposed by the USBR (1973) to be used as a standard T_C estimate in hydrological designs, especially culvert designs based on the California Culvert Practice (1955; cited by Li and Chibber, 2008). However, Equation 3.7 is essentially a modified version of the Kirpich method (Equation 3.5) and in South Africa; SANRAL (2006) also recommends the use thereof in defined, natural watercourses/channels. It is also used as a default in conjunction with Equation (3.1) to estimate the total travel time (overland and channel flow) for deterministic design flood estimation methods in South Africa. Van der Spuy and Rademeyer (2008) highlighted that Equation 3.7 tends to result sometimes in estimates that are either too high or too low and recommended the use of a correction factor (τ) as proposed by Kovács (unpublished) and listed in Table 3.1.

$$T_{Cch} = \tau\left(\frac{0.87 L_{CH}^{2}}{1000 S_{CH}}\right)^{0.385} \quad (3.7)$$

where:

T_{Cch} = channel flow time of concentration [hours],

L_{CH} = length of longest watercourse [km],

S_{CH} = average main watercourse slope [m.m^{-1}], and

τ = correction factor.

Table 3.1 Correction factors (τ) for T_C (Van der Spuy and Rademeyer, 2008)

Area [*A*, km²]	**Correction factor [τ]**
< 1	2
1 - 100	2-0.5log*A*
100 - 5 000	1
5 000 - 100 000	2.42-0.385log*A*
> 100 000	0.5

3.4 Lag Time

Conceptually, T_L is generally defined as the time between the centroid of effective rainfall and the peak of the resultant direct runoff hydrograph (*c.f.* Figure 3.3). Computationally, T_L can be estimated as a weighted T_C value, when for a given storm, the catchment is divided into sub-areas and the travel times from the centroid of each sub-area are established by the relationship expressed in Equation 3.8. This relationship is also illustrated in Figure 3.2 (USDA NRCS, 2010).

$$T_L = \frac{\sum\left(A_i Q_i T_{Ti}\right)}{\sum\left(A_i Q_i\right)} \quad (3.8)$$

where:

T_L = lag time [hours],

A_i = incremental catchment area/sub-area [km²],

Q_i = incremental runoff from A_i [mm], and

T_{Ti} = travel time from the centroid of A_i to catchment outlet [hours].

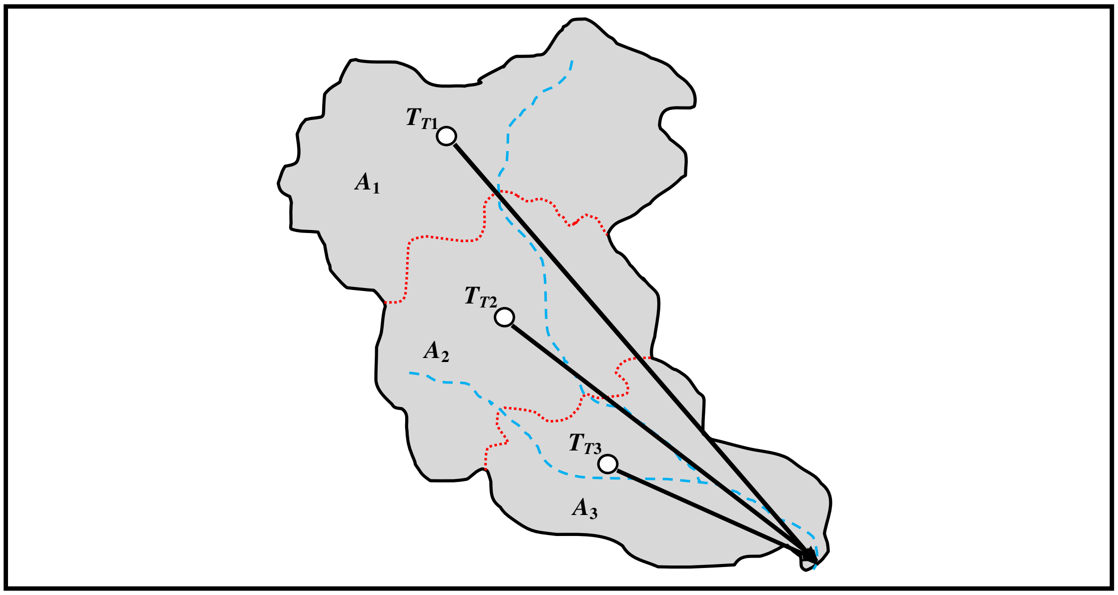

Figure 3.2 Conceptual travel time from the centroid of each sub-area (USDA NRCS, 2010)

In flood hydrology, T_L is normally not estimated using Equation 3.8. Instead, stepwise multiple regression analyses are normally used to analyse the relationship between the response time and meteorological and geomorphological parameters of a catchment. In the following section, the meteorological parameters, as defined by different interpretations of observed rainfall: runoff distribution definitions will be explored.

3.4.1 Lag time estimates from observed data

In Section 3.3.1, it was emphasised that scientific literature often fails to clearly define and distinguish between T_C and T_L, especially when observed data (hyetographs and hydrographs) are used to estimate these time parameters. Time variables from various points on hyetographs to various points on the resultant hydrographs are sometimes misinterpreted as T_C. The following methods as illustrated in Figure 3.3 are occasionally used to estimate T_L as a time parameter from observed hyetographs and hydrographs (Heggen, 2003):

(a) The time from the centroid of effective rainfall to the time of the peak flow of direct runoff.

(b) The time from the centroid of effective rainfall to the time of the peak flow of total runoff.

(c) The time from the centroid of effective rainfall to the centroid of direct runoff.

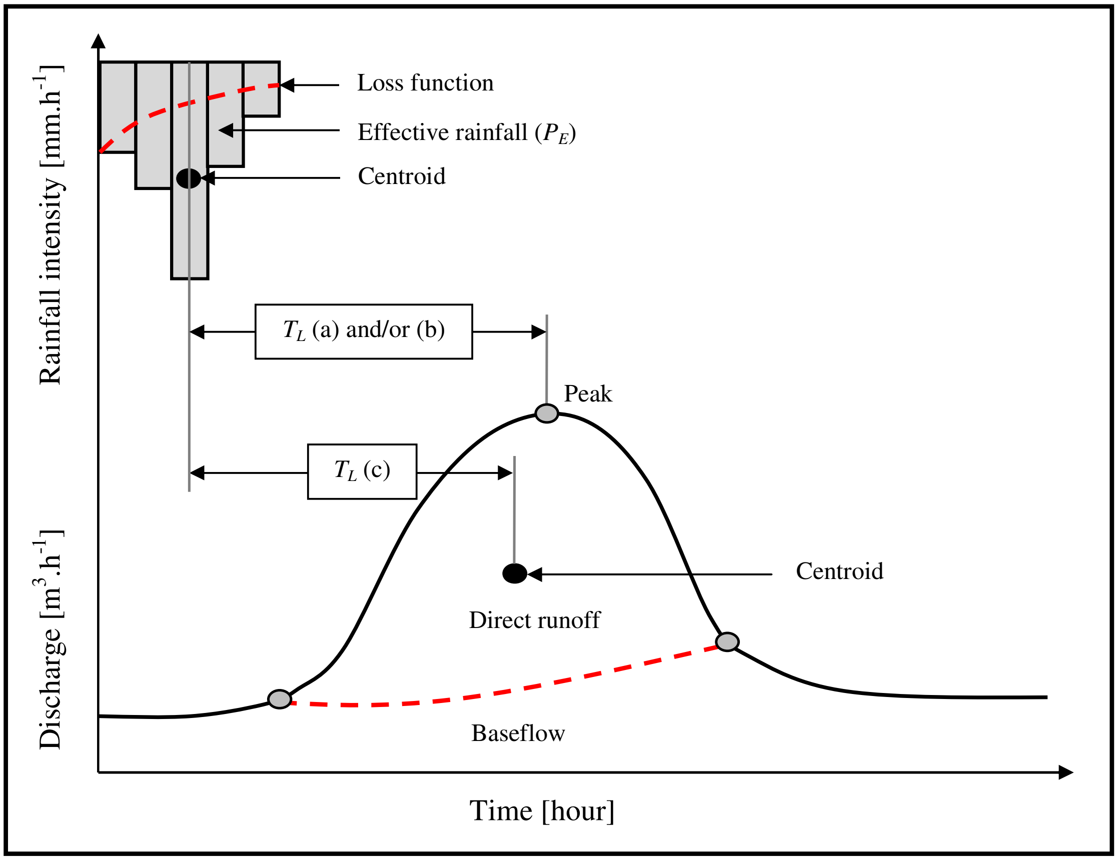

Figure 3.3 Schematic relationship between different T_L definitions (after Heggen, 2003)

