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Key words: SDF method, design flood estimation, probabilistic analysis, catchment parameters

Evaluation of the standard design flood method in selected basins in South Africa

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Design flood estimations display relatively wide confidence bands of uncertainty around all estimates of flood magnitude-frequency relationships. Taking cognisance of this, and the fact that most of the available design flood estimation methods in South Africa were developed in the 1970s and have not been updated since, led to the development of the Standard Design Flood (SDF) method (Alexander 2002a; 2002b; 2003). In this study, the SDF method was evaluated by establishing the accuracy of the regionalised SDF runoff coefficients, taking both the areal extent and homogeneous hydrological catchment responses into consideration. The SDF runoff coefficients were evaluated, calibrated and verified at a quaternary catchment level in SDF basin 9 (primary study area) and in 19 of the other 29 SDF basins in South Africa (secondary study areas) by establishing catchment parameters and evaluating the ratios between the results obtained through the SDF method and probabilistic analysis. The results showed that the original SDF method overestimated the magnitude and frequency (return period) of flood peaks in all the basins under consideration, while the verification results confirmed that the calibrated/verified SDF method, based on quaternary runoff coefficients, significantly improves the accuracy in comparison with the probabilistic analysis results. The result confirmed that the probabilistic-based approach of the original SDF method does not have the ability to overcome the deficiencies evident in the other design flood estimation techniques used in South Africa. Revision of the runoff coefficients at a quaternary catchment level is proposed.

INTRODUCTION

The last decade in southern Africa was characterised by several damaging flood events, especially the February 2000 floods in the northeastern part of South Africa, Zimbabwe and Mozambique (Alexander 2002a). On considering the economic and environmental impact of these and other flood events, the importance of flood frequency analysis becomes evident (Smithers 2011). However, reliable estimates of flood frequency in terms of peak flows and volumes remain a constant challenge in hydrology (Cameron *et al* 1999). Cordery & Pilgrim (2000) also highlighted that the international demands for improved design flood estimations have not been met with any increased understanding of the fundamental hydrological processes. According to Van der Spuy & Rademeyer (2010), this is also the case in South Africa where the search continues for a universally applicable method for design flood estimation.

In essence, the failures of civil engineering structures (e.g. bridges, culverts, dam spillways and drainage canals) caused by floods are largely due to the immense variability in the flood response of catchments to storm rainfall, which is innately variable

in its own right. Consequently, flood estimations for design purposes can be expected to display relatively wide confidence bands of uncertainty around all estimates of flood magnitude-frequency relationships (Alexander 2002a; 2002b; 2003). Thus, both the occurrence and the frequency of flood events, along with the uncertainty involved in the estimation thereof, as well as the lack of updated design flood estimation methods in South Africa since the 1970s, indicate that there is an urgent need to revise existing methods or develop alternative design flood estimation methods by using about 40 years of additional observed data.

The developmental effort in this regard by Alexander (2002a) led to the development of a numerically calibrated version of the Rational Method (RM), known as the Standard Design Flood (SDF) method, which incorporates engineering factors of safety to accommodate the uncertainties in hydrological analyses at a regional level (Alexander 2002a; 2002b; 2003). In this study, the SDF method was evaluated in specific areas by establishing the accuracy of the regionalised SDF runoff coefficients, taking both the areal extent and homogeneous

hydrological catchment responses into consideration. The question of whether or not the probabilistic-based approach of the SDF method has the ability to overcome some of the deficiencies evident in the other techniques used for design flood estimation, was investigated and alternative revisions at a quaternary catchment scale were proposed.

The development of the original SDF method is reviewed in the next section. The purpose of the study is discussed and explained in the section thereafter, followed by an overview of the spatial distribution and characteristics of the study areas. The methodologies involved in assessing the paper's purpose and objectives are then expanded on in detail, followed by the results and discussion, conclusions and recommendations.

DEVELOPMENT OF THE ORIGINAL STANDARD DESIGN FLOOD METHOD

In the Introduction the wide confidence bands of uncertainty around all estimates of flood magnitude-frequency relationships were emphasised. However, Alexander (2002a; 2002b; 2003) indicated that these uncertainties cannot be satisfactorily accommodated, and necessitate a new, single approach to the estimation of the design flood, namely the SDF method.

