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Catchment parameter analysis in flood hydrology using GIS applications

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The use of Geographical Information Systems (GIS) has permeated almost every field in the engineering, natural and social sciences, offering accurate, efficient, reproducible methods for collecting, viewing and analysing spatial data. GIS do not inherently have all the hydrological simulation capabilities that complex hydrological models do, but are used to determine many of the catchment parameters that hydrological models or design flood estimation methods require. The purpose of this study was to perform catchment parameter analysis using GIS applications available in the ArcGIS^{TM} environment. The paper will focus on the deployment of special GIS spatial modelling tools versus conventional manual methods used in conjunction with standard GIS tools to estimate typical catchment parameters, e.g. area, average catchment and watercourse slopes, main watercourse lengths and the catchment centroid. The manual catchment parameter estimation methods with GIS-based input parameters demonstrated an acceptable degree of association with the special GIS spatial modelling tools, but proved to be sensitive to biased user-input at different scale resolutions. GIS applications in an ArcGIS^{TM} environment for the purpose of catchment parameter analyses are recommended to be used as the standard procedure in any proposed hydrological assessment.

INTRODUCTION

The use of Geographical Information Systems (GIS) has permeated almost every field in the engineering, natural and social sciences, offering accurate, efficient, reproducible methods for collecting, viewing and analysing spatial data. These spatial data sets represent the key components in the hydrological response of catchments to storm rainfall and the resulting runoff. GIS do not inherently have the hydrological simulation capabilities that complex hydrological models do, but are used to determine many of the catchment parameters that hydrological models or design flood estimation methods require.

In hydrological catchment parameter analyses, a Digital Elevation Model (DEM) and spatial data sets represent the two fundamental data sets initially required. The DEM contains raster information of the catchment and surrounding areas, while the spatial data sets contain the spatial information which originates from other sources than the DEM. The DEM is used to do a complete catchment parameter analysis, including the determination of flow directions, catchment areas, land surface and river channel characteristics. The spatial data sets contain layers of combined spatial information used to analyse the spatial distribution and associated attributes of geology, soil, land use and vegetation.

In addition to catchment parameter analysis, GIS also provide a powerful data management framework with a consistent, intuitive platform for organising and analysing relationships amongst the spatial variables and information associated with those variables encountered in the field of flood hydrology. Various GIS software packages exist. This paper will, however, only refer to the Environmental Systems Research Institute (ESRI) GIS software in the form of ArcGIS^{TM} 9.3.

The purpose of the study is discussed and explained in the next section, followed by an overview of the study area's spatial distribution and characteristics. In the section thereafter, the methods used in South Africa to estimate catchment parameters are reviewed in detail. The methodologies involved in assessing the paper's purpose and objectives are then expanded on in detail, followed by the results, discussion and conclusions.

PURPOSE OF STUDY

The purpose of this study was to perform catchment parameter analysis using GIS applications available in the ArcGIS^{TM} environment. The focus was on the deployment of special GIS spatial modelling tools versus conventional manual methods used in conjunction with standard GIS tools to estimate typical catchment parameters,

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Key words: catchment parameters, GIS, DEM, average slope, flood hydrology

Table 1 General catchment information (Gericke 2010)

Catchment descriptor	Gauging station name	Area (A, km^2)	Contributing tertiary/ quaternary catchment(s)
C5R001	Tierpoort Dam	921,6	C51D
C5R002	Kalkfontein Dam	10 259,9	C51A to H and J
C5R003	Rustfontein Dam	936,7	C52A
C5R004	Krugersdrift Dam	6 330,9	C52A to G
C5R005	Groothoek Dam	116,4	C52B
C5H003	Modder River at Likatlong	1 650,0	C52A to B
C5H012	Riet River at Kromdraai	2 366,3	C51A and C51B
C5H015	Modder River at Stoomhoek	6 009,0	C52A to G
C5H016	Riet River at Biesiesbult	33 277,2	C51 and C52A to H and J to L
C5H018	Modder River at Twee River	17 360,3	C52A to H and J to L
C5H022	Kgabanyane River at Bedford	38,0	C52B
C5H054	Renosterspruit at Bishop's Glen	687,8	C52F

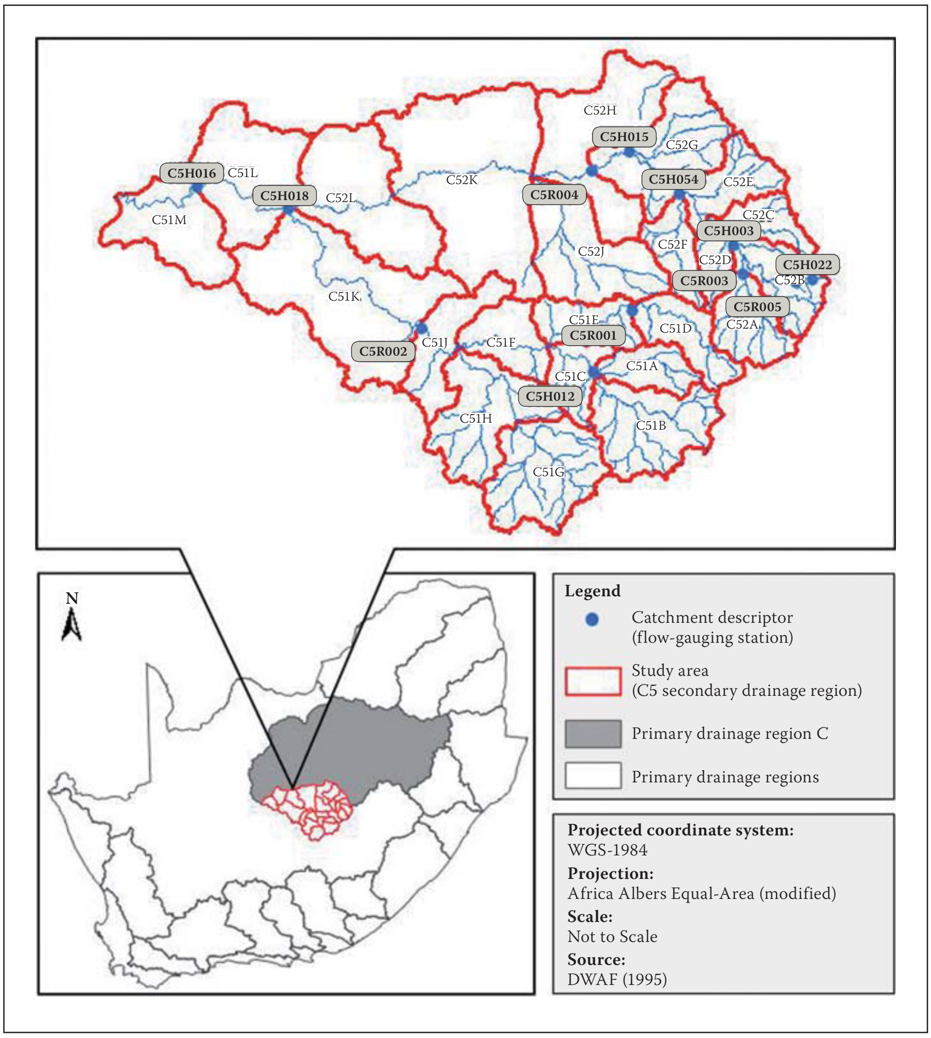


Figure 1 Location of study area in relation to the primary drainage regions of South Africa

e.g. area, average catchment and watercourse slopes, main watercourse lengths and the catchment centroid.

It was hypothesised that the accuracy of conventional manual procedures used in flood hydrology to establish typical catchment parameters could be improved by using automated GIS input processing functionalities, since manual inputs are regarded as insufficiently accurate and outdated. It was further hypothesised that the spatial distribution of slope classes, used as primary input data to the deterministic flood estimation methods, are not sufficiently representative of the specific conditions under evaluation. Many practitioners in the field of flood hydrology typically ignore the importance thereof and follow a "thumb-suck" approach. In addition, hydrologists and engineers are frequently doubtful when deciding on, or determining, the position of the catchment centroid.

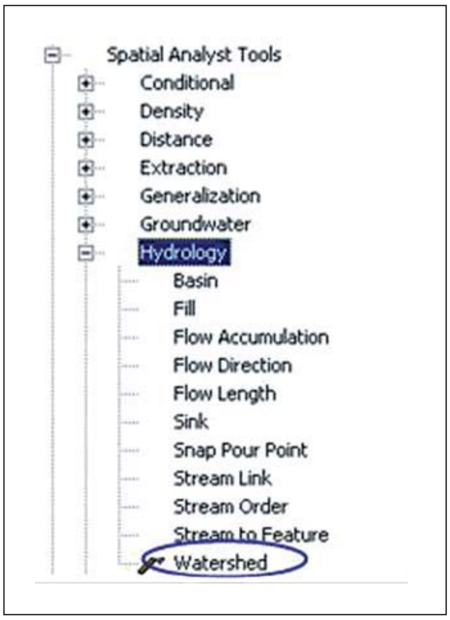


Figure 2 *Hydrology* toolset and associated *Watershed* tool

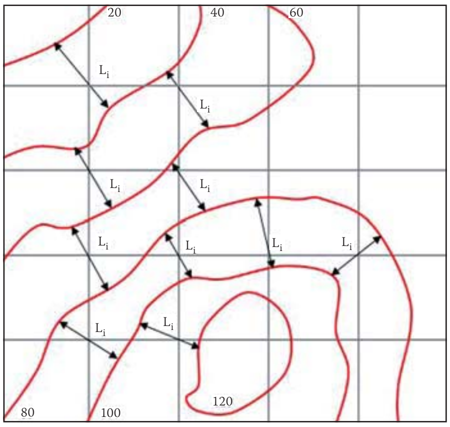


Figure 3 Average catchment slope using the Grid method (Alexander 2001)

STUDY AREA

The study area covers 34 795 km^2 between 28°25' and 30°17' South and 23°49' and 27°00' East, and comprises the C5 secondary drainage region. The tertiary drainage regions of concern are C51 (Riet River Catchment (RRC)) and C52 (Modder River Catchment (MRC)), covering an area of 17 435 km^2 and 17 360 km^2 respectively. The MRC and RRC consist of eleven and twelve quaternary catchments respectively (Midgley *et al* 1994). The topography is gentle (average quaternary catchment slopes between 2,4% and 5,5%), while the mean altitude above sea level varies between 997 m and 2 122 m (NASA 2002).