Section 3.3.1 also highlighted that the methods used to estimate T_C are based on uncertain, random time variables, which is also the case when T_L is estimated. However, methods (a) to (c) listed above use "centroid values" and are therefore considered likely to be more stable time variables representative of the catchment response in large catchments. Methods (a) to (c) are generally used or defined as T_L (Simas, 1996; Hood *et al.*, 2007; Folmar and Miller, 2008; Pavlovic and Moglen, 2008), although method (b) is also sometimes used to define T_C. Dingman (2002; cited by Hood *et al.*, 2007) recommended the use of Equation 3.9 to estimate the centroid values of hyetographs or hydrographs respectively.

$$C_{P,Q} = \frac{\sum_{i=1}^{N} X_i t_i}{\sum_{i=1}^{N} X_i} \qquad (3.9)$$

where:

$C_{P,\,Q}$ = centroid value of rainfall or runoff [mm or $m^3.s^{-1}$],

t_i = time for period i [hour],

N = sample size, and

X_i = rainfall or runoff for period i [mm or $m^3.s^{-1}$].

Owing to the difficulty in estimating the centroid of mass, other T_L estimation techniques have been proposed. Instead of using T_L as an input for design flood estimation methods, it is rather used as input to the computation of T_C. In using method (c), T_C and T_L are normally related by $T_C = 1.417T_L$. In methods (a) and (b), the proportionality factor increases to 1.67 (McCuen, 2009). The empirical methods used to estimate T_L internationally will be reviewed in the following sections.

3.4.2 Empirical estimation methods

The following empirical methods are occasionally used to estimate T_L in small, medium and/or large catchments:

(a) **Snyder's method:** Snyder (1938; cited by Viessman *et al*., 1989; Pilgrim and Cordery, 1993; McCuen, 2005), developed a synthetic unit hydrograph (SUH) method derived from the relationships between standard unit hydrographs and geomorphological catchment descriptors for catchment areas between 25 km² and 25 000 km² in the Appalachian Highlands, USA. The catchment storage coefficient's (C_T) were established regionally and include the effects of slope and storage. T_L was defined as the time between the centroid of effective rainfall and the time of peak discharge. The following relationship (Equation 3.10) can be used to express T_L:

$$T_L = C_T\left(L_H L_C\right)^{0.3} \qquad (3.10)$$

where:

T_L = lag time [hours],

C_T = catchment storage coefficient [typically between 1.8 and 2.2],

L_C = centroid distance [km], and

L_H = hydraulic length [km].

(b) **Taylor-Schwarz method:** Taylor and Schwarz (1952; cited by Chow, 1964), proved that the catchment storage coefficient (C_T) as used in Equation 3.10 is primarily influenced by the average catchment slope. Subsequently, a revised version (Equation 3.11) of Equation 3.10 was proposed. A total of 20 catchments in the North and Middle Atlantic States, USA were used to establish Equation 3.11.

$$T_L = \frac{0.6}{\sqrt{S}}\left(L_H L_C\right)^{0.3} \tag{3.11}$$

where:

T_L = lag time [hours],

L_C = centroid distance [km],

L_H = hydraulic length of catchment [km], and

S = average catchment slope [%].

(c) **USACE method:** According to Linsley *et al.* (1988), the United States Army Corps of Engineers (USACE) developed a general expression for T_L in 1958 based on Equations 3.10 and 3.11. However, the average catchment slope (S, %) was replaced with the average main watercourse slope (S_{CH}, m.m^{-1}) in Equation 3.12. Typical C_T values proposed were: 0.24 (valleys), 0.50 (foothills) and 0.83 (mountains).

$$T_L = C_T\left(\frac{L_H L_C}{\sqrt{S_{CH}}}\right)^{0.38} \tag{3.12}$$

where:

T_L = lag time [hours],

C_T = catchment storage coefficient,

L_C = centroid distance [km],

L_H = hydraulic length of catchment [km], and

S_{CH} = average main watercourse slope [m.m^{-1}].

(d) **HRU method:** This method was developed by the HRU (1972) in conjunction with the development of SUHs for South Africa. Historical flow and rainfall data from 96 catchment areas were used to derive 1-hour unit hydrographs, which were then rendered dimensionless by expressing the time abscissa and the discharge ordinates in terms of T_L and the peak discharge respectively. The 96 catchments (between 21 and 22 163 km²) were then regionally grouped into nine homogeneous veld-type regions with representative SUHs. The regionalisation scheme took into consideration all catchment characteristics (topography, soil types, vegetation and rainfall), which are most likely to influence catchment storage and therefore T_L.

The catchment-index ($L_H L_C S_{CH}^{-0.5}$), as proposed by USACE in Equation 3.12, was used to represent the delay of runoff in the catchments. The observed T_L values, defined as the time lapse between the centres of area of input hyetographs and the resulting output hydrographs, were plotted against the catchment indices on logarithmic scales. Least-square regression analyses were then used to derive a family of T_L equations for each veld-type region, which can be expressed by a general equation (Equation 3.13). This equation is also proposed by SANRAL (2006) for general use in rural catchments smaller than 5 000 km² in South Africa. However, the 5 000 km² area limit is questionable, since the catchment area upper limit used during the development thereof was 22 163 km².

$$T_L = C_T \left(\frac{L_H L_C}{\sqrt{S_{CH}}} \right)^{0.36} \qquad (3.13)$$

where:

T_L = lag time [hours],

C_T = regional storage coefficient,

L_C = centroid distance [km],

L_H = hydraulic length of catchment [km], and

S_{CH} = average main watercourse slope [m.m^{-1}].

(e) **Natural Environmental Research Council (NERC) method:** The United Kingdom Flood Studies Report (UK FSR) (NERC, 1975; cited by Loukas and Quick, 1996) proposed the use of Equation 3.14 to estimate T_L in ungauged UK catchments.

$$T_L = 2.8\left(\frac{L_{CH}}{\sqrt{S_{CH}}}\right)^{0.47} \quad (3.14)$$

where:

T_L = lag time [hours],

L_{CH} = main watercourse length [km], and

S_{CH} = average main watercourse slope [m.km^{-1}].

(f) **SCS lag method:** In Section 3.3.3.1 it was indicated that this method was developed by the USDA SCS (1975) to estimate T_C where mixed overland flow conditions in catchment areas up to 8 km² exists. However, in appreciation of the relationship of $T_L = 0.6T_C$ (Refer to Section 3.5), Equation 3.15 can also be used to estimate T_L in catchment areas up to 16 km² (McCuen, 2005).

$$T_L = \frac{L_{CH}^{\ 0.8}\left[\frac{25\,400}{CN} - 228.6\right]^{0.7}}{168.85\,S^{0.5}} \quad (3.15)$$

where:

T_L = lag time [hours],

CN = runoff curve number,

L_{CH} = main watercourse length [km], and

S = average catchment slope [m.m^{-1}].

(g) **Schmidt-Schulze method:** Schmidt and Schulze (1984) estimated T_L from observed data in 12 agricultural catchment areas smaller than 3.5 km² in South Africa and the USA by using three different methods to develop Equation 3.16. This equation is used in preference to the original SCS lag method (Equation 3.15) in South Africa, especially when stormflow response includes both surface and subsurface runoff as frequently encountered in areas of high MAP or on natural catchments with good land cover (Schulze *et al.*, 1992).

$$T_L = \frac{A^{0.35} MAP^{1.10}}{41.67\,S^{0.3} i_{30}^{\ 0.87}} \quad (3.16)$$

where:

T_L = lag time [hours],

A = catchment area [km²],

i_{30} = 2-year return period 30-minute rainfall intensity [mm.h^{-1}],
MAP = mean annual precipitation [mm], and
S = average catchment slope [%].