The identification of representative, homogeneous flood-producing regions, which followed the boundaries of the drainage regions as depicted by the Department of Water Affairs and Forestry (DWAF) (1995), was a major step in the development of the SDF method. These regions are referred to as SDF basins and a total of 29 basins in South Africa were identified (Alexander 2002a; 2002b; 2003). Thereafter, Alexander (2002a; 2002b; 2003) reviewed all the different design flood estimation methods (deterministic, empirical and probabilistic) in use in South Africa and selected the conventional RM as the basis for the SDF method to be used in the delineated basins. At least one hydrological flow-gauging station and one representative daily rainfall station were selected for each of the 29 basins in the development of the SDF method. Probabilistic analyses of the annual maximum series (AMS) were conducted at 152 flow-gauging stations to calibrate and verify the SDF method in the various basins (Alexander 2002a; 2002b; 2003). The design rainfall information was based on the data of 1 946 daily rainfall stations contained in Technical Report (TR) 102 (Adamson 1981). The SDF basins are shown in Figure 1.

The developed SDF method was intended to replace the previously recommended RM and Synthetic Unit Hydrograph (SUH)

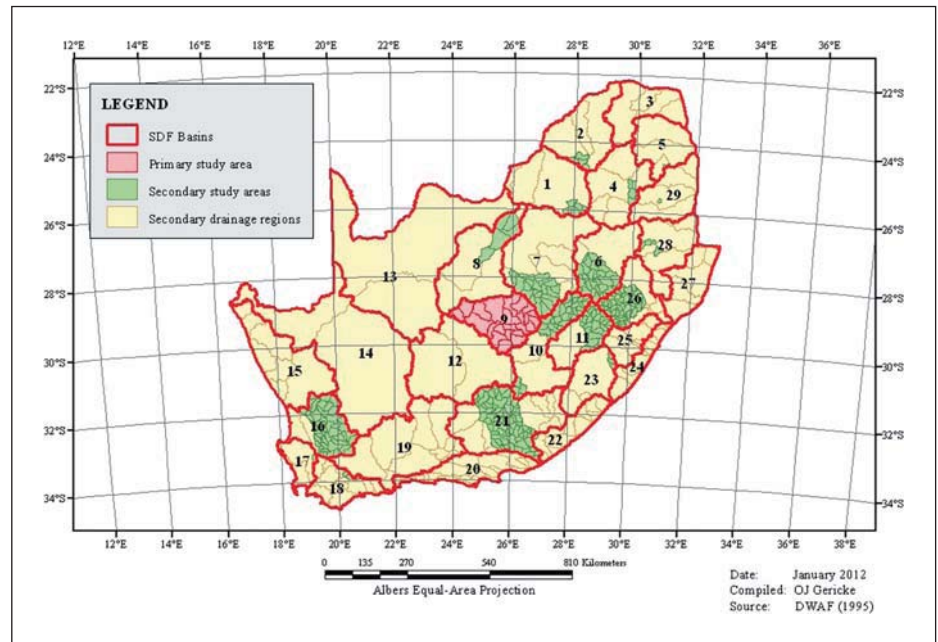


Figure 1 Location of primary and secondary study areas within the SDF basins

method. Although the basic philosophy of the SDF method is based on planning (cost-optimising procedures with engineering factors of safety) and design (estimation of conservative floods) objectives (Alexander 2002b; 2003), the question remains whether these two objectives will obviate the need for design engineers to undertake sophisticated hydrological analyses to accommodate the inherent uncertainties present in the current design flood estimation procedures. It is anticipated that the results from this study will assist in addressing the design engineers' problems regarding decision-making in design flood estimation.

PURPOSE OF STUDY

The purpose of this study was to evaluate, calibrate and verify the SDF runoff coefficients at a quaternary catchment level in SDF basin 9 (primary study area) and in 19 of the other 29 SDF basins in South Africa (secondary study areas) by establishing the catchment parameters and the ratios between results obtained with the SDF method and those obtained through the probabilistic analysis of the observed flow data (SDF/probability distribution ratios). These newly calibrated quaternary runoff coefficients were then compared with the existing regional SDF runoff coefficients. The work done by Van Bladeren (2005) during the compilation of the South African National Roads Agency Limited (SANRAL) *Drainage Manual* resulted in a proposal that adjustment factors be used to balance the tendency of the SDF method to provide over-conservative results. The runoff coefficient adjustment factors as proposed by Van Bladeren (2005) were therefore also evaluated as part of this study.