Twelve catchments with contributing catchment areas consisting of either single or multiple C51 or C52 quaternary catchments were evaluated individually in the study area. A Department of Water Affairs (DWA) flow-gauging station is situated at the outlet of each of these catchments. The flow-gauging station numbers were therefore used as the catchment descriptor for easy reference in all the Tables and Figures included in this paper. The general information applicable to these catchments is listed in Table 1, while the location thereof within the study area and in relation to the primary drainage regions of South Africa is shown in Figure 1.

REVIEW OF CATCHMENT PARAMETER ESTIMATION METHODS

To provide the background for further discussion, the manual and automated methods used in design flood estimation to establish catchment parameters, will now be discussed briefly.

Catchment area

The standard maps recommended to manually determine the catchment areas for use in flood hydrology are either the 1:50 000 scale topographical maps and/or 1:10 000 scale orthophotos. The latter are normally used if the catchment area under consideration is less than 10 km². The manual procedure to determine the catchment area entails that the demarcated catchment boundary on the map is copied onto graph paper, after which the number of squares within the catchment are counted by including squares more than halfway into the catchment. A conversion factor is then used to convert the number of squares to the catchment area in km² (Alexander 2001). Planimeters are also still in use to measure the manually demarcated catchment areas.

Alternatively, the aforementioned standard maps in an electronic format can be imported to a suitable Computer-Aided Design (CAD) environment as a picture file, after which standard CAD functions are used for the demarcation and area calculation respectively. The use of *Google Maps* as alternative is also worthwhile to consider.

In an ArcGIS^{TM} 9.3 environment, the *Watershed* tool contained in the *Hydrology* toolset of the *Spatial Analyst Tools* toolbox (Figure 2) can be used to identify catchment areas for specified pour points representative of the catchment outlet. However, a hydrologically correct and depressionless DEM must be prepared for these calculations, using most of the tools contained in the *Hydrology* toolset.

Average catchment slope

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 any one of the Grid, Empirical or Neighbourhood methods in conjunction with standard tools available in the ArcGIS^{TM} 9.3 environment.

Grid method

A grid of at least 50 squares must be superimposed over the catchment area. At each grid intersection point, the horizontal (shortest) distance between the contour intervals which straddle the grid point along a line that passes through the grid point, is measured. The average catchment slope is consequently defined as the average slope perpendicular to the nearest contour line at each grid point. This is presented diagrammatically in Figure 3 and expressed by Equation 1 (Alexander 2001).

$$S_1 = \frac{\Delta H}{\sum_{i=1}^{N} \frac{L_i}{N}} \qquad (1)$$

where:

S_1 = average catchment slope (m/m)
ΔH = contour interval (m)
L_i = horizontal distance between consecutive contours (m), and
N = number of grid points.

Empirical method

According to Schulze *et al* (1992), the average catchment slope can be determined by making use of the following empirical relationship (Equation 2):

$$S_2 = \frac{M \Delta H * 10^{-2}}{A} \qquad (2)$$

where:

S_2 = average catchment slope (m/m)
A = catchment area (km²)
ΔH = contour interval (m), and
M = total length of all contour lines within the catchment (m).

Equation 2 is not widely used, especially due to the tedious task to determine the M values manually. However, the use of Equation 2 in its more rudimentary form (derived from first principles), in conjunction with standard functions in ArcGIS^{TM}, will be highlighted further in the Methodology.

Neighbourhood method

This method is also known as the Average Maximum Technique (Equation 3) and is included as the standard slope algorithm in the ArcGIS^{TM} environment to generate slope rasters from raw DEM and/or point elevation GIS data sets to enable the determination of average catchment slopes and steepness frequency distributions. The slope raster generation is based on a cell matrix approach which represents the maximum change in elevation over the distance between the cell and its eight neighbouring cells. 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 2006b).

$$S_3 = \sqrt{\left(\frac{\Delta z}{\Delta x}\right)^2 + \left(\frac{\Delta z}{\Delta y}\right)^2} \qquad (3)$$

where:

S_3 = average catchment slope (m/m)
$\frac{\Delta z}{\Delta x}$ = rate of change of the slope surface in a horizontal direction from centre cell
$= \left[\frac{(C_3 + 2C_6 + C_9) - (C_1 + 2C_4 + C_7)}{(Nx_C)}\right]$
$\frac{\Delta z}{\Delta y}$ = rate of change of the slope surface in a vertical direction from centre cell
$= \left[\frac{(C_7 + 2C_8 + C_9) - (C_1 + 2C_2 + C_3)}{(Ny_C)}\right]$
$C_{1-4/6-9}$ = surrounding cells
C_5 = centre cell
N = number of grid points or cells
x_C = horizontal cell size, and
y_C = vertical cell size.

Length and average slope of main watercourses

The main watercourse is a defined flow path along which water will travel the longest time to reach the catchment outlet from a point on or near the catchment boundary. This distance can be measured manually on orthophotos or topographical maps by using dividers set at a predefined incremental distance which is a function of the map scale (Alexander 2001). The average main watercourse slope can be determined manually by using the following methods (Alexander 2001; Van der Spuy & Rademeyer 2010):

Equal-area method

An average slope line is drawn or positioned in relation to the longitudinal profile of the main watercourse in such a way that the area above (A_1) this line equals the area below (A_2) the line. This relationship is expressed by Equation 4 and illustrated in Figure 4.

$$S_{CH1} = \frac{(H_T - H_B)}{L} \qquad (4)$$

where:

S_{CH1} = average main watercourse slope (m/m)

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

$$H_T = \frac{\left(\sum_{i=1}^{N} A_i{}^{*}2\right)}{\mathrm{L}} + H_B$$

H_B = height at catchment outlet (m)

H_i = specific contour interval height (m)

L = length of main watercourse (m), and

L_i = distance between two consecutive contours (m).

10-85 method

This method was developed by the United States Geological Survey (USGS) and is the most widely used in South Africa (SANRAL 2006). This relationship is expressed by Equation 5 and illustrated in Figure 5.

$$S_{CH2} = \frac{H_{0,85L} - H_{0,10L}}{750L} \qquad (5)$$

where:

S_{CH2} = average main watercourse slope (m/m)

L = length of main watercourse (km)

$H_{0,85L}$ = height (m) of main watercourse at length 0,85L, and

$H_{0,10L}$ = height (m) of main watercourse at length 0,10L.

Taylor-Schwarz method

This method is preferred by the Department of Water Affairs (DWA) and the Natural Environment Research Council (NERC 1975). The latter also proposed the use thereof in the United Kingdom Flood Studies Report (UK FSR 1975) (Van der Spuy & Rademeyer 2010). The main watercourse profile is subdivided into sub-reaches of which the velocities are related to the square root of the slope. The index is equivalent to the slope of a uniform channel with the same length as the longest watercourse and an equal travel time. This relationship is expressed by Equation 6 and illustrated in Figure 6.

$$S_{CH3} = \left(\frac{L}{\sum_{i=1}^{N} \frac{L_i}{\sqrt{S_i}}}\right) \qquad (6)$$

where:

S_{CH3} = average main watercourse slope (m/m)

L = length of main watercourse (m)

L_i = distance between two consecutive contours (m), and

S_i = slope between two consecutive contours (m/m).