The three different methods used to develop Equation 3.16 are based on the following (Schmidt and Schulze, 1984):

Firstly, the relationship between peak discharge and volume was investigated by regressing linear peak discharge distributions (single triangular hydrographs) on the corresponding runoff volume obtained from observed runoff events to determine the magnitude and intra-catchment variability of T_L. The single triangular hydrographs, as obtained from isolated single-peaked runoff events, were considered to be representative of the triangular unit hydrograph of each runoff event in a catchment, based on the assumption that the depth, temporal and spatial distributions of effective rainfall are uniform, while its duration equals T_C. Initially, a logarithmic regression analysis of peak discharge against volume was conducted in each catchment to evaluate the applicability of the SCS method's linear assumptions. The slope of the best-fit regression relationship provided an indication of the degree of non-linearity of the runoff distribution and hence the consistency of T_L in each catchment. Any non-linear variations in T_L were related to the characteristics of rainfall events, rather than runoff events.

In order to accomplish this, the T_L values in each catchment were re-calculated assuming a linear catchment response function based on the above-mentioned regression analysis. These T_L values were then compared with the original SCS T_L equation (Equation 3.15) in order to develop a regression equation to predict catchment T_L. The coefficient of determination (r^2) was used to indicate the proportional variability between peak discharge and volume based on constant T_L values. Over- or underestimation of individual linear-based peak discharges occurred due to the non-linear changes in the rainfall pattern and catchment conditions between individual events, while the deviation of T_L-based discharges from observed discharges can be ascribed to the non-linear rainfall variations in each catchment.

Secondly, the above-mentioned incremental triangular hydrographs were convoluted with observed effective rainfall to form compound hydrographs representative of the peak discharge and temporal runoff distribution of observed hydrographs. The shape of the incremental hydrographs was kept constant with 37.5% of the total volume of runoff under the rising limb of the hydrograph. The storm lag times for individual events in each catchment were optimised and averaged to provide representative catchment T_L values which provide synthetic hydrographs of peak discharge equal to the observed peak discharge. Actual *CN* values estimated for each runoff event were used to determine the runoff volume of each incremental hydrograph, in other words, used to equate the synthetic runoff volumes with observed runoff volumes. The coefficient of efficiency (E_c) was used to determine how accurate the observed hydrograph shapes were modelled by the synthetic hydrographs. The ratios of storm lag times versus catchment T_L values were then regressed against rainfall characteristics in order to evaluate the dependence of T_L upon intra-catchment rainfall variability. However, due to the highly variable nature of the storm lag times; no single rainfall parameter could be satisfactorily used to estimate individual storm lag times. The hydrographs were also synthesised using the incremental SCS triangular hydrographs. The actual *CN* values were used as input to Equation (3.15) in order to assess the accuracy of the peak discharge estimates based on Equation (3.15).

Lastly, the average time response between effective rainfall and direct runoff was measured in each catchment to determine an index of catchment lag time. The large scatter of individual T_L values evident from the analysis confirmed that measured T_L values are impractical for peak runoff rate predictions. However, Schmidt and Schulze (1984) proposed that an extensive study of the relationship between peak runoff rate and volume should be undertaken to provide a simple and effective method for runoff predictions in ungauged catchments.

It was concluded that intra-catchment T_L estimates in unguaged catchments can be improved by incorporating indices of climate and regional rainfall characteristics into an empirical lag equation. The 2-year return period 30-minute rainfall intensity proved to be the dominant rainfall parameter that influences intra-catchment variations in T_L estimates (Schmidt and Schulze, 1984).

(h) **Simas-Hawkins method:** Simas (1996), and Simas and Hawkins (2002), established T_L, defined as the time difference between the centroid of effective rainfall and direct runoff, from over 50 000 rainfall: runoff events in 168 catchment areas between 0.1 ha and 1412.4 ha in the USA. The catchments were grouped into different geographical, catchment management practice, land use and hydrological behaviour regions to explain the variation of T_L between catchments and to conduct multiple regression analyses to establish the most representative T_L relationship, shown as Equation 3.17.

$$T_L = 0.22653\left(\frac{\left(\frac{A}{L_H}\right)^{0.5937}\left(\frac{25400}{CN}-254\right)^{0.3131}}{S^{0.1505}}\right) \qquad (3.17)$$

where:

T_L = lag time [hours],

A = catchment area [km²],

CN = runoff curve number,

L_H = hydraulic length of catchment [km], and

S = average catchment slope [m.m^{-1}].

The use of various catchment and time variables to define the most prominent time parameters, T_C and T_L, as used in hydrological designs, were discussed in Sections 3.3 and 3.4. It was apparent from the definitions and methodologies discussed, that there is a direct relationship between T_C and T_L, which will be addressed in the following section.

3.5 Relationship between Time Parameters

All the time parameters introduced in Sections 3.3 and 3.4 are interdependent and related to one another. Computationally, it was highlighted in Section 3.4 that T_L can be estimated as a weighted T_C value by dividing a catchment into sub-areas with the travel times from the centroid of each sub-area expressed as a function of the incremental areas and runoff volumes (USDA NRCS, 2010).

The most widely used and acceptable definitions of T_L are based on centroid time variables, but centroid of mass estimates generally proved difficult to estimate

(McCuen, 2009). Therefore, T_L is rather used as input to the computation of T_C, than as input for design flood estimation methods. The USDA SCS (1975), proposed an empirical relationship (Equation 3.18a) between T_L and T_C, with a proportionality factor of 0.6. In such a relationship, T_L is defined as the time lapse between the centroid of effective rainfall and peak discharge of a single-peaked direct or total runoff hydrograph. Overton and Meadows (1976; cited by McCuen, 2009), proposed the use of a proportionality factor of 0.625 instead of 0.6. However, McCuen (2009) argued that this would result in only a minor difference within the confidence bands associated with T_C estimates. If T_L is based on the time lapse between the centroid of effective rainfall and direct runoff, then the T_L: T_C relationship is as shown in Equation 3.18b:

$$T_L = 0.6T_C \quad (3.18a)$$

$$T_{LD} = 0.7057T_C \quad (3.18b)$$

where:

T_L = lag time [hours],

T_{LD} = lag time based on the time lapse between the centroid of effective rainfall and direct runoff [hours], and

T_C = time of concentration [hours].

The regionalisation of time parameters is discussed in the next section.

3.6 Regionalisation of Time Parameters

In essence, the main objective of time parameter regionalisation is to improve and augment the accuracy of design flood estimations at gauged and ungauged sites, which is normally reflected by Goodness-of-Fit (GOF) statistics of regionalised equations compared with those at a single site. The two most difficult aspects of the regionalisation process are to (Burn, 1997; McCuen, 2005):

(a) Establish whether regionalisation is actually required; and

(b) Identify and to establish the number of homogeneous hydrological regions required which warrant the combination and transfer of representative catchment responses and extreme flow characteristics. In this context, a region refers to a collection of catchments with similar hydrological responses, but not necessarily in geographically contiguous areas.

In the subsequent paragraphs, various regionalisation methods and identification of homogeneous regions are reviewed.

In hydrology, various methods have been proposed for the regionalisation of hydrological parameters, but most of these methods tend to yield universally varying results (Rao and Srinivas, 2003). The following methods are regarded as suitable to regionalise time parameters in conjunction with flood statistics, *viz.*:

(a) The residual method in which regions are formed by grouping catchments with residuals of a similar sign and magnitude (McCuen, 2005);
(b) The clustering method, where the reciprocal of the Euclidian distance in a space of site characteristics is used to measure the degree of similarity (Hosking and Wallis, 1997; cited by Smithers and Schulze, 2000b); and
(c) The region-of-influence (ROI) method in which threshold values of dissimilarity measures are selected to in- or exclude sites from the region of influence for a particular catchment (Burn, 1990; 1997).

In methods (a) to (c), the variables and/or parameters are normally selected to define pair-wise similarity or dissimilarity of catchments in a particular region. Geomorphological catchment characteristics at a specific site (*c.f.* Chapter 2) are use for regionalisation, while flood statistics (L-moment ratios and other statistical estimated measures from observed data) are used to test the homogeneity of identified regions. Hosking and Wallis (1997; cited by Smithers and Schulze, 2000b) regarded the clustering method as the most appropriate method to establish regions from large data sets.

Typical examples of regionalisation of hydrological parameters in South Africa include the research conducted by the HRU (1972), Kovács (1988), Smithers and Schulze (2000a; 2000b) and Görgens (2007). In the latter case, Görgens (2007) further developed the run hydrograph concept developed by Hiemstra and Francis (1979) for South Africa, referred to as the Joint Peak-Volume (JPV) design flood methodology. This methodology enables the estimation of the exceedance probability of a design flood volume given a design peak discharge using regionally pooled Kovács flood and/or HRU veld-type factors along with regional index-floods, regional log-standardised peaks and volume relationships, and regional standardised hydrographs for what Görgens (2007) defines as small (< 1 000 km²) and large (> 1 000 km²) catchments.