The secondary study areas were purposely evaluated to enhance the understanding of the results obtained from the primary study area, as well as to illustrate the relevance thereof in a South African context. This served as clarification of the influence of different climatic regions (Highveld as opposed to Mediterranean/southern coastal regions), types of weather systems (summer convective as opposed to winter/all year orographic/frontal rainfall) and rainfall occurrence frequencies on the depth, area, duration and movement of storm rainfall, which in turn influence the magnitude and frequency of floods as estimated by the SDF method.

Firstly, it was hypothesised that the calibration of the SDF method at a quaternary catchment level will improve the accuracy and practical use thereof. Secondly, it was hypothesised that the extent of the current delineated SDF basins is too large, with associated non-homogeneous flood-producing characteristics. Thirdly, it was hypothesised that the runoff coefficients are essentially functions of the return period and time of concentration. The fourth hypothesis was that the Log-Normal (LN), Log-Pearson Type III (LP3) and the General Extreme Value (GEV) probability distributions, or a combination thereof, are the most suitable for flood frequency analyses at a single site in South Africa.

STUDY AREAS

The primary study area covers 34 795 km² between 28°25' and 30°17' South and 23°49' and 27°00' East and comprises the C5 secondary drainage region (SDF basin 9), which consists of the tertiary Riet River and

Modder River catchments. The primary study area is characterised by 99,1% rural areas, 0,7% urbanisation and 0,2% water bodies (CSIR 2001). The natural vegetation is dominated by Grassland of the Interior Plateau, False Karoo and Karoo (light bush). Cultivated land is the largest human-induced vegetation alteration in the rural areas, while residential and suburban areas dominate the urban areas. The topography is gentle (slopes between 2,4% and 5,5%) and water tends to pond easily, thus influencing the attenuation and translation of floods. The Mean Annual Precipitation (MAP) is 424 mm, ranging from 275 mm in the west to 685 mm in the east. It is characterised as highly variable and unpredictable. The rainy season starts early September and ends mid-April with a dry winter (Midgley *et al* 1994). The Modder and Riet Rivers are the main river reaches and discharge into the Orange-Vaal River drainage system (Seaman *et al* 2001). Like most inland rivers in South Africa, these rivers were traditionally seasonal rivers, but due to the construction of significant storage dams, they now resemble permanent rivers.

The secondary study area catchments ranged in size from 126 km² to 33 277 km² and are located within basins 1, 2, 4 - 11, 16 - 18, 21 - 23, 26, 28 and 29. The locations of the primary and secondary study areas are shown in Figure 1.

METHODOLOGY

This section provides the detailed methodology followed during this study, which focuses on the evaluation and calibration of SDF runoff coefficients and flood peaks, the verification of calibrated runoff coefficients and flood peaks, and the statistical assessment of results.

Evaluation and calibration of runoff coefficients and flood peaks

To evaluate and verify the original (Alexander 2003), adjusted (Van Bladeren 2005) and calibrated (this study) SDF methods at a quaternary catchment level in SDF basin 9 (primary study area) and the other randomly selected SDF basins in South Africa (secondary study areas), the following procedures were followed: establishment of physical catchment parameters, probabilistic analyses, selection of representative rainfall stations, and numerical calibration of runoff coefficients.

These procedures are discussed in the following sub-sections:

Establishment of physical catchment parameters

All the required catchment input parameters of SDF basin 9 (average main watercourse length and slope, time of concentration,

design rainfall intensities, average number of days per year during which thunder was heard (*R*) and areal reduction factors (ARFs) were determined in a similar fashion as for the original SDF method (Alexander 2002a; 2002b; 2003). In all the other SDF basins under consideration, the catchment areas and time of concentration were based on previous research conducted by Petras & Du Plessis (1987) and Parak & Pegram (2006).

Probabilistic analyses

Probabilistic analysis of the AMS was conducted at a representative flow-gauging station in each catchment under consideration to summarise the observed flood peak data, estimate parameters and select appropriate theoretical probability distributions. The observed flood peak data was summarised by ranking the AMS in a descending order of magnitude. The Cunnane plotting position, based on a general plotting formula, was used to assign a probability to the flood peaks. The parameter estimation was largely based on the Method of Moments (MM), although the usefulness of Linear-Moments (LM) estimation to fit the General Logistic (GLO) probability distribution was also investigated.