In the ArcGIS$^{\mathrm{TM}}$ environment, both fully and semi-automated methods are available

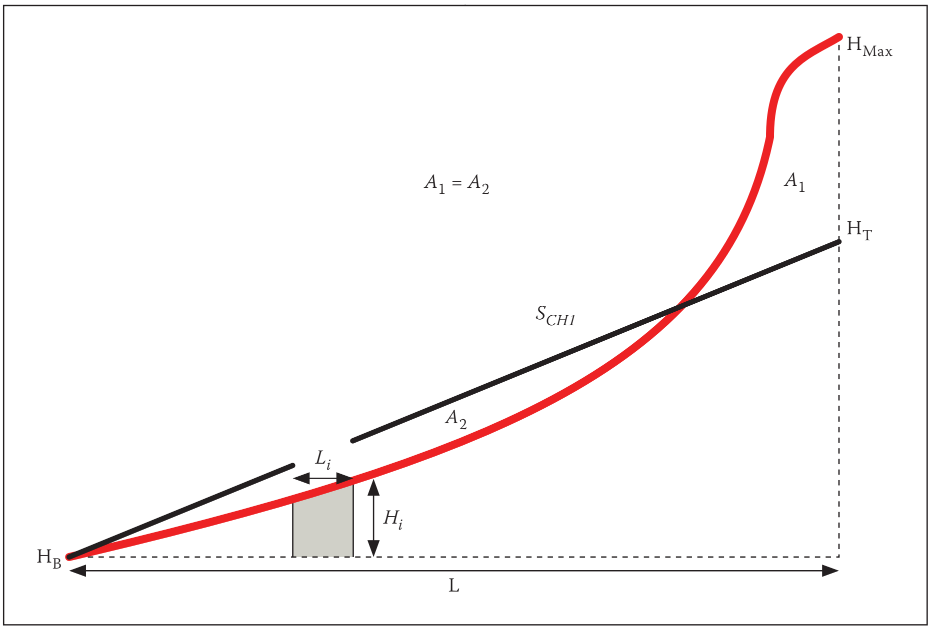


Figure 4 Equal-area method (SANRAL 2006)

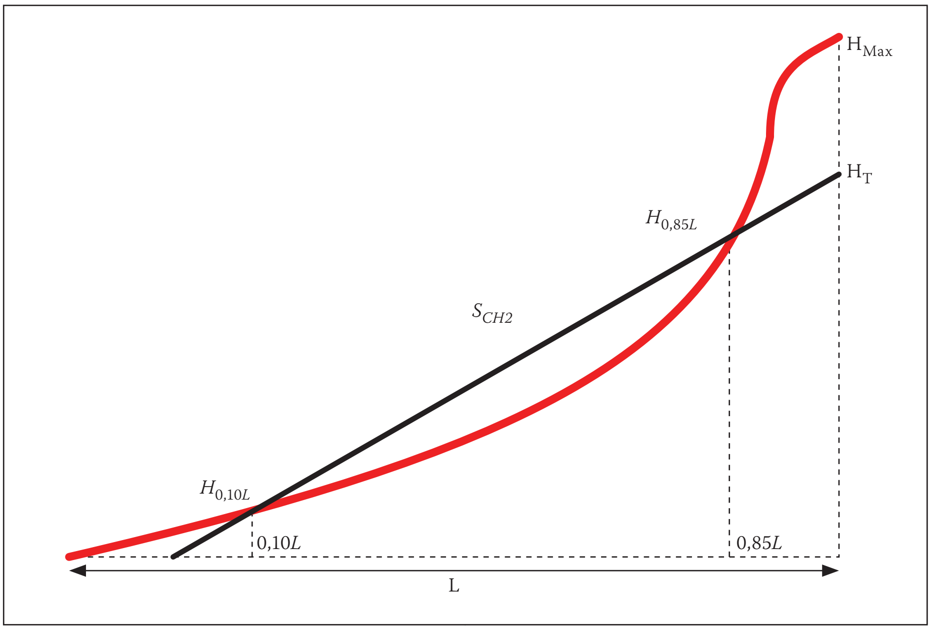


Figure 5 10-85 method (SANRAL 2006)

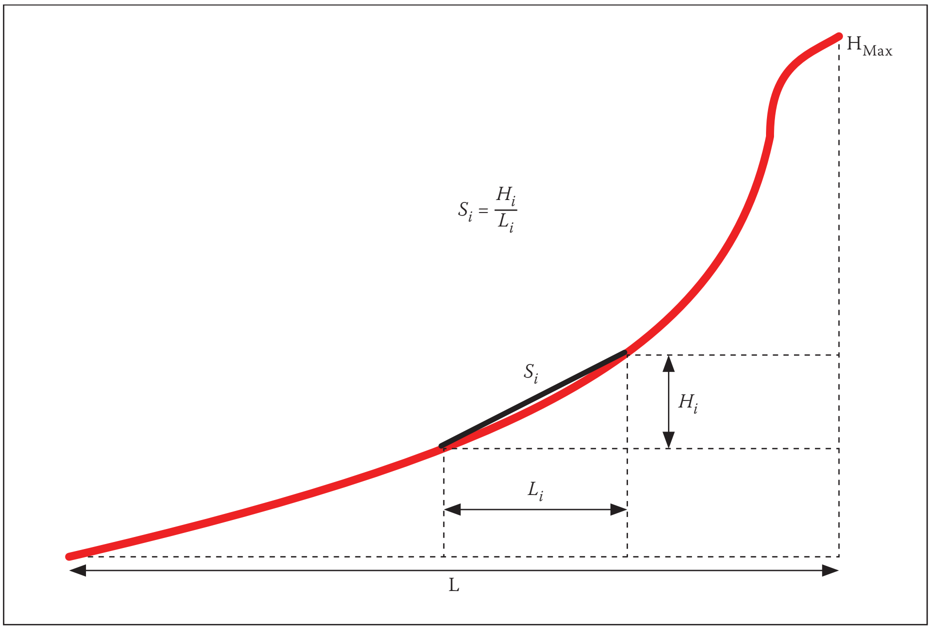


Figure 6 Taylor-Schwarz method (Gericke 2010)

to estimate the main watercourse length. The *Longest Flow Path* tool which forms part of the *ArcHydro* toolbox automatically determines the longest watercourse. However, a hydrologically correct and depressionless DEM based on extensive input rasters with increased computing time is required. The use of semi-automated methods in conjunction with Equations 4 to 6 will be expanded on in detail in the Methodology.

Distance to catchment centroid

According to Alexander (2001), an eyeball estimate of the location of the catchment centroid is adequate. In practice, the distance to the centroid can be determined manually by using a cut-out of the catchment area to hang freely from a pin inserted close to a border of the catchment area. A string with a weight attached to the bottom, attached to the pin and hanging vertically under gravity from the pin, provides a guideline on the paper cut-out of the catchment. With the guideline drawn on the catchment, the pin is then moved to another position (approximately rotated 90° from the first position) close to the boundary of the catchment. The intersection of the two guidelines on the catchment provides the approximate position of the centroid.

In the ArcGIS^{TM} environment, the location of the catchment centroid can be automatically determined by making use of the *Mean Center* tool available in the *Measuring Geographic Distributions* toolset of the *Spatial Statistics Tools* toolbox, which will be expanded on in more detail in the Methodology.

METHODOLOGY

To evaluate the deployment of special GIS spatial modelling tools versus conventional manual methods used in conjunction with standard GIS tools to estimate typical catchment parameters, the following procedures were followed:

Projections and catchment geometry calculations

All the relevant GIS and catchment related data were obtained from the DWA (Directorate: Spatial and Land Information Management), which is responsible for the acquisition, processing and digitising of the data. These data sets are normally presented as geographical coordinate systems; in other words, the position of a geographical location on the earth's surface is described by using spherical measures of latitude and longitude (in degrees) from the centre of the earth to a point on the earth's surface.

Table 2 Modified Albers Equal-Area projection for South Africa (ESRI 2006a)

Parameter description	Modified (original) value
False easting	0 (0)
False northing	0 (0)
Central meridian	24 (25)
Standard parallel 1	-18 (20)
Standard parallel 2	-32 (-23)
Latitude of origin	0 (0)
Linear unit	metre

These geographical input data sets need to be transformed to a projected coordinate system, which portrays the curved surface of the earth on a flat surface, during which the distance, area, shape and direction, or a combination thereof, might be distorted (ESRI 2006a).

The Africa Albers Equal-Area projected coordinate system, with modification, was used during this study. This approach is best suited for land masses extending in an east-to-west orientation (as in the case of the study area), rather than those lying north-to-south. This conic projection uses two standard parallels to reduce some of the distortion of a projection with one standard parallel. Although neither shape nor linear scale is truly correct, the distortion of these properties is minimised in the region between the standard parallels. All areas are proportional to the same areas on the earth, while distances are most accurate in the middle latitudes (ESRI 2006a).

The standard parallels were established by using the *one-sixth rule* by determining the range in latitude (degrees) north to south, divided by six. The first standard parallel is positioned at one-sixth the range above the southern boundary and the second standard parallel minus one-sixth the range below the northern boundary (ESRI 2006a). These modifications are listed in Table 2.

The specific GIS data features classes (lines, points and polygons) applicable to the study area, and individual sub-catchments were extracted and created from the original GIS data sets by using the *Clip* tool available from the *Extract* toolset contained in the *Analysis Tools* toolbox. The *Clip* tool cuts out a piece of one feature class using one or more of the features in another feature class as a cookie cutter. Either the tertiary or quaternary drainage region polygons were used as clip feature classes, since a clip feature class has to be a polygon. The data extraction was followed by data projection and transformation, editing of attribute tables and recalculation of catchment geometry (areas, perimeters and distances).

Digital Elevation Model

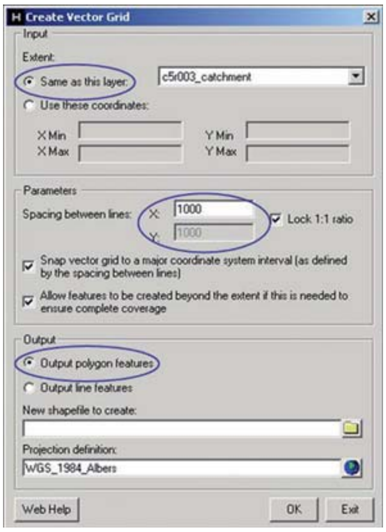
The Shuttle Radar Topography Mission (SRTM) elevation data for southern Africa at 90 metre resolution (NASA 2002) was extracted, projected and transformed for the study area and used as the DEM. An alternative DEM was also generated by making use of point elevation and/or contour data as the input features. The *Interpolation* toolset contained in the *Spatial Analyst Tools* toolbox was used to generate rasters for the DEM interpolation process. The input features (contours or point elevations) were selected, the *Output Surface Raster* was specified and *Tolerance 1* was set to a value of 10, which is equal to half the contour interval, or set to zero if point elevations are predominately used. The *Output Cell Size*, which specifies the output raster cell size, was then selected. A smaller cell size increases the amount of cells in the raster matrix with both an increased accuracy and computing time. A trade-off between time and accuracy was used in selecting the output cell size.