In order to assess the JPV methodology, it was compared to at-site estimates and the SUH method. However, the original data sets used to develop the SUH method in South Africa were used during this assessment and it is not clear whether these are independent of the sites used in the development of the JPV methodology. The assessment results were characterised by considerable overestimations in three catchments, with the wide-pooled General Extreme Value (GEV) results generally better than either the SUH or the wide-pooled Log-Pearson Type III (LP3) results (Görgens, 2007).

In this section of Chapter 3, the various regionalisation methods and identification of homogeneous regions were reviewed. In Chapter 4 which follows, a critical synthesis and discussion of the literature review conducted in Chapters 2 and 3 are presented.

4. DISCUSSION AND CONCLUSIONS

The body of literature focusing on catchment and time variables which influence the catchment response time by using suitable time parameters is substantial. In this chapter, the discussion and conclusions pertaining to the literature reviews contained in Chapters 2 and 3 are included as Sections 4.1 and 4.2 respectively.

4.1 Variables Influencing Catchment Response Time

From the literature reviewed in Chapter 2, it is clear that catchment characteristics, such as climatological variables, catchment geomorphology, catchment variables, and channel geomorphology have a significant influence on the catchment response time. Many researchers identified the catchment area as the single most important geomorphological variable as it demonstrates a strong correlation with many flood indices affecting the catchment response time. Apart from the catchment area, other catchment variables such as hydraulic and main watercourse lengths, centroid distance, average catchment and main watercourse slopes also proved to be evenly important and worthwhile to be considered as predictor variables to estimate T_C and T_L at a large catchment or regional level.

In addition to these geomorphological catchment variables, the importance and influence of climatological and catchment variables on the catchment response time were also evident. Owing to the high variability of catchment variables at a large catchment or regional level, the use of weighted *CN* values as representative predictor variables to estimate T_C and T_L as opposed to site-specific values could be considered. Simas (1996) and Simas and Hawkins (2002), proved that *CN* values can be successfully incorporated to estimate lag times in medium to large catchments (*c.f.* Chapter 3). The weighted *CN* values can be based on various data sets such as the:

(a) National Land Cover Database of the Council of Scientific and Industrial Research (CSIR); and

(b) Taxonomical soil forms and associated hydrological soil series (Schulze *et al*., 1992).

However, weighted *CN* values are representative of a linear catchment response and therefore, the use of *MAP* values as a surrogate for these values could be considered in order to present the non-linear catchment responses better.

The inclusion of climatological (rainfall) variables as suitable predictors of catchment response time in South Africa has, to date, been limited to the research conducted by Schmidt and Schulze (1984; 1987), which uses the two-year return period 30-minute rainfall intensity variable in small, natural (agricultural) catchments. Rainfall intensity-related variables such as this might be worthwhile to be considered as catchment response time predictor variables. However, since this study focuses on larger catchments at a regional level, the antecedent soil moisture status and the quantity and distribution of rainfall relative to the attenuation of the resulting flood hydrograph as it moves towards the catchment outlet are probably of more importance than the relationship between rainfall intensity and the infiltration rate of the soil.

4.2 Classification of Flows, Time Variables and Parameters

In Chapter 3 it was evident that many researchers have developed time parameters for specific hydrological applications. The literature review was structured into four major sections:

(a) Classification of flow types;
(b) Synthesis of conceptual and computational time parameter nomenclature;
(c) Review and assessment of existing hydraulic and empirical time parameter estimation methods; and
(d) The regionalisation of time parameters to be used in ungauged catchments.

The classification of flow types was considered explicitly to highlight and describe the direct influence on the time parameters used to express the catchment response time, while direct runoff was identified as the major contributor during floods. Since this study will focus on larger catchments, the dominant flow type is assumed to be main watercourse or channel flow.

The importance of time parameters based on either hydraulic or empirical estimation methods became evident from Chapter 3 and it was confirmed that none of the hydraulic and empirical methods are highly accurate or reproducible to provide the true value of these time parameters. In addition, many of these methods/equations proved to be in a disparate form presented without explicit unit specifications and suggested constant values, with migration between dimensional systems and what seems to be a Manning's *n*-value, is in fact a special-case roughness coefficient. Heggen (2003), which cited more than 80 T_C and T_L estimation methods in hydrological literature, confirmed afore-mentioned findings.

Apart from the questionable accuracy and disparate form of these time parameter estimation methods, it was also evident that these time parameters, such as T_C and T_L, also have multiple definitions. The definitions of T_C introduced in Chapters 1 and 3 highlighted that T_C is a hydraulic parameter, and not a true hydrograph parameter. Hydrological literature, unfortunately, often fails to make this distinction. Time intervals from various points during a storm to various points on the resultant hydrograph are often misinterpreted as T_C. In fact, these points should be designated as T_L (refer to Section 3.4.1, Chapter 3). Some T_L estimates are interpreted as the time lapse between the centroid of a hyetograph and hydrograph, while in other definitions the time starts at the centroid of effective rainfall, and not the total rainfall. It can also be argued that the accuracy of T_L estimation is, in general, so poor that such difference in T_L starting and ending points is not significant. However, according to McCuen (2009), the use of different time variables to estimate T_C or T_L would obviously lead to different estimates, which is partially indicative of the uncertainty involved in the process of time parameter estimation.

Therefore, based on the literature review and the conceptual/computational misinterpretations mentioned above, the following time parameter definitions will be considered in this study:

(a) **Time of concentration (T_C):**
   - (i) *Conceptual definition:* The time required for a water particle to travel from the hydraulically most distant catchment boundary along the longest watercourse to the catchment outlet.
   - (ii) *Observed hyetograph-hydrograph definition:* The time from the start of effective rainfall to the peak discharge of a total runoff hydrograph.

(b) **Lag time (T_L):** The time from the centroid of effective rainfall to the peak discharge of a direct runoff hydrograph.

Furthermore, definition (b) is based on "centroid values", which actually denote "average values" and are therefore considered likely to be more stable time variables representative of the catchment response in larger catchments where flood volumes are central to the design.

Hydrological T_C and T_L estimates based on observed data pose some problems, since design accuracy depends on the computational accuracy of the input variables, *e.g.* rainfall and runoff data. The rainfall data in South Africa are generally only widely available at more aggregated levels, such as daily. According to Smithers and Schulze (2000a), this reflects a paucity of rainfall data at sub-daily timescales, both in the number of rainfall gauges and length of the recorded series. Under natural conditions, especially in large catchments at a regional level, uniform effective rainfall seldom occurs, since both spatial and temporal variations affect the resulting runoff. Apart from the paucity of rainfall data and non-uniform distribution, Schmidt and Schulze (1984) noted that T_L for an individual event cannot always be measured directly from autographic records owing to the difficulties in determining the start time, end time and temporal and spatial distribution of effective rainfall. Problems are further compounded by poorly synchronised rainfall and runoff recorders which contribute to inaccurate T_L estimates.

The NRCS velocity method (Equation 3.2) will be used in this study to represent the hydraulic estimates of T_C, while a selection of empirical T_C and T_L methods with comparable input parameters, such as catchment area, hydraulic and main watercourse lengths, centroid distance, average catchment and main watercourse slopes, and *CN* values will be used for assessments against the empirical regression algorithms to be developed during this study. However, it may be argued that the use of Equation 3.2 will introduce additional uncertainty in the rainfall: runoff process, due to uncertainties associated with the method's required input parameters obtained from different data sources, such as: (i) surface roughness (Manning's *n*-value), (ii) average main watercourse slope and length, and (iii) hydraulic radius. However, the use of accurate GIS data could overcome the perceived inaccuracies related to (ii), since the ArcGIS™ environment enables the use of accurate, efficient and reproducible methods to collect, view and analyse spatial data from different sources within a single framework.