Several of the AMS data sets were characterised by insufficient record lengths (e.g. missing data, low outliers and flood peaks exceeding the hydraulic capacity of flow-gauging structures), which made it impossible to conclusively select a single probability distribution that could consistently provide flood frequency estimates for return periods much greater than the period of record. To overcome this limitation of single site analyses, a Mean Logarithm Value Approach (MLVA), based on the mean values of the logarithms of two or more probability distributions, were used as the most suitable combined probability distribution at a single site or flow-gauging station. The MLVA, as expressed in Equation 1, is also used as a standard method in the DWA (Directorate: Flood Studies) (Van der Spuy & Rademeyer 2010).

$$Q_p = 10 \exp \left[\frac{\log[(Q_i)(Q_{i+1}) \dots (Q_N)]}{N} \right] \quad (1)$$

where:

Q_p = peak flow based on the MLVA (m³/s)

$Q_{i, i+1}$ = peak flows based on a recognised theoretical probability distribution, with a minimum of two probability distributions used in combination (m³/s), and

N = number of probability distributions used.

The individual peak flows (Q_i) can either be based on the combination of two or more theoretical probability distributions, e.g. Extreme/Log-Extreme Value Type I (EV1/LEV1), LN, LP3, GEV and/or GLO distributions. Statistical properties, visual inspection of the plotted values and Goodness-of-Fit (GOF) statistics were used to select the most suitable single probability or combined probability distribution in Equation 1. Both the EV1 and LEV1 probability distributions have a fixed skewness of 1,14; hence the limited use thereof in flood hydrology. The LN distribution was only used where the logarithms of the observed data have near symmetrical distribution or where the skewness coefficients were close to zero. In all other asymmetrical data sets, the LP3 distribution was used instead. The GEV distributions were used at asymmetrical data sets characterised by either positive (Extreme Value Type II) or negative (Extreme Value Type III) skewness coefficients.

A total of 44 catchments were evaluated of which 12 fall within the primary study area. The probabilistic analysis results of eight of the catchments were based on the GEV distribution, as obtained from previous research conducted by Parak & Pegram (2006). These results were therefore not analysed again. However, the nature and record length of the observed flood peak data sets initially used by these authors are unknown.

Selection of representative rainfall stations

The design rainfall information used in this study was based on the Regional L-Moment Algorithm South African Weather Service *n*-day design point rainfall database (RLMA-SAWS) (after Smithers & Schulze 2000b), as opposed to the original SDF method which used the TR102 information. The RLMA-SAWS database contains design rainfall information of 3 946 daily rainfall stations up to the year 2002. The SAWS contributed the majority (82,2%) of the data of these daily rainfall stations, while the Institute for Soil, Climate and Water (ISCW), the South African Sugar Association Experiment Station (SASEX) and private individuals provided the remaining daily rainfall data (Smithers & Schulze 2000b). In contrast, the TR102 daily design rainfall database has ± 20 years less information available and is limited to 1 946 rainfall stations (Adamson 1981). The selection of the single rainfall station, to be used in the calibrated SDF method at a quaternary catchment level, was based on the following criteria:

- **Average meteorological conditions:** The MAP and design rainfall depths associated with return periods ranging from 2 to 200 years of the selected station must have a

Table 1 Probabilistic analysis results in SDF basin 9 (Gericke 2010)