Average catchment slope

The average catchment slope of the study area, as well as of individual catchments, was determined by using the following manual methods with GIS-based input parameters:

Grid method

The *Create Vector Grid* tool available in the *Sampling* toolset of the *Hawth's Analysis Tools* toolbox was used to superimpose a grid over the catchment areas. Refer to Figure 7 for the *Create Vector Grid* data input screen. In Figure 7, the *Extent* selection was in accordance with the extent of the catchment boundary under consideration, while polygon features were selected as the required *Output*, since this option enables geometry (area) calculations. Shapefiles containing the polylines as feature type were created in ArcGIS^{TM}, via the *Sketch* tool accessible from the *Edit* toolbar, to represent the horizontal distances measured at each grid intersection point between two consecutive contours (e.g. Figure 8). The attribute table of each developed shapefile was edited and the length of each polyline was determined by making use of the *Calculate Geometry* function. These attribute tables were then exported to Microsoft Excel for further computations.


Create Vector Grid

Input

Extent:

● Same as this layer: c5r003_catchment

○ Use these coordinates:

X Min
X Max
Y Min
Y Max

Parameters

Spacing between lines: X: 1000 Y: 1000 ☑ Lock 1:1 ratio

☑ Snap vector grid to a major coordinate system interval (as defined by the spacing between lines)

☑ Allow features to be created beyond the extent if this is needed to ensure complete coverage

Output

● Output polygon features

○ Output line features

New shapefile to create:

Projection definition: WGS_1984_Albers

Figure 7 *Create Vector Grid* data input screen

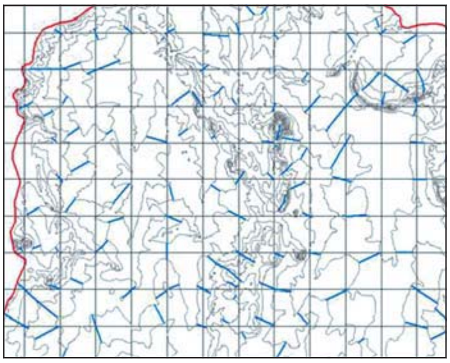
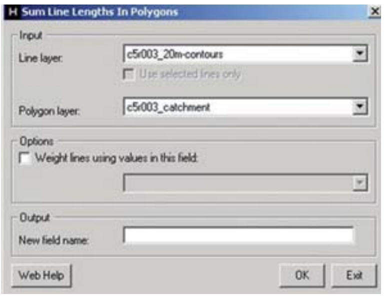


Figure 8 Example of horizontal distances at grid intersection points


Sum Line Lengths In Polygons

Input

Line layer: c5r003_20m-contours

☐ Use selected lines only

Polygon layer: c5r003_catchment

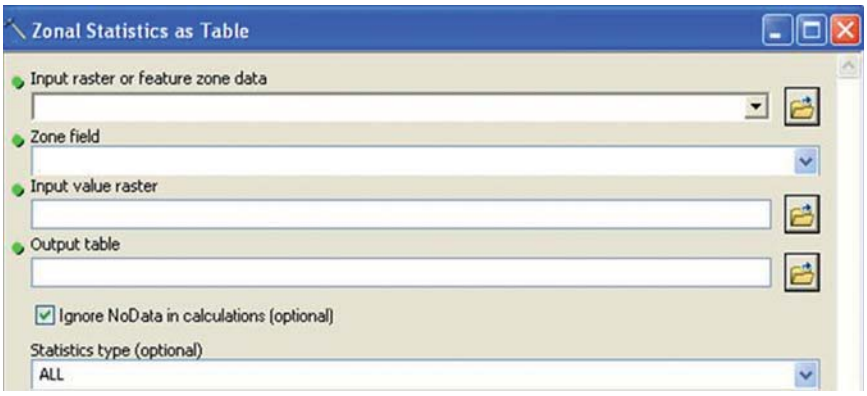
Options

☐ Weight lines using values in this field:

Output

New field name:

Figure 9 *Sum Line Lengths in Polygons* data input screen


Zonal Statistics as Table

Input raster or feature zone data

Zone field

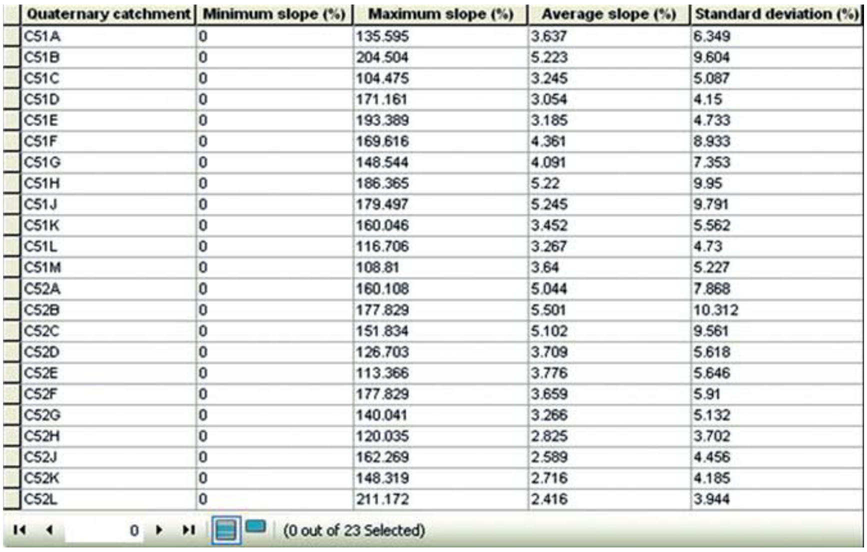
Input value raster

Output table

☑ Ignore NoData in calculations (optional)

Statistics type (optional): ALL

Figure 10 *Zonal Statistics as Table* data input screen



Quaternary catchment	Minimum slope (%)	Maximum slope (%)	Average slope (%)	Standard deviation (%)
C51A	0	135.595	3.637	6.349
C51B	0	204.504	5.223	9.604
C51C	0	104.475	3.245	5.087
C51D	0	171.161	3.054	4.15
C51E	0	193.389	3.185	4.733
C51F	0	169.616	4.361	8.933
C51G	0	148.544	4.091	7.353
C51H	0	186.365	5.22	9.95
C51J	0	179.497	5.245	9.791
C51K	0	160.046	3.452	5.562
C51L	0	116.706	3.267	4.73
C51M	0	108.81	3.64	5.227
C52A	0	160.108	5.044	7.868
C52B	0	177.829	5.501	10.312
C52C	0	151.834	5.102	9.561
C52D	0	126.703	3.709	5.618
C52E	0	113.366	3.776	5.646
C52F	0	177.829	3.659	5.91
C52G	0	140.041	3.266	5.132
C52H	0	120.035	2.825	3.702
C52J	0	162.269	2.589	4.456
C52K	0	148.319	2.716	4.185
C52L	0	211.172	2.416	3.944

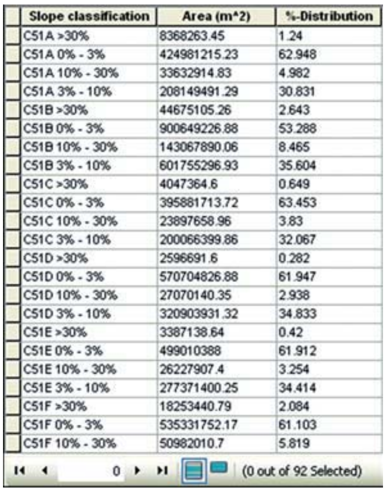
0 (0 out of 23 Selected)

Figure 11 *Summary* table of average slopes in each quaternary catchment

It is important to note that the *Hawth's Analysis Tools Version 3.27* (Beyer 2004) is not a standard toolbox available in ArcGIS^{TM} 9.3, but it can be downloaded from either www.ESRI.com or www.spatialecology.com/htools. However, this toolbox is only compatible with ArcGIS^{TM} 9.3 or earlier versions, since the ArcGIS^{TM} programming interface (ArcObjects) changed with the update to ArcGIS^{TM}10. In this new version of ArcGIS^{TM} the *Hawth's Analysis Tools* was replaced with a toolbox known as the *Geospatial Modelling Environment (GME)*. The *GME* incorporates most of the functionality of its predecessor, but has a greater range of analysis and modelling tools, supports batch processing, offers new graphing functionality, automatically records work-flows for future reference and supports geodatabases (Beyer 2009).

Empirical method

The *Sum Line Lengths in Polygons* tool (Figure 9) in the *Analysis Tools* toolset contained in the *Hawth's Analysis Tools* toolbox was used to calculate the total length of all contour lines (M) within each catchment, after which it was used as an input variable for Equation 2. The other input variables, area (A) and the contour interval (ΔH), were obtained from the relevant developed feature classes of the study area.