The literature review on regionalisation of time parameters highlighted the importance to develop time parameters for unguaged catchments. Apart from the question of whether regionalisation is actually required and how to identify the number of homogeneous hydrological regions, it might be worthwhile to establish whether time parameter estimation methods must be grouped according to the existing homogeneous flood, rainfall and veld-type regions of South Africa. Therefore, the regionalisation attempts made by the HRU (1972), Kovács (1988), Smithers and Schulze (2000a; 2000b), and Görgens (2007) must be investigated. If a new regionalisation scheme is required, the clustering method (Hosking and Wallis, 1997; cited by Smithers and Schulze, 2000b) will be used, since this method is most suitable to establish regions from large data sets.

The research conducted respectively by Schmidt and Schulze (1984; 1987) to improve peak flow rates using modified SCS lag time equations and Görgens (2007) using the regionally pooled JPV methodology to enable the exceedance probability estimation of a design flood volume given a design peak discharge, emphasise the importance and urgent need for improved regional flood estimation methods. Therefore, it is envisaged that the development of regionalised algorithms to estimate catchment response time parameters, such as T_C and T_L will improve the translation of runoff volume and peak discharge into regionally representative design hydrographs. Thus, in conjunction with methodologies to improve rainfall input, the fundamental input to all deterministic rainfall-based methods of design flood estimation used in South Africa, will be improved significantly.

Chapter 5 which follows contains the research project proposal which investigates the problem statement, followed by a well-defined study purpose and outlined methodology. The latter is also aligned with the specific objectives and outcomes of this study.

5. PROJECT PROPOSAL

This brief proposal covers the problem statement and purpose, aims, hypothesis and specific objectives of the study to investigate the problem statement. The proposed methodology to be used during this study and a work plan, time schedule, list of required equipment and resources are also included. In conclusion, intellectual property considerations and the expected outcomes, deliverables and contributions to new knowledge are also highlighted.

5.1 Problem Statement

The problem statement, *inter alia*, the research question, is centered around problems associated with the accurate estimation of the spatial and temporal distribution of runoff by using suitable time parameters to accurately reflect the catchment response time, since as much as 30% to 75% of the total error in peak discharge estimates could be ascribed to time parameter errors. The following paragraphs focus on problems associated with observed hyetograph-hydrograph data in terms of baseflow separation and hydraulic and empirical time parameter estimation methods.

Universally accepted methods of separating either baseflow from direct runoff or losses from effective rainfall do not exist. Therefore, these separation requirements can introduce a significant variation in the estimation of time parameters from observed data. Apart from this introduced variation, factors such as the antecedent soil moisture, intermittent rainfall patterns, non-linearity in the convolution process and rainfall recurrence interval variations must also be recognised and accounted for; however, most methods do not consider these (McCuen, 2005).

Most of the hydraulically-based methods are limited to the application of the kinematic/dynamic wave theory in small agricultural and urban catchments where overland flow is the dominant runoff generating mechanism. Verification tests confirmed that most of these methods proved to be only reliable estimates in their original developmental regions (McCuen *et al.*, 1984; Akan, 1986; Aron *et al*., 1991). Most of these methods, whether overland or channel flow, also require many input variables, *e.g.* catchment area, average catchment slope, average main watercourse slope, watercourse length and catchment shape parameters, all of which can be time-consuming to determine accurately and which are equally sensitive to biased user-input at different scale resolutions from different data sources (Gericke, 2010).

In addition to above-mentioned problems associated with hydraulic estimates, it was also highlighted in Chapter 3 that the NRCS velocity method (Equations 3.2a-c) used to estimate T_C where the main watercourse is assumed to be the dominant channel separated into homogeneous segments and extended to the catchment boundary, have a number of shortcomings. Firstly, overland flow is assumed only to be applicable to a small proportion of the principal flow path, while overland flow may occur over a significant proportion of the catchment surface. Thus, such T_C estimates based only on the principal flow path would be biased, since it may not reflect the dominant hydrological processes of the entire catchment. Secondly, catchment and channel storages, which can lead to longer T_C values, are also ignored. Although the conceptual implications of Equations (3.2a-c) are clear, it is not evident whether it provides a realistic reflection of the entire catchment's hydrological response. Thus, if the runoff characteristics of the whole catchment are not highly correlated with those of the principal flow path, then T_C estimates based on Equations (3.2a-c) could be erroneous, both biased and imprecise and not reflecting the actual timing of runoff. Consequently, the underestimation of the catchment response time will result in the overestimation of the peak discharge.

Apart from selecting the most appropriate and representative flow path, the hydraulic methods using catchment characteristics as input variables, normally assume a single equation (Manning or Chézy) as valid with constant roughness coefficients applied throughout a flow regime. In ignoring both the difficulties to select single roughness coefficient values in homogeneous flow regimes and the assumption of a constant hydraulic radius, most of the hydraulic methods are inconsistent and require the subjective assessment of input variable values. In other words, these methods provide different answers when applied by different users. This can be ascribed to the fact that different users would select different input variable values even when applying a method on the same catchment area (McCuen, 2005).

Green and Nelson (2002) noted that the use of lumped parameter empirical methods is limited to their homogeneous catchments or regions of original development, since the runoff parameters are lumped into a single equation to generalise the flow path and runoff in the entire catchment/region. However, the actual flow path traverses heterogeneous areas with different slopes, land uses and other hydraulic conditions. McCuen *et al.* (1984) also highlighted that empirically-based T_C and T_L estimates are subject to considerable error when applied to a single catchment and emphasised that the presence of potential observation, spatial and temporal errors/variations in geomorphological and meteorological data cannot be ignored. Even the assumption of a constant T_L value for a given catchment may be questioned, since T_L is mainly rainfall dependent and all other factors remain stationary (Heggen, 2003).

In addition, Ball (1994) and Askew (1970) respectively demonstrated that T_C and T_L are not constant catchment characteristics, but vary with rainfall patterns and are influenced by catchment storage. Schmidt and Schulze (1984) also noted that the verification of empirically-based T_L estimate accuracies poses several problems, since T_L varies with each observed runoff event and thus has to be estimated for a number of events and then averaged to provide a representative catchment estimate. It was also emphasised that unrealistic estimates of either the effective storm duration or hydrograph baselength will result in inaccurate peak discharge estimates, while due to this, Morgan and Johnson (1962; cited by Schmidt and Schulze, 1984) considered T_L as the weakest link in the application of the SUH method.

Taking all above-mentioned factors, as well as the overall aim to improve peak discharge estimates into consideration, it is evident that the current time parameter estimation methods used at a larger catchment or regional scale in South Africa requires a major overhaul. At these catchment scales the resulting runoff is, usually, generated as channel flow through a defined watercourse. Subsequently, this may result both in either the underestimation of the catchment response time and associated overestimation of peak discharges or vice versa, *viz.* the overestimation of catchment response time resulting in underestimated peak discharges. Such under- or overestimations of the peak discharge may result in the over- or under-design of civil engineering structures, with associated socio-economic implications, which might render some projects as infeasible (Görgens, 2002).

5.2 Objectives of Study

The overall objective of this study is to improve peak discharge estimates at a large catchment or regional level in South Africa by developing algorithms to estimate the catchment response time, since this has a significant influence on the resulting hydrograph shape and peak discharge. The algorithms will probably incorporate the most appropriate time variables and catchment storage effects into the regressed empirical time parameter equations to improve the reliability and to reduce the uncertainty when estimating the spatial and temporal distribution of runoff.

5.2.1 Research aims

The *primary aim* of this study is to develop regionalised empirically-based algorithms to express the catchment response time both in terms of the T_C and T_L by recognising the relationships between key climatological and geomorphological parameters which influence the peak discharge and volume estimations at various catchment scales (*e.g.* small and large) in South Africa. Ultimately, these results will enable the estimation of hydrographs from a given volume and regionalised hydrograph shape parameters.

5.2.2 Hypothesis

It is hypothesised that regionalised relationships to estimate typical catchment responses can be developed for South Africa which will improve the estimation of peak discharge and hydrograph shape parameters.

5.2.3 Specific objectives

To achieve the research aims and investigate the hypothesis, the specific objectives are to:

(a) Develop methods to estimate catchment response times with consistency to improve the estimation of peak discharge and hydrograph shape; to
(b) Independently verify the algorithms developed to estimate catchment response time; and to
(c) Independently verify the improvements in peak discharge and hydrograph shape estimation using the algorithms developed.