Station	Return period	Design flood based on probability distributions (m ³ /s)					Comments
		GEV/MM	LN/MM	LP3/MM	GLO/LM	Q _p (Eq 1)	
C5R001	2	40	32	31	32	31	Return period range: 1,25 – 200 years LP3/MM distribution
	5	145	95	94	80	94	
	10	231	167	169	135	169	
	20	327	266	276	216	276	
	50	477	451	482	390	482	
	100	611	641	701	604	701	
	200	766	884	992	930	992	
C5R002	2	243	196	218	195	218	Return period range: 1,25 – 200 years LP3/MM distribution
	5	765	604	616	470	616	
	10	1 201	1 089	1 004	762	1 098	
	20	1 704	1 770	1 460	1 177	1 577	
	50	2 506	3 059	2 160	2 024	2 327	
	100	3 242	4 405	2 758	3 015	2 990	
	200	4 115	6 150	3 410	4 468	3 746	
C5R003	2	126	80	75	66	75	Return period range: 10 – 200 years GEV/MM distribution
	5	323	230	225	162	225	
	10	465	401	416	259	440	
	20	609	635	705	392	655	
	50	810	1 064	1 303	652	810	
	100	972	1 502	1 988	945	972	
	200	1 143	2 058	2 953	1 361	1 143	
C5R004	2	302	225	266	317	290	Return period range: 1,25 – 200 years GLO/LM distribution
	5	637	643	654	637	646	
	10	893	1 114	961	910	935	
	20	1 168	1 755	1 266	1 241	1 253	
	50	1 571	2 925	1 654	1 807	1 807	
	100	1 913	4 112	1 933	2 366	2 366	
	200	2 293	5 617	2 195	3 075	3 075	
C5R005	2	46	36	35	34	35	Return period range: 1,25 – 200 years LP3/MM distribution
	5	103	87	86	73	86	
	10	146	137	139	112	139	
	20	189	200	208	165	198	
	50	251	306	329	266	287	
	100	301	407	449	377	368	
	200	355	528	599	533	461	
C5H003	2	182	100	87	63	87	Return period range: 10 – 200 years GEV/MM distribution
	5	481	305	287	164	287	
	10	689	546	583	268	634	
	20	897	884	1 095	411	897	
	50	1 179	1 521	2 337	697	1 179	
	100	1 400	2 182	3 993	1 023	1 400	
	200	1 629	3 038	6 659	1 492	1 629	

Station	Return period	Design flood based on probability distributions (m ³ /s)					Comments
		GEV/MM	LN/MM	LP3/MM	GLO/LM	Q _p (Eq 1)	
C5H012	2	57	35	50	52	57	Return period range: 1,25 – 5 years GEV/MM distribution
	5	110	133	130	98	120	
	10	147	267	180	133	180	
	20	183	474	219	173	219	
	50	231	907	256	234	256	
	100	269	1 397	275	290	275	
	200	307	2 075	288	356	288	
C5H015	2	359	245	309	331	320	Return period range: 1,25 – 200 years GLO/LM distribution
	5	698	730	736	640	686	
	10	925	1 291	1 030	887	956	
	20	1 147	2 068	1 288	1 172	1 229	
	50	1 438	3 514	1 575	1 635	1 635	
	100	1 659	5 003	1 754	2 070	2 070	
	200	1 882	6 914	1 904	2 599	2 599	
C5H016	2	114	90	95	104	104	Return period range: 1,25 – 200 years GEV/MM distribution
	5	206	197	199	186	203	
	10	266	296	284	249	275	
	20	322	414	376	321	322	
	50	392	605	508	433	392	
	100	444	780	615	536	444	
	200	494	983	728	659	494	
C5H018	2	96	76	84	105	80	Return period range: 1,25 – 200 years LN/MM distribution
	5	284	238	242	243	240	
	10	440	431	401	377	416	
	20	619	703	593	556	646	
	50	903	1 221	895	896	1 045	
	100	1 163	1 763	1 161	1 269	1 431	
	200	1 469	2 469	1 457	1 786	1 897	
C5H022	2	12	8	9	10	10	Return period range: 1,25 – 200 years LP3/MM distribution
	5	26	24	25	21	25	
	10	35	43	39	31	39	
	20	45	68	56	43	56	
	50	58	117	81	63	81	
	100	68	166	102	83	102	
	200	79	230	125	109	125	
C5H054	2	18	17	16	11	16	Return period range: 1,25 – 200 years LP3/MM distribution
	5	62	41	40	25	40	
	10	97	65	67	41	67	
	20	137	95	104	66	104	
	50	198	147	175	123	175	
	100	254	196	250	197	250	
	200	318	256	349	316	349	

high degree of association with the MAP and design rainfall depths as obtained by the Thiessen polygon method using the total number of rainfall stations within the catchment(s) under consideration.

- **Record length:** Where possible, a minimum record length of 50 years must be used in order to enable the selection of a distribution that could consistently provide adequate rainfall frequency estimates for return periods much greater than the period of record. However, shorter records (between 40 and 47 years) were used in 11% of the secondary study areas to evaluate the SDF method due to the limited number of suitable rainfall stations available in five of these catchments.