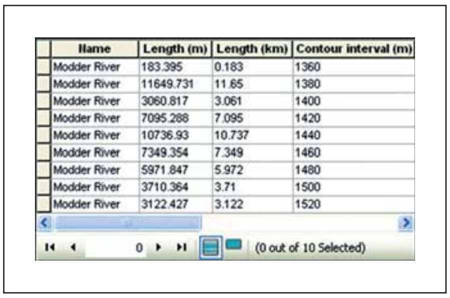
Slope classification	Area (m^2)	%-Distribution
C51A >30%	8368263.45	1.24
C51A 0% - 3%	424981215.23	62.948
C51A 10% - 30%	33632914.83	4.982
C51A 3% - 10%	208149491.29	30.831
C51B >30%	44675105.26	2.643
C51B 0% - 3%	900649226.88	53.288
C51B 10% - 30%	143067890.06	8.465
C51B 3% - 10%	601755296.93	35.604
C51C >30%	4047364.6	0.649
C51C 0% - 3%	395881713.72	63.453
C51C 10% - 30%	23897658.96	3.83
C51C 3% - 10%	200066399.86	32.067
C51D >30%	2596691.6	0.282
C51D 0% - 3%	570704826.88	61.947
C51D 10% - 30%	27070140.35	2.938
C51D 3% - 10%	320903931.32	34.833
C51E >30%	3387138.64	0.42
C51E 0% - 3%	499010388	61.912
C51E 10% - 30%	26227907.4	3.254
C51E 3% - 10%	277371400.25	34.414
C51F >30%	18253440.79	2.084
C51F 0% - 3%	535331752.17	61.103
C51F 10% - 30%	50982010.7	5.819

0 (0 out of 92 Selected)

Figure 12 Example of reclassified *Summary* table with slope frequency distribution classes

Neighbourhood method

A slope raster was generated from the raw DEM data using the *Slope* tool available from the *Surface* toolset contained in the *Spatial Analyst Tools* toolbox. The generated slope raster is based on a cell matrix approach, which represents the maximum change in elevation over the distance between the cell and its eight neighbouring cells, thus the maximum slope for each cell. The *Zonal Statistics as Table* tool in the *Zonal* toolset contained in the *Spatial Analyst Tools* toolbox (Figure 10) was applied on the slope raster to generate a summary table containing the statistical information about the input data or raster for a defined zone within



Name	Length (m)	Length (km)	Contour interval (m)
Modder River	183.395	0.183	1360
Modder River	11649.731	11.65	1380
Modder River	3060.817	3.061	1400
Modder River	7095.288	7.095	1420
Modder River	10736.93	10.737	1440
Modder River	7349.354	7.349	1460
Modder River	5971.847	5.972	1480
Modder River	3710.364	3.71	1500
Modder River	3122.427	3.122	1520

Figure 13 Example of main watercourse attribute table

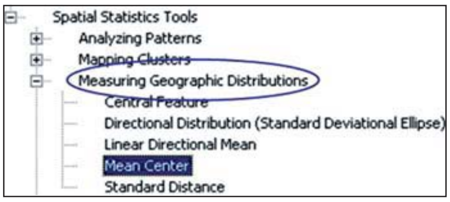


Figure 14 *Measuring Geographic Distributions* toolset for catchment centroid estimation

the data frame, thus the average slope for each catchment (Figure 11). The slope raster was converted to a feature class (polygons) and reclassified into four slope frequency distribution classes, e.g. 0-3%, 3-10%, 10-30% and >30% as required by the deterministic flood estimation methods (SANRAL 2006; Van der Spuy & Rademeyer 2010) to establish the surface slope coefficients associated with different Mean Annual Precipitation (MAP) ranges. This conversion was done by using the *Raster to Polygon* tool in the *Conversion Tools* toolbox of *ArcToolbox*, while the *Reclassify* tool in the *Reclass* toolset contained in the *Spatial Analyst Tools* toolbox was used for the reclassification. The reclassified summary table is shown in Figure 12.

Length and average slope of main watercourses

The main watercourse in each catchment was manually identified in ArcMap. A new shapefile containing polyline feature classes representative of the identified main watercourse was created by making use of the *Trace* tool in the *Editor* toolbar. Each identified main watercourse was traced using the polyline feature classes of the 20 m interval contour shapefile as the specified offset or point of intersection, resulting in chainage distances between two consecutive contours. The attribute table of each shapefile was then edited by using the *Add Field* function to include the reduced heights of the contour intervals, and the length of each polyline was determined by making use of the *Calculate Geometry* function. These attribute tables (e.g. Figure 13) can then be exported to Microsoft Excel for further computations and used as input data for the deterministic and empirical methods used in design flood estimation.

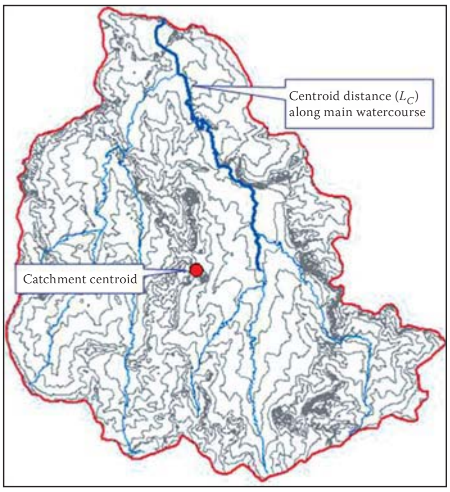


Figure 15 Example of catchment centroid location and distance

Table 3(a) Altitude above sea level frequency distribution (Gericke 2010)

Altitude above sea level class (m)	Area (A, km²)	% Distribution
997 – 1 200	6 592,6	18,90
1 200 – 1 400	18 443,2	53,00
1 400 – 1 600	9 273,2	26,70
1 600 – 1 800	474,1	1,40
1 800 – 2 122	11,8	0,03
Total	34 794,8	100

Table 3(b) Slope frequency distribution (Gericke 2010)

Catchment description	Slope classification (%)	% Distribution
Study area	0 – 3	62,8
	3 – 10	31,4
	10 – 30	4,8
	> 30	1

Distance to catchment centroid

The centroid of each catchment under consideration was determined by making use of the *Mean Center* tool in the *Measuring Geographic Distributions* toolset contained in the *Spatial Statistics Tools* toolbox (Figure 14). Only the input polygon feature class representative of each catchment has to be selected to result in a point output feature class and associated attribute table representative of the x and y coordinate of the geometric centroid of each catchment (e.g. Figure 15). The length of the identified main watercourse in each catchment to a point opposite the identified centroid within the catchment was established by using the *Measure* tool in ArcMap. This measured length (L_C) represents the distance along the main watercourse between the outlet and the point closest to the centroid of the catchment (*e.g.* Figure 15).

RESULTS AND DISCUSSIONS

The results based on the methodology used during this study will now be discussed.

Projections and catchment geometry calculations

The frequency distribution of the altitude-above-sea-level classes present in the study area is summarised in Table 3 (a), while the slope-frequency-distribution classes based on the developed DEM (slope raster) are listed in Table 3 (b). The class-to-class variation and frequency distribution of the altitude-above-sea-level classes are indicative that the topography is relatively flat and that flood peaks will be attenuated and translated both in magnitude and duration respectively. The developed DEM for the study area is illustrated in Figure 16.

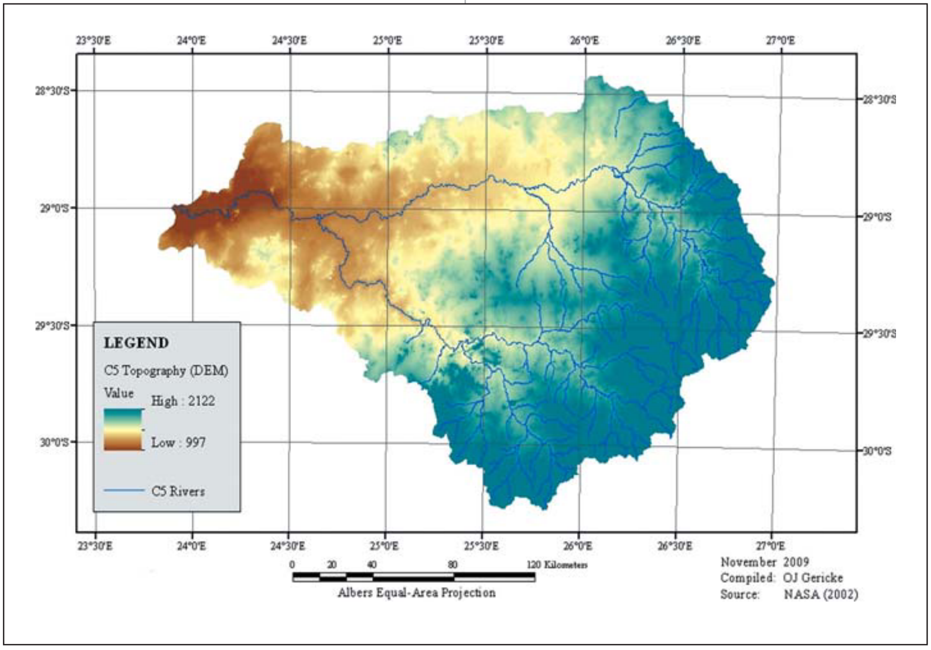


Figure 16 DEM of the study area (Gericke 2010)