5.3 Methodology

In order to address the specific objectives identified to achieve the purpose of the study, the following methodological approaches are proposed:

5.3.1 Establishment of a flood database

The flood database will be established by evaluating, preparing and extracting an aggregated sample of up-to-date primary flow and rainfall data. The primary flow data would consist of an aggregate up-to-date sample (2011) of the continuous flow gauges used during previous flood studies conducted by the HRU (1972), Hiemstra and Francis (1979), Alexander (2002b), Görgens (2007) and Görgens *et al.* (2007). The primary rainfall data would consist of up-to-date (2011) aggregated, catchment specific samples of autographic daily and sub-daily rainfall stations as previously used by Smithers and Schulze (2000a; 2000b) and Lynch (2004). Table 7.1 in Appendix A provides a summary of 195 potential catchments/flow gauging stations to be considered during this study. These were used in the flood studies as mentioned above. The location and spatial distribution of all these catchments/flow gauging stations are shown in Figure 8.1, Appendix B.

5.3.2 GIS data development and applications

All the relevant GIS and DEM data will be obtained from the DWA (Directorate: Spatial and Land Information Management). The specific GIS data feature classes (lines, points and polygons) and DEM rasters applicable to all the catchments under consideration will be extracted and created from these original data sets. The data extraction will then be followed by data projection and transformation, editing of attribute tables and recalculation of catchment characteristics (areas, perimeters and distances).

5.3.3 Variable rainfall and runoff data analyses

The delineated catchment boundaries and existing rainfall databases (Smithers and Schulze, 2000a; 2000b and Lynch, 2004) will be used to determine the number and spatial distribution of sub-daily and daily rainfall stations within each catchment under consideration. Mutual time intervals, in other words, the degree of synchronisation between the point rainfall data sets at each of these stations will firstly be established, after which, it will be converted to averaged compounded rainfall hyetographs using conventional methods, *e.g.* Arithmetic mean, Thiessen polygon and/or Isohyetal methods.

Alternatively, more sophisticated deterministic interpolation (*e.g.* Inverse Distance Weighted (IDW) and Spline) methods or geostatistical (*e.g.* Kriging) methods could be used. Taking cognisance of the shortcomings of these methods, the potential use of the methodology proposed by Frezghi and Smithers (2008) to merged observed rainfall data and radar images to provide representative averaged catchment rainfall, could be investigated. In addition, especially in smaller catchments with a sub-daily catchment response time, the disaggregation of daily rainfall into hourly rainfall information using the methodology proposed by Knoesen and Smithers (2008), might also be useful to explore.

The convolution process required to assess the time parameters (T_C and T_L) will be based on the temporal relationship between the averaged compounded hyetographs and hydrographs. Conceptually, the proposed procedure will assume that the volume of direct runoff is equal to the volume of effective rainfall, that all rainfall prior to the start of direct runoff is initial abstraction, after which, the loss rate is assumed to be constant. However, this simplification might ignore the "memory effect" of previous rainfall events, and therefore an alternative approach should be developed in this study.

5.3.4 Establishment of time parameter relationships

The T_C and T_L pair values obtained from analysing each rainfall: runoff event will then be used to establish the direct relationship between T_C and T_L at a large catchment or regional level. The effect of using alternative T_C and T_L-definitions (*c.f.* Chapter 3) on the proportionality factor variability will also be investigated.

5.3.5 Regionalisation

Firstly, the relevance of existing homogeneous flood, rainfall, geomorphological and veld-type regions in South Africa (*c.f.* Chapter 3) to the regionalisation of catchment time parameters will be established. The outcome of this investigation will provide directives whether a combination of the above-mentioned regions must be used or alternatively, whether new catchment response time regions must be established. If the latter case is identified as the most suitable option; the catchments and associated observed time parameter results will be grouped together using the clustering method of regionalisation to provide combined homogeneous flood-producing regions based on the geographical, geomorphological and climatological characteristics.

5.3.6 Verification of catchment response time algorithms

The developed catchment response algorithms will be verified against observed catchment response time parameters obtained from catchments not used during the calibration exercise. In addition, the developed catchment response algorithms could also be compared with the selection of hydraulic/empirical T_C and empirical T_L methods contained in Chapter 3 to establish the relevance thereof in the channel flow regime. Apart from these comparisons, the NRCS velocity method (Equation 3.2) will also be compared with a selection of conventional overland flow methods. Typically, overland flow methods such as Kerby's method (Equation 3.1) and the SCS method (Equation 3.3) could be considered to present overland flow over the entire catchment area.

5.3.7 Improved time parameters for design flood estimation

The empirical T_C and T_L algorithms developed will be used and tested in a selection of single-event or continuous simulation design flood estimation methods to illustrate the improved translation of runoff volume into hydrographs and associated peak discharge estimates at a large catchment or regional level. This will serve as the ultimate test of consistency, robustness and accuracy. However, such a large scale implementation for verification purposes is considered to be beyond the primary focus and scope of this study.

Having discussed the methodology, it is apparent that all the research activities should be carefully planned for by using a well-defined time schedule, and will therefore be addressed in the next section. The list of required equipment and resources are included in Section 5.5, while the intellectual property considerations and expected outcomes, deliverables, and contributions to new knowledge are highlighted in Sections 5.6 and 5.7 respectively.

5.4 Work Plan and Time Schedule

In order to follow and successfully complete the methodological approaches described in the previous section, the following work plan (Table 5.1) and associated activities linked to a monthly time schedule are proposed to ultimately achieve the purpose of the study:

(a) **Activity 1:** Application and registration at the University of KwaZulu-Natal;

(b) **Activity 2:** Literature review and formal project proposal;

(c) **Activity 3:** Submission and review of draft project proposal;

(d) **Activity 4:** Submission of final project proposal, presentation and examination;

(e) **Activity 5:** Establishment of flood database in collaboration with JP Calitz;

(f) **Activity 6:** GIS data development and applications;

(g) **Activity 7:** Variable rainfall and runoff data analyses;

(h) **Activity 8:** Regionalisation;

(i) **Activity 9:** Multiple regression analyses and calibration;

(j) **Activity 10:** Hypothesis testing and statistical measures;

(k) **Activity 11:** Verification of developed regression equations;

(l) **Activity 12:** Comparison of time parameter estimation methods; and

(m) **Activity 13:** Compilation and dissertation writing.

Table 5.1 Bar chart: Duration of monthly activities

<table>
<tr><th colspan="12">YEAR 1 (2011)</th></tr>
<tr><th>J</th><th>F</th><th>M</th><th>A</th><th>M</th><th>J</th><th>J</th><th>A</th><th>S</th><th>O</th><th>N</th><th>D</th></tr>
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<tr><th colspan="12">YEAR 2 (2012)</th></tr>
<tr><th>J</th><th>F</th><th>M</th><th>A</th><th>M</th><th>J</th><th>J</th><th>A</th><th>S</th><th>O</th><th>N</th><th>D</th></tr>
<tr><td colspan="8">Activity 5</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="8">Activity 6</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Activity 7</td></tr>
<tr><td colspan="12">Activity 13</td></tr>
<tr><th colspan="12">YEAR 3 (2013)</th></tr>
<tr><th>J</th><th>F</th><th>M</th><th>A</th><th>M</th><th>J</th><th>J</th><th>A</th><th>S</th><th>O</th><th>N</th><th>D</th></tr>
<tr><td colspan="2">Activity 7</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td></td><td></td><td></td><td colspan="4">Activity 10</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="4">Activity 11</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Activity 12</td><td></td><td></td><td></td></tr>
<tr><td colspan="12">Activity 13</td></tr>
</table>

5.5 Equipment and Resources

The following expenses related to equipment and resources are envisaged for the period 2011 to 2013:

(a) **Academic-related expenses (R 25 000):**

i. Registration, tuition and continuation fees (R 25 000).

(b) **Project-capital expenses (R 25 000):**

i. GIS and 30-metre resolution DEM data sets (R 10 000);
ii. Annual renewal of ArcGIS 9.3 or later student licence (R 6 000; 2011- 2013);
iii. Language revision (R 5 000); and
iv. Binding and printing of dissertation (R 4 000).

(c) **Running expenses (R 20 000):**

i. Subsistence and travel (Visits to supervisor, Prof JC Smithers, R 10 000); and
ii. Meetings/workshops and supplies/services (R 10 000).

5.6 Intellectual Property Considerations

The official documentation of the University of KwaZulu-Natal related to intellectual property titled: *Intellectual Property and Proprietary Information Agreement (Form IP2)*, was signed and submitted to the School of Bioresources Engineering and Environmental Hydrology on the 21st of February 2011.