Numerical calibration of runoff coefficients

The numerical calibration of the runoff coefficients used in the SDF method followed the probabilistic analyses and the selection of a single rainfall station in all the catchments under consideration in both the primary and secondary study areas. The purpose of the calibration was to fit the results obtained by the probabilistic analysis with those of the SDF method in order to establish the SDF/probability distribution ratios and adapted quaternary SDF runoff coefficients for return periods, ranging from 2 to 200 years. This was accomplished by determining the C_2 (2-year return period) and C_{100} (100-year return period) runoff coefficients in Equation 2 (Alexander 2003) in such a way that the calibrated runoff coefficients (C_T) for a range of return periods resulted in the best fit between the design values of flood peaks based on the probabilistic analysis and the SDF method (Equation 3; Alexander 2003).

$$C_T = \frac{C_2}{100} + \left(\frac{Y_T}{2,33} \right) \left(\frac{C_{100}}{100} - \frac{C_2}{100} \right) \quad (2)$$

$$Q_T = 0,278 C_T I_T A \quad (3)$$

where:

C_T = calibrated runoff coefficient

Q_T = design flood peak (m^3/s)

A = catchment area (km^2)

C_2 = 2-year return period runoff coefficient

C_{100} = 100-year return period runoff coefficient

I_T = average design rainfall intensity (mm/h), and

Y_T = return period factor.

These coefficients (C_2 and C_{100}) were changed manually until an appropriate fit with the probabilistic analysis results was achieved, after which values of C_T were

Table 2 MAP of selected catchments in SDF basin 9 (Gericke 2010)

Catchment description	MAP (mm)		Number of rainfall stations (N_i)
	Arithmetic mean	Thiessen polygon	
Study area	439	424	185
C5R001	492	488	7
C5R002	421	420	61
C5R003	553	549	8
C5R004	530	518	47
C5R005	642	660	3
C5H003	553	549	8
C5H012	448	444	11
C5H015	530	518	47
C5H016	440	429	183
C5H018	479	461	93
C5H022	686	660	3
C5H054	542	523	13

Table 3 Selected single SDF rainfall stations used in SDF basin 9 (Gericke 2010)

Catchment description	Station number	MAP (mm)		Record length (N , years)
		Single SDF station	Thiessen polygon	
C5R001	0261750W	497	488	55
C5R002	0232018W	420	420	86
C5R003	0232123W	555	549	88
C5R004	0261523W	518	518	94
C5R005	0262734W	649	660	43
C5H003	0232123W	555	549	88
C5H008	0232018W	420	420	86
C5H012	0231395W	454	444	71
C5H015	0261523W	518	518	94
C5H016	0291899W	433	429	79
C5H018	0260163W	461	461	74
C5H022	0262734W	649	660	43
C5H054	0261523W	518	523	94

Table 4 Design information applicable to SDF basin 9 (Gericke 2010)

Catchment description	Method	SDF design information				
		C_2	C_{100}	MAP (mm)	M (mm)	R (days/year)
C5R002	SDF _{Original}	15	60	376	43	47
	SDF _{Adjusted}	15	60	376	43	47
	SDF _{Calibrated}	9	54	420	42	54
C5R003	SDF _{Original}	15	60	376	43	47
	SDF _{Adjusted}	15	60	376	43	47
	SDF _{Calibrated}	9,5	47,5	555	48	54
C5R004	SDF _{Original}	15	60	376	43	47
	SDF _{Adjusted}	15	60	376	43	47
	SDF _{Calibrated}	18	59	518	44	62
C5R005	SDF _{Original}	15	60	376	43	47
	SDF _{Adjusted}	15	60	376	43	47
	SDF _{Calibrated}	11	33	649	48	66

coaxially plotted with the regional SDF runoff coefficients from Alexander (2003) against the return period. This exercise was repeated with the runoff coefficient adjustment factors as proposed by Van Bladeren (2005) to validate these runoff coefficient adjustment factors.

Verification of calibrated runoff coefficients and flood peaks

Verification tests were conducted in 16 catchments that were not used in the calibration exercise to establish whether the calibrated runoff coefficients were predictable and to confirm that the method was reliable. In order to verify the C_T values achieved during calibration, it was necessary to find some physical or regional descriptors with which to relate the runoff coefficients and to enable the use and extension of the calibrated runoff coefficients to ungauged catchments. Several regional descriptors, such as MAP, average catchment slope and land-use distribution, were taken into consideration in combination with the C_T values to establish whether or not any relationship existed on which to regress the runoff coefficients.