Table 4 Average catchment slope based on Neighbourhood method (DEM data) (Gericke 2010)

Catchment descriptor	Area (A, km²)	Average slope (S, %)
C5R001	921,6	3,054
C5R002	10 259,9	4,369
C5R003	936,7	5,044
C5R004	6 330,9	4,186
C5R005	116,4	5,501
C5H003	1 650,0	5,044
C5H012	2 366,3	4,771
C5H015	6 009,0	4,186
C5H016	33 277,2	3,598
C5H018	17 360,3	3,211
C5H022	38,0	5,501
C5H054	687,8	3,659

Table 5 Average catchment slope based on Grid method (Gericke 2010)

Catchment descriptor	Area (A, km²)	Proposed number of grid points (N_P Alexander 1990)	Actual number of grid points used (N)	Average slope (S_I, %)	% Difference compared to Neighbourhood method
C5R001	921,6	≥ 50	250	2,072	32,2
C5R002	10 259,9	≥ 50	3 400	3,060	30,0
C5R003	936,7	≥ 50	450	4,123	18,3
C5R004	6 330,9	≥ 50	2 220	2,919	30,3
C5R005	116,4	≥ 50	50	3,713	32,5
C5H003	1 650,0	≥ 50	450	4,200	16,7
C5H012	2 366,3	≥ 50	1 030	3,610	24,3
C5H015	6 009,0	≥ 50	2 220	2,850	31,9
C5H016	33 277,2	≥ 50	7 200	2,461	31,6
C5H018	17 360,3	≥ 50	3 300	2,211	31,1
C5H022	38,0	≥ 50	50	3,720	32,4
C5H054	687,8	≥ 50	305	2,479	32,2

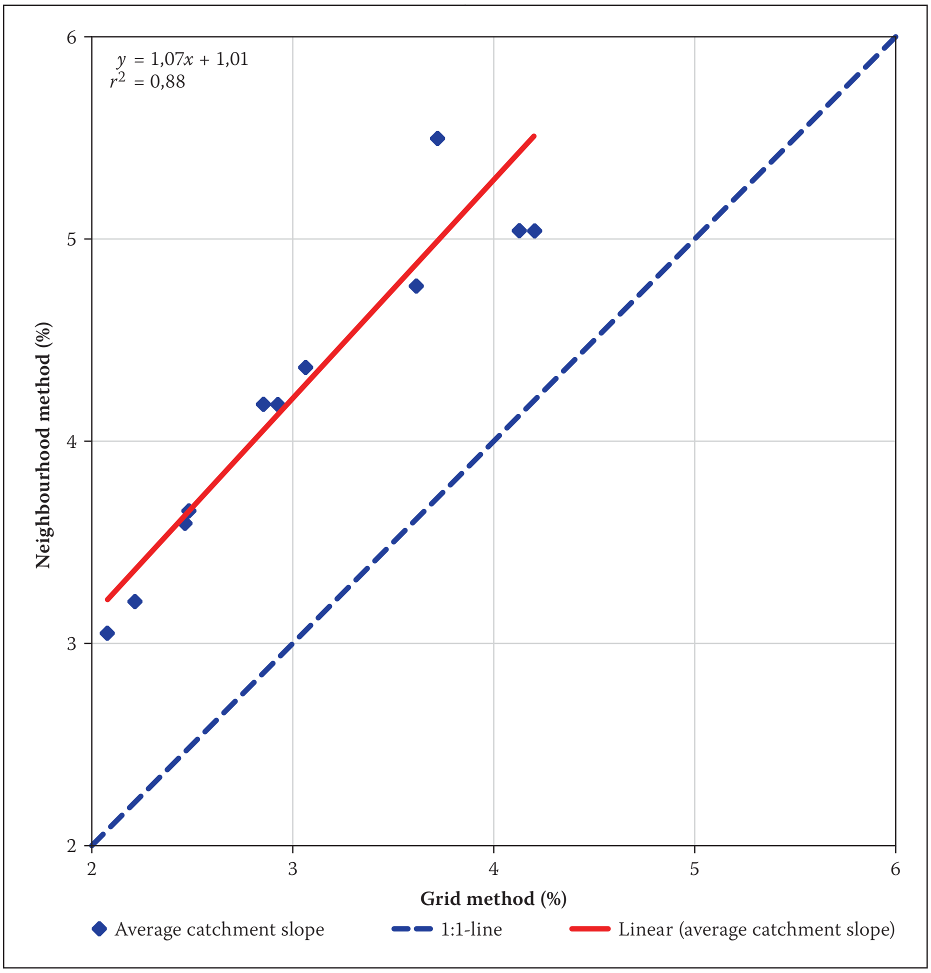


Figure 17 Neighbourhood method versus Grid method (Gericke 2010)

Average catchment slope

The results of the average catchment slope calculations based on the Neighbourhood method (DEM data), Grid method and Empirical method as used in the specific catchments, are listed in Tables 4 to 6. The scatter plots are shown in Figures 17 and 18. The developed DEM data was used as the baseline data for the evaluation of and/or comparisons with the two other methods.

According to Alexander (1990) there must be at least 50 grid points within a catchment, while Van der Spuy & Rademeyer (2010) suggested that the minimum number of grid points in catchments smaller or larger than 10 km² must be 20 and 50 respectively. The number of grid points used varied from 50 to 7 200, with an overall average of 0,45 grid points per km². The results indicated that either an increase or decrease in the number of grid points per km² does not necessarily guarantee higher accuracies when compared with the Neighbourhood method (DEM data). For comparison purposes, the average catchment slopes (as %) for all the catchments were plotted as a scatter plot using the Neighbourhood method slopes against the Grid method slopes. The results are illustrated in Figure 17.

The Grid method underestimated the average catchment slope in all the catchments under consideration compared to the Neighbourhood method. The underestimation varied between 16,7% (0,48 grid points/km²) and 32,5% (0,34 grid points/km²). Thus, if the DEM data based on the Neighbourhood method are accepted as true and accurate, then the average slope calculation using the Grid method with GIS-based input parameters must be increased with a value of between 17% and 33%. The inverse is also true. No definite relationship between the catchment area and these underestimations could be established.

The coefficient of determination (r^2) of 0,88 is indicative of a high degree of association between the two methods. The Grid method is also useful for the development of slope frequency distribution classes used in the deterministic flood estimation methods. The Grid method is, however, time-consuming and sensitive to biased user input at different scale resolutions, extent of catchment areas and contour intervals used.

The results (Figure 18), based on the Empirical method (Equation 2), compared well with the Neighbourhood method. Since Equation 2 is a function of the catchment area (A), contour interval (ΔH) and total length of all contour lines within the catchment (M), the influence of each variable was evaluated. The results (Table 6) were indicative that there is only a direct relationship between M and A for slopes steeper than 4%, since flatter slopes will result in a lower

Table 6 Average catchment slope based on Empirical method (Gericke 2010)

Catchment descriptor	Area (A, km^2)	Length of contours (M, m)	M: A ratio (m/km^2)	Average slope (S_2, %)	% Difference compared to Neighbourhood method
C5R001	921,6	1 126 973,4	1 223	2,446	19,9
C5R002	10 259,9	18 823 502,6	1 835	3,669	16,0
C5R003	936,7	2 166 950,9	2 313	4,627	8,3
C5R004	6 330,9	10 776 515,8	1 702	3,404	18,7
C5R005	116,4	319 988,3	2 749	5,499	0,0
C5H003	1 650,0	3 817 275,0	2 314	4,627	8,3
C5H012	2 366,3	4 753 023,0	2 009	4,017	15,8
C5H015	6 009,0	10 227 318,0	1 702	3,350	20,0
C5H016	33 277,2	44 534 606,5	1 338	2,677	25,6
C5H018	17 360,3	19 454 617,6	1 121	2,241	30,2
C5H022	38,0	104 477,2	2 749	5,400	1,8
C5H054	687,8	940 089,2	1 367	2,734	25,3