5.7 Expected Outcomes and Deliverables

The following outcomes and deliverables are envisaged as a final product from this study:

(a) **Knowledge contributions:**

i. One Doctor of Philosophy in Agricultural Engineering dissertation;
ii. Two/more published articles in accredited journals;
iii. One/more national and international conference attendance/presentation; and
iv. Improved design flood estimation using regionalised methods to estimate catchment response times in South Africa.

(b) **Societal contributions:** Society will benefit from the knowledge contributions listed in (a), as well as the associated updated methods to assess the risks of floods in South Africa, which will result in the improved design of hydraulic structures.

(c) **Health and economical contributions:** The results from the study will improve the reliability of design flood estimation in South Africa, hence reducing the probability of failure of hydraulic structures and associated potential loss of life.

(d) **Environmental contributions:** The impacts of the failure of hydraulic structures on the environment will be reduced as a consequence of the improved estimates of design floods.

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7. APPENDIX A: TABULATED DATA

Table 7.1 Observed flow data used during previous flood studies

Reference number	Catchment number	Area (km^2)	HRU (1972)	Hiemstra and Francis (1979)	Alexander (2002b)	Görgens (2007) and Görgens *et al.* (2007)	Record length		
							Start	**End**	**Years**
1	A2H001	2 909		X			1904	1922	18
2	A2H002	1 207	X	X			1904	1922	18
3	A2H003	495	X	X	X		1904	1929	25
4	A2H004	137			X		1903	1946	43
5	A2H005	808			X		1904	1950	46
6	A2H006	1 028	X		X	X	1905	2003	98
7	A2H007	142			X		1905	1951	46
8	A2H012	2 551		X	X	X	1922	2003	81
9	A2H013	1171	X		X	X	1922	2003	81
10	A2H015	23 940					1927	1931	4
11	A2H017	70					1927	1936	9
12	A2H019	613				X	1951	1983	32
13	A2H020	4 558					1951	1970	19
14	A2H021	7 483				X	1955	2003	48
15	A3H001	1 165	X	X	X		1906	1939	33
16	A4H002	1 777			X		1948	2003	55
17	A5H004	629			X	X	1962	2003	41
18	A6H002	984			X		1971	2003	32
19	A6H006	168			X	X	1949	2003	54
20	A7H003	6 700			X		1947	2003	56
21	A9H001	912	X				1931	2003	72
22	A9H002	96	X				1931	2003	72
23	A9H003	62	X				1931	2003	72
24	B1H001	3 989	X		X		1904	1951	47
25	B1H004	376				X	1959	2003	44
26	B2H001	1 594	X	X	X		1904	1951	47
27	B4H003	2 240		X	X		1955	2003	48
28	B6H001	508	X		X	X	1909	2003	94
29	B6H002	97	X				1909	1939	30
30	B7H002	58	X		X		1948	2003	55
31	B7H003	98				X	1948	1973	25
32	B7H004	136	X	X	X	X	1950	2003	53
33	B8H008	4 716				X	1959	2003	44
34	B8H009	851	X			X	1960	2003	43
35	B8H010	477	X			X	1960	2003	43
36	C1H001	8 193		X	X	X	1905	2003	98
37	C1H002	4 152			X		1906	2003	97
38	C2H001	3 595			X		1904	2003	99
39	C2H003	38 564				X	1923	2003	80
40	C2H018	49 120				X	1938	2003	65
41	C3H003	10 990			X		1923	2003	80
42	C3H004	10 204		X			1923	1947	24
43	C3H007	24 097				X	1948	2003	55
44	C4H001	5 504		X	X		1923	1947	24
45	C4H002	17 550		X	X		1935	1972	37
46	C4H003	5 404			X		1938	1954	16
47	C5H003	1 650	X				1918	1954	36

Table 7.1 Observed flow data used during previous flood studies (continued)

Reference number	Catchment number	Area (km²)	HRU (1972)	Hiemstra and Francis (1979)	Alexander (2002b)	Görgens (2007) and Görgens *et al.* (2007)	Record length		
							Start	End	Years
48	C5H004	5 012	X	X	X		1904	1947	43
49	C5H007	348	X	X	X		1923	2003	80
50	C5H008	593			X		1931	1986	55
51	C5H010	1 994		X			1931	1948	17
52	C5H012	2 372	X	X	X		1936	2003	67
53	C5H015	6 009		X	X		1949	1983	34
54	C6H001	5 674			X		1913	2003	90
55	C7H001	5 255		X	X		1923	1948	25
56	C8H001	15 673				X	1923	2003	80
57	C8H003	806	X		X	X	1964	2003	39
58	C9H003	120 902		X		X	1909	2003	94
59	C9H006	108 652		X			1937	2003	66
60	C9H008	115 057				X	1947	2003	56
61	D1H001	2 397	X		X		1912	2003	91
62	D1H003	37 075			X		1914	2003	89
63	D1H004	348	X		X		1925	1981	56
64	D1H005	10 680		X	X	X	1932	2003	71
65	D1H006	3051			X		1949	2003	54
66	D2H001	13 421			X		1919	1978	59
67	D2H003	1 424	X				1935	1954	19
68	D2H005	3 857	X	X			1941	1956	15
69	D3H005	91 994		X			1948	2003	55
70	D4H002	342	X		X		1927	1964	37
71	D5H001	2 129		X	X		1927	1953	26
72	D5H002	17 154			X		1927	1948	21
73	D5H003	1 509			X	X	1927	2003	76
74	D5H004	5 799		X	X		1929	1979	50
75	D5H008	354	X				1935	1950	15
76	D5H009	766	X				1936	1947	11
77	D6H002	6 440	X	X			1926	1942	16
78	E2H002	6 903	X	X	X		1923	2003	80
79	E2H003	24 044	X		X	X	1927	2003	76
80	E2H006	24 044			X		1927	2003	76
81	G1H002	187	X	X			1951	1970	19
82	G1H003	46	X		X		1959	2003	44
83	G1H004	70	X		X	X	1979	2003	24
84	G1H007	712	X		X		1951	1979	28
85	G1H008	395	X		X	X	1954	2003	49
86	G2H008	121	X		X		1979	2003	24
87	G4H005	146			X	X	1957	2003	46
88	G5H005	658			X		1952	1980	28
89	G5H006	3			X		1956	2003	47
90	H1H003	657	X		X		1923	2003	80
91	H1H006	753		X		X	1950	2003	53
92	H1H007	84	X	X	X	X	1950	2003	53
93	H1H018	113		X		X	1969	2003	34
94	H2H003	718	X		X	X	1950	2003	53
95	H3H001	611			X		1925	1947	22
96	H4H005	24			X	X	1950	1981	31
97	H4H006	2 939			X	X	1950	2003	53

Table 7.1 Observed flow data used during previous flood studies (continued)

Reference number	**Catchment number**	**Area (km²)**	**HRU (1972)**	**Hiemstra and Francis (1979)**	**Alexander (2002b)**	**Görgens (2007) and Görgens *et al.* (2007)**	**Record length**		
							Start	**End**	**Years**
98	H6H003	497			X		1932	1974	42
99	H6H008	38			X		1964	2003	39
100	H7H003	451	X				1949	1967	18
101	H7H004	28	X	X	X	X	1951	2003	52
102	H7H005	28			X		1951	2003	52
103	J1H006	319			X		1948	1977	29
104	J2H003	17 815		X	X		1924	1942	18
105	J2H005	253			X	X	1955	2003	48
106	J2H007	25				X	1955	2003	48
107	J3H001	1 484	X				1912	1922	10
108	J3H003	422			X		1913	1965	52
109	J3H004	4 252		X	X		1923	2003	80
110	J3H005	95			X		1926	1947	21
111	K1H001	144			X		1953	1977	24
112	K1H002	3.8			X		1958	2003	45
113	K2H002	131	X		X	X	1961	2003	42
114	K3H001	47	X				1961	2003	42
115	K4H002	22	X		X	X	1961	2003	42
116	K4H003	72	X			X	1961	2003	42
117	K5H002	133	X			X	1961	2003	42
118	L2H002	899	X				1925	1952	27
119	L7H002	25 587		X			1928	1985	57
120	N1H003	1 040	X				1927	1932	5
121	N2H002	11 395				X	1923	2003	80
122	N3H001	1 598	X				1928	1947	19
123	Q1H001	9 091		X	X		1918	2003	85
124	Q1H006	1 577	X				1927	1948	21
125	Q2H001	2 445	X				1982	2003	21
126	Q3H001	862	X		X		1926	1948	22
127	Q6H001	686	X				1918	1937	19
128	Q7H001	18 989		X			1906	1928	22
129	Q7H002	18 452		X			1922	1948	26
130	Q7H003	18 503			X		1928	1948	20
131	Q8H001	19 134	X				1972	2003	31
132	Q8H004	808			X		1957	1986	29
133	Q9H002	1 245	X		X	X	1926	2003	77
134	Q9H004	409	X		X		1926	1964	38
135	Q9H008	748	X		X		1921	1970	49
136	Q9H010	29 328		X			1930	1957	27
137	Q9H011	539	X		X		1931	1967	36
138	Q9H012	23 067		X			1935	2003	68
139	R1H001	238	X		X		1928	2003	75
140	R1H002	665	X				1938	1950	12
141	R1H005	482	X		X	X	1948	2003	55
142	R1H013	1 515			X		1950	1986	36
143	R2H005	411	X		X		1977	1980	3
144	R2H007	82	X		X		1947	1981	34
145	R2H008	61	X		X		1947	2003	56
146	R2H009	103			X		1947	2003	56
147	S2H001	500	X				1972	2003	31