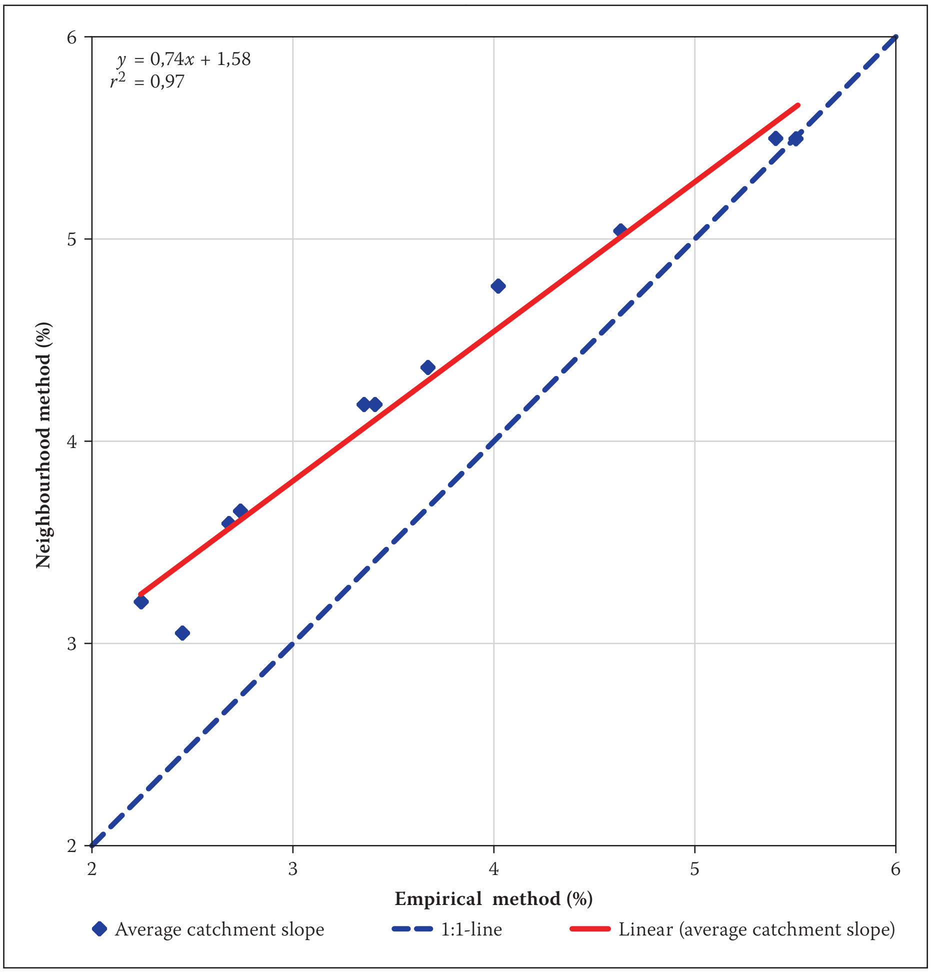


Figure 18 Neighbourhood method versus Empirical method (Gericke 2010)

Table 7 Summary of Grid and Empirical methods versus Neighbourhood method (Gericke 2010)

Conservation statistics	Grid method	Empirical method	Neighbourhood method
Observed mean (x)	3,12	3,72	4,34
Percentage difference (%)	–28,11	–14,29	–
Observed standard deviation (S_x)	0,74	1,12	0,85
Percentage difference (%)	–12,94	31,75	–
Regression statistics	Grid method	Empirical method	Neighbourhood method
Base constant/y-intercept (a)	1,01	1,58	–
Slope (b)	1,07	0,74	–
Coefficient of efficiency (E_C)	–1,42	0,27	–
Coefficient of determination (r^2)	0,88	0,97	–

contour density and associated M values. This trend was particularly evident for catchment areas exceeding 15 000 km^2. The Empirical method underestimated the average catchment slope in all the catchments under consideration, except in catchment C5R005, where the average catchment slope result agreed with that of the Neighbourhood method.

$M : A$ ratios of less than 1 500 resulted in an underestimation of between 20% and 30,2%, while $M : A$ ratios between 1 700 and 2 750 were associated with underestimations between 18,7% and 0%. Thus, the higher the $M : A$ ratios, the more accurate Equation 2 becomes. The coefficient of determination (r^2) of 0,97 is also indicative of a high degree of association.

The visual comparison of results can be highly subjective. Therefore, the data pairs in each catchment under consideration were compared and evaluated using an array of conservation and regression statistics. Values of the y-intercept (a), slope (b), coefficients of efficiency (E_C) and determination (r^2), which provide quantitative amplification of the results discussed above, are presented in Table 7.

The conservation statistics percentage differences in Table 7 reflect the differences between the average results as obtained with the Grid and Empirical methods compared respectively to the Neighbourhood method results. In both cases, the objective function (OF) is to minimise these percentage differences, of which the Empirical method's OF proved to be the minimum, with, on average, the underestimation limited to 14,3%. The y-intercept (a) and slope values (b) of the Grid and Empirical methods showed that these two methods could have different predictive abilities at flat and steep slope classes respectively. In the case of the Grid method, the positive y-intercept (1,01) is indicative of a possible overestimation of flatter slopes, while the slope value (b) which slightly exceeded unity (1,07), highlighted that the overestimation of steeper slopes is neither excluded nor impossible. The Empirical method's positive y-intercept value (1,58) highlighted that this method is even more likely to overestimate flatter slopes, while the slope value (b) less than unity (0,74) is associated with the underestimation of steeper slope classes.

Length and average slope of main watercourses

The main watercourse average slope results based on the Equal-area, 10-85 and Taylor-Schwarz methods are listed in Table 8, while the scatter plots are shown in Figures 19 to 21.

The degree of association between these methods was very high, since the coefficient of determination varied between 0,995 and 0,998. In the past, preference was given to the 10-85 method, since the Equal-area method is largely a graphical procedure and the use of the Taylor-Schwarz method is not widely known in South Africa.

Distance to catchment centroid

The results contained in Table 9 are indicative that the length of the watercourse to a position closest to the centroid (L_C) is influenced by the size and shape of the catchment, but more importantly, influenced by the average catchment slope. It is clearly evident from Table 9 that an increase in the average catchment slope is associated with a decrease in the $L_C : L$ ratio, which varied between 0,48 and 0,62.

CONCLUSIONS AND RECOMMENDATIONS

Projections and catchment geometry calculations

The DEM developed from the SRTM elevation data for southern Africa at 90 metre resolution proved to provide highly accurate raster information which can be used to calculate various catchment parameters (area, length and slope).

Average catchment slope

The developed DEM data based on the Neighbourhood method was assumed to be the most accurate representation of the actual average catchment slope and was therefore used as the baseline data to evaluate the Grid and Empirical methods. The Grid method underestimated the average catchment slope in all the catchments under consideration, while the results were indicative that either an increase or decrease in the number of grid points per km^2 does not necessarily guarantee higher accuracies when compared with the DEM data. The use of at least 50 grid points in catchments up to 10 km^2 is recommended; thereafter additional grid points at a grid density of 0,5 grid points/km^2 in catchments up to a 1 000 km^2, followed by 0,1 grid points/km^2 in catchments exceeding 10 000 km^2.

The Empirical method also underestimated the average catchment slope in all the catchments under consideration, except in catchment C5R005, where the average catchment slope result agreed with that of the Neighbourhood method. The results were indicative that there is a direct relationship between the area (A) and the total length of all contour lines within the catchment (M).

Table 8 Average main watercourse slopes (Gericke 2010)

Catchment descriptor	Main watercourse length (L, km)	Average watercourse slope (S_{CH}, %)		
		Equal-area method	10-85 method	Taylor-Schwarz method
C5R001	86,44	0,197	0,229	0,225
C5R002	201,69	0,113	0,133	0,108
C5R003	53,80	0,272	0,273	0,266
C5R004	186,70	0,102	0,131	0,113
C5R005	16,20	0,723	0,895	0,819
C5H003	71,18	0,195	0,232	0,195
C5H012	86,96	0,203	0,269	0,222
C5H015	166,95	0,099	0,139	0,103
C5H016	430,72	0,091	0,078	0,081
C5H018	375,39	0,073	0,079	0,075
C5H022	7,91	1,316	1,687	1,493
C5H054	68,04	0,252	0,261	0,283

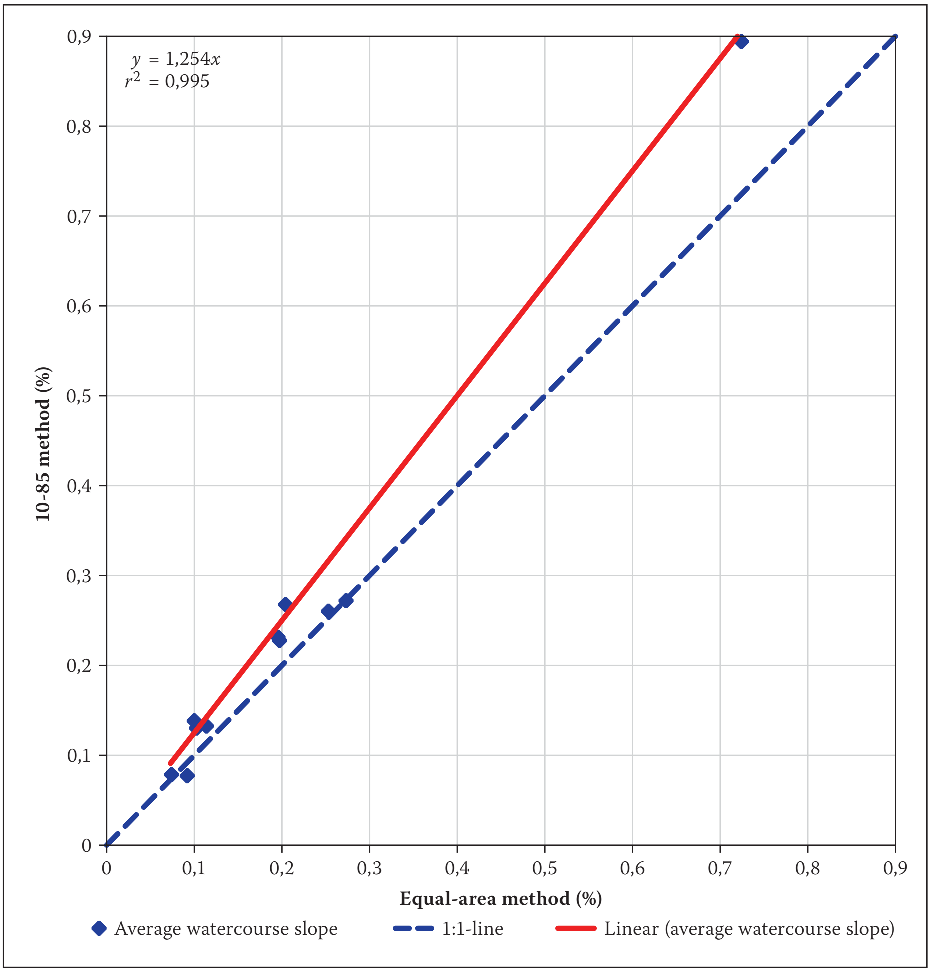


Figure 19 10-85 method versus Equal-area method (Gericke 2010)

Table 9 Catchment centroid distances (Gericke 2010)

Catchment descriptor	Main watercourse length (L, km)	Centroid distance (L_C, km)	$L_C : L$ ratio	Average slope (S_3, %)
C5R001	86,44	53,18	0,62	3,054
C5R002	201,69	96,72	0,48	4,369
C5R003	53,80	31,11	0,58	5,044
C5R004	186,70	113,02	0,61	4,186
C5R005	16,20	7,90	0,49	5,501
C5H003	71,18	41,18	0,58	5,044
C5H012	86,96	47,62	0,55	4,771
C5H015	166,95	101,06	0,61	4,186
C5H016	430,72	237,14	0,55	3,598
C5H018	375,39	232,99	0,62	3,211
C5H022	7,91	3,86	0,49	5,501
C5H054	68,04	33,05	0,49	3,659

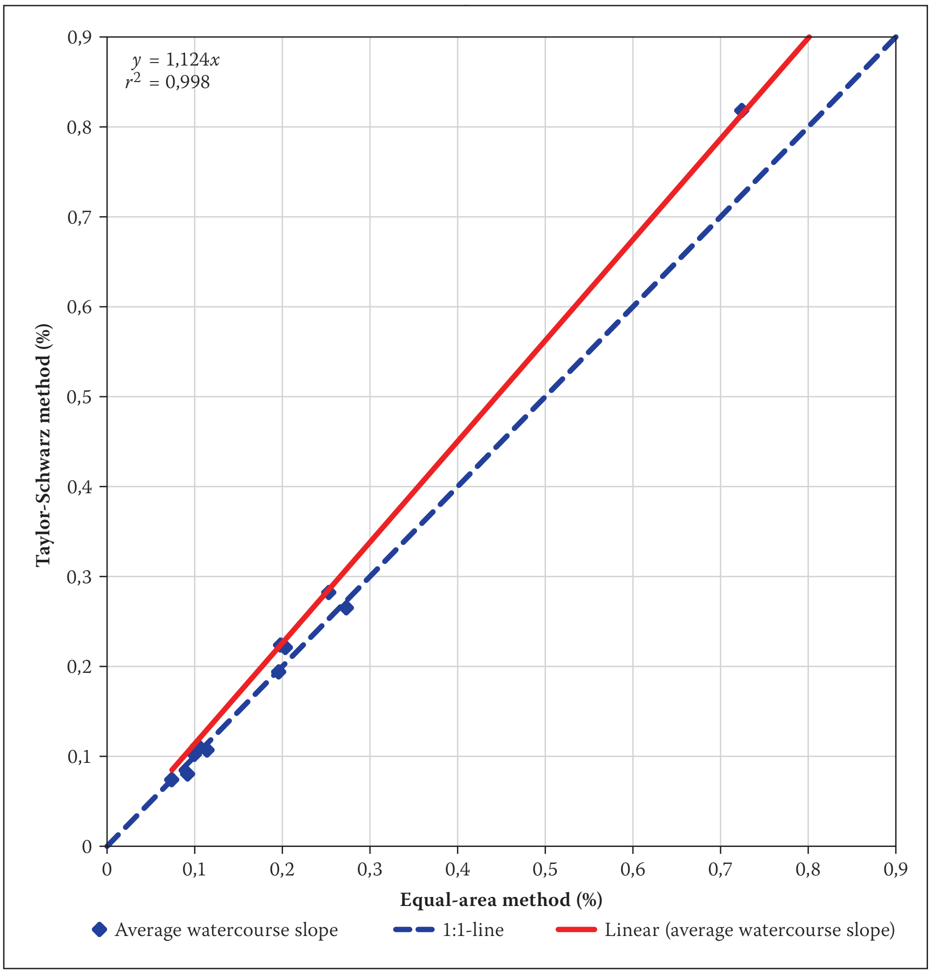


Figure 20 Taylor-Schwarz method versus Equal-area method (Gericke 2010)

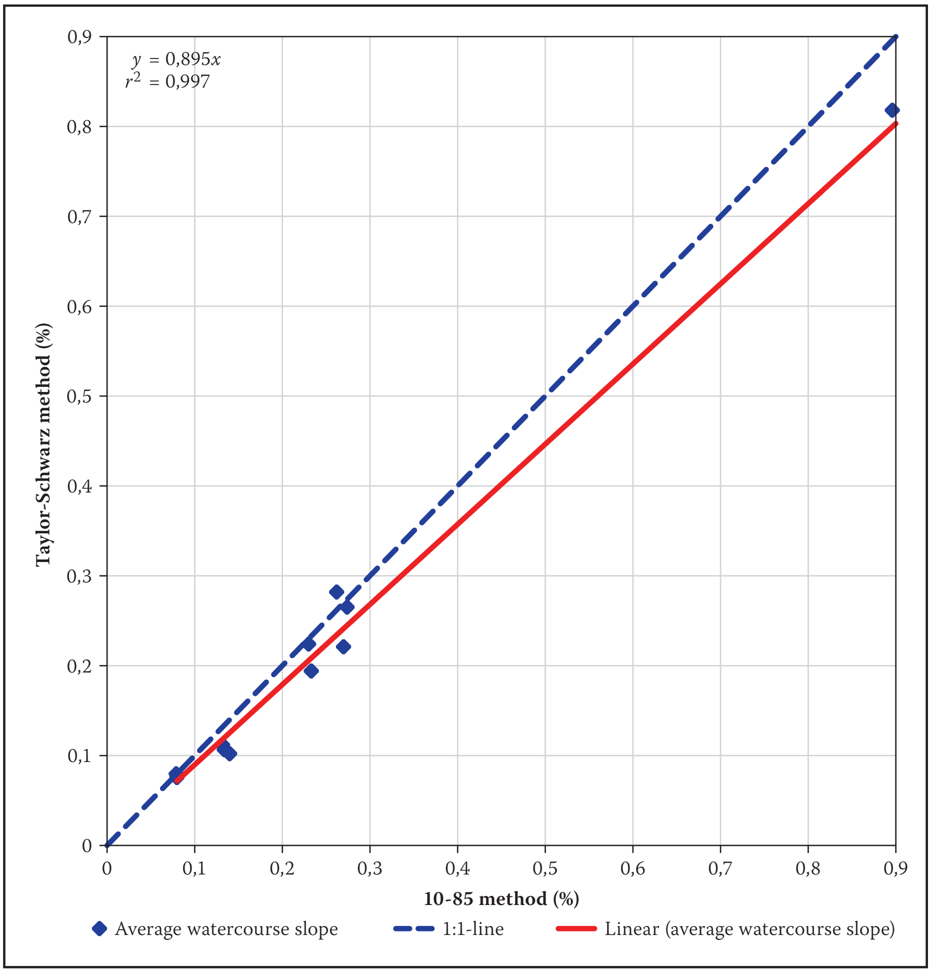


Figure 21 Taylor-Schwarz method versus 10-85 method (Gericke 2010)

The higher the $M : A$ ratios, the more accurate the results calculated using the Empirical method.

Both the Grid and Empirical methods demonstrated high degrees of association with the DEM data and can be used along with suitable tools in the ArcGIS^{TM} environment to estimate the average catchment slope. The Grid method is especially useful for the development of slope frequency distribution classes, but the method is sensitive to biased user-input at different scale resolutions, extent of catchment areas and contour intervals used.

On the other hand, the Empirical method in its more rudimentary form (derived from first principles), in conjunction with standard functions in ArcGIS^{TM}, proved to be quicker and more accurate, while it is also very suitable for the development of slope frequency distribution classes. The higher accuracy was reflected by the higher r^2 value (0,97) and the balance in tendency to either over- and underestimate the flat and steep average catchment slopes respectively. The results conclusively confirmed the preferential use thereof in conjunction with standard tools in the ArcGIS^{TM} environment.

Average main watercourse slope

The high degree of association between the Equal-area, 10-85 and Taylor-Schwarz methods proved that any of these methods can be used satisfactorily and with confidence in design flood estimation. However, this high degree of association between these methods does not necessarily guarantee the correctness thereof when used to estimate the time of concentration (T_C). In essence, the use of the average main watercourse slope as a suitable predictor variable for T_C estimation can only be justified when compared to T_C estimates based on the temporal distribution of rainfall (observed hyetographs) and runoff (observed hydrographs). In such a case, the validity of the established empirical relationship is also limited to the catchments or regions of original development.

Distance to catchment centroid

The average $L_C : L$ ratio of 0,56 obtained from this study is indicative that the general assumption of using a $L_C : L$ ratio of between 0,5 and 0,6 times the distance along the main watercourse is sufficiently accurate in most cases to be used in the various design flood estimation methods (Rademeyer 2012; Van der Spuy 2012). This is also a more definite guideline than the eyeball estimate thereof as proposed by Alexander (2001). However, practitioners are advised to evaluate each catchment individually using the tools available in ArcGIS^{TM}, before just using the proposed $L_C : L$ ratios.

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