Table 7.1 Observed flow data used during previous flood studies (continued)

Reference number	**Catchment number**	**Area (km^2)**	**HRU (1972)**	**Hiemstra and Francis (1979)**	**Alexander (2002b)**	**Görgens (2007) and Görgens *et al.* (2007)**	**Record length**		
							Start	**End**	**Years**
148	S3H002	796	X		X		1947	2003	56
149	S6H001	90			X	X	1947	2003	56
150	S6H002	49	X				1947	2003	56
151	T1H004	4 908			X	X	1953	2003	50
152	T3H002	2 101	X	X	X		1949	2003	54
153	T3H004	1 029	X		X		1947	2003	56
154	T3H005	2 597	X			X	1951	2003	52
155	T3H006	4 268				X	1951	2003	52
156	T4H001	715	X		X	X	1942	2003	61
157	T5H001	3 643	X		X		1931	2003	72
158	T5H004	545	X		X		1949	2003	54
159	U2H005	2 519			X	X	1950	2003	53
160	U2H006	339				X	1954	2003	49
161	U2H011	176				X	1957	2003	46
162	U2H012	438	X			X	1960	2003	43
163	U2H013	299	X				1960	2003	43
164	U4H002	316			X		1949	2003	54
165	V1H003	1 689			X		1931	2003	72
166	V1H004	441	X				1949	1974	25
167	V1H006	441			X		1949	1974	25
168	V1H009	196	X			X	1954	2003	49
169	V2H001	1 976	X		X		1934	1947	13
170	V2H002	937	X		X	X	1950	2003	53
171	V3H005	676			X	X	1951	2003	52
172	V3H007	129				X	1948	2003	55
173	V5H002	28 920			X	X	1956	2003	47
174	V6H002	12 862			X		1927	2003	76
175	W2H002	3 468	X		X		1947	1962	15
176	W3H001	1 467	X				1928	2003	75
177	W4H002	7 081	X				1929	1968	39
178	W4H003	5 788			X		1929	1968	39
179	W4H004	948	X				1950	2003	53
180	W5H005	804	X	X	X		1950	2003	53
181	W5H006	180			X		1950	2003	53
182	W5H007	531	X				1951	1968	17
183	W5H008	701			X		1951	2003	52
184	X1H001	5 499	X		X	X	1909	2003	94
185	X2H002	176		X			1904	1947	43
186	X2H008	180	X		X	X	1948	2003	55
187	X2H009	280	X		X		1946	1966	18
188	X2H010	126			X	X	1948	2003	55
189	X2H011	402	X			X	1956	2003	47
190	X2H015	1 554	X			X	1959	2003	44
191	X2H018	618	X				1960	2003	43
192	X2H022	1 639	X				1960	2003	43
193	X3H001	174			X		1916	2003	87
194	X3H003	52	X			X	1948	2003	55
195	X3H006	766	X		X	X	1958	2003	45
Total number of stations used			**96**	**43**	**119**	**65**	**Average record length**		**47**

8. APPENDIX B: GIS-BASED DATA

FLOOD DATABASE: PROPOSED 195 CATCHMENTS/FLOW GAUGING STATIONS

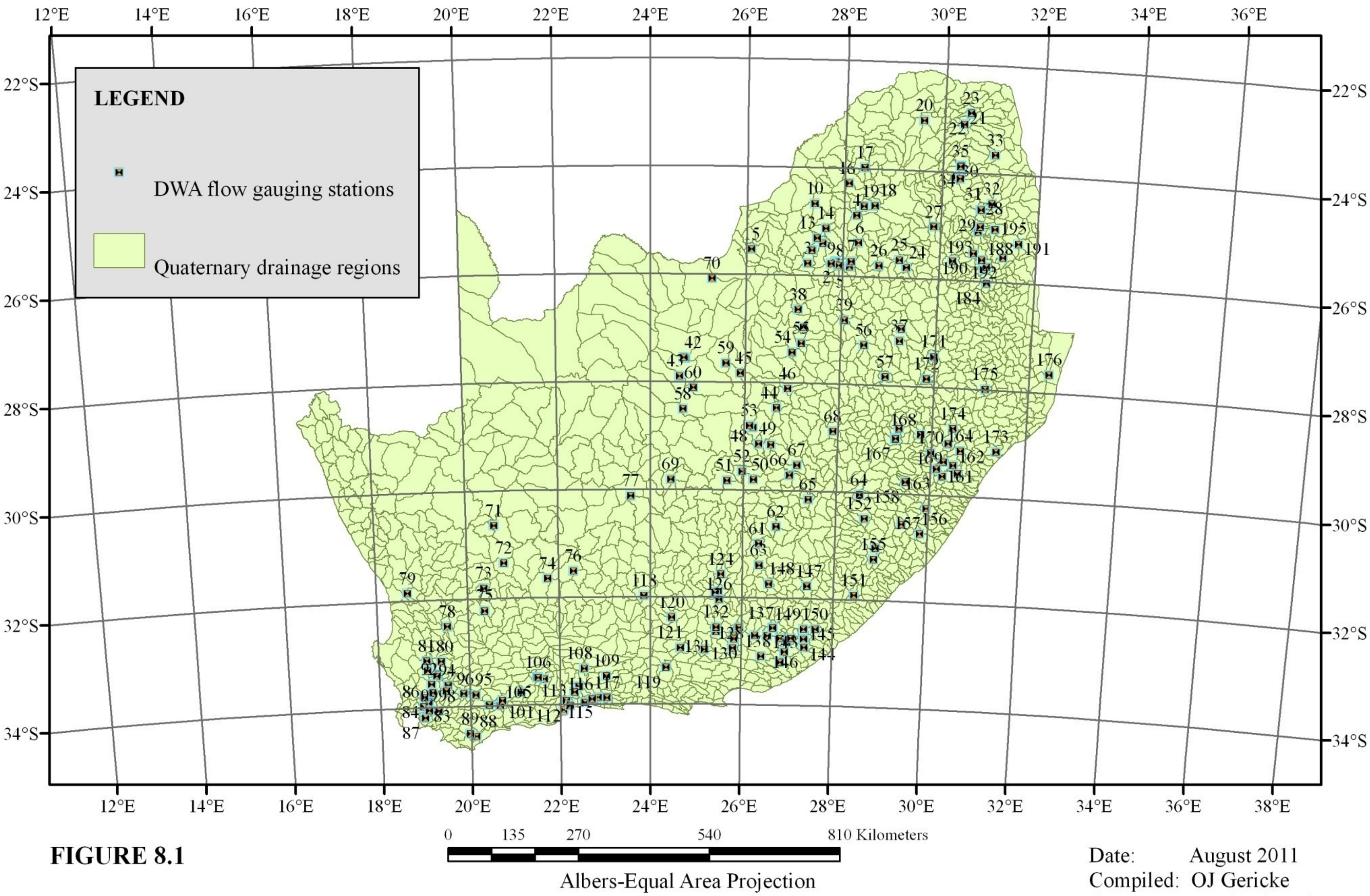

FIGURE 8.1

Date: August 2011
Compiled: OJ Gericke
Source: DWAF (1995)