The 16 catchments used in the verification exercise, and for which AMS were available, were selected based on the fact that their physical or regional descriptors were similar to the catchments used during the calibration exercise, in order to result in near homogeneous hydrological responses. These catchments ranged in size from 26 km² to 23 067 km², with eight catchments within SDF basin 9 (primary study area) and eight catchments within SDF basins 6, 7, 10, 18 and 21 (secondary study areas).

Statistical assessment of results

Regression (coefficient of determination) and descriptive (Chi-square) statistics were used to evaluate the GOF of the probabilistic analyses (fitted probability distributions). The coefficient of determination (r^2) calculations were based on the full record length where the ranked observed values, with their associated probability or return period, were compared with the theoretical probability distributions. The Chi-square statistics were evaluated by making use of the concept of contingency tables, consisting of margin totals, which were used to establish the expected estimated values. The comparisons between the probabilistic analyses and the calibrated and verified versions of the SDF method were evaluated in the same manner.

RESULTS AND DISCUSSION

The results based on the methodology used in this study are discussed next. The

evaluation and calibration of SDF runoff coefficients and flood peaks are discussed first, followed by a discussion on the verification of calibrated runoff coefficients and flood peaks. In conclusion, the statistical assessment of results are highlighted.

Evaluation and calibration of runoff coefficients and flood peaks

Probabilistic analyses

The MLVA not only overcame the limitation of AMS data sets at a single site characterised by insufficient record lengths, but also took cognisance of the strong evidence that in South Africa most of the high flood peaks are a result of rare and severe meteorological phenomena. Alexander (2012) also confirmed that the AMS of these floods could consist of a mixture of two or more statistical populations with different parameter values and associated flood peak frequency relationships, particularly if preceding severe rainfall storms occur in close succession. Alexander (2012) also emphasised that: *“It is a serious mistake to assume that a single probability distribution method can be applied to all the data at the site.”*

The MLVA inclusive of the LP3-GEV/MM distributions dominated the probabilistic analyses in 42% of the catchments, followed by the MLVA inclusive of the LP3-GEV-LN/MM distributions in 28% of the catchments. The LP3/MM distribution was the only distribution which was used as a single most suitable distribution in 11% of the catchments. The remaining 19% of the catchments under consideration were characterised by a different combination of the above-mentioned distributions. However, when Equation 1 was used to combine two or more probability distributions, it was impossible to indicate which probability distribution would be the best suited for a specific return period range in all the catchments. The SDF basin 9 (primary study area) results for return periods ranging from 2 to 200 years based on the most relevant distributions are listed in Table 1.

Selection of representative rainfall stations

The different results obtained using the arithmetic mean and Thiessen polygon methods respectively to calculate the average catchment design rainfall are listed in Table 2. Table 3 provides the selected single rainfall stations in each catchment under consideration in SDF basin 9 in comparison with the catchment design rainfall calculated using the Thiessen polygon method.

The number of rainfall stations used for averaging the design rainfall varied from catchment to catchment with an overall

average of one station per 100 km². It was observed that the arithmetic mean values slightly exceeded the Thiessen polygon values in each catchment, but the coefficient of determination (r^2) of 0,98 confirmed the high degree of association, and highlighted the even areal distribution of the rainfall stations and the relatively flat topography.

Numerical calibration of runoff coefficients

The original, adjusted and calibrated C_2 and C_{100} runoff coefficients applicable to SDF basin 9 are presented in Table 4. The corresponding MAP, two-year one-day rainfall (M) and R values are also shown. The following notations are applicable to Tables 4 to 7:

$SDF_{Original}$	Values as used in the original SDF method (Alexander 2003)
$SDF_{Adjusted}$	Values as used in the adjusted SDF method based on the adjustment factors (Van Bladeren 2005)
$SDF_{Calibrated}$	Values as used in the calibrated SDF method at a quaternary catchment level based on the methodology of this study
$SDF_{Verified}$	Verified SDF method at a quaternary catchment level used to evaluate the calibrated version of the SDF method.

The original and calibrated C_2 and C_{100} runoff coefficients of SDF basin 9 presented in Table 4 are characterised by large proportional differences between the values. The differences between the original and adjusted runoff coefficients were found to be 45% (60 – 15) in all cases, since the adjustment factors as proposed by Van Bladeren (2005) are only used to adjust the final C_T coefficients.

In the case of the calibrated runoff coefficients, the proportional differences tended to decrease with an increase in the MAP, with a 45% difference for MAP less than 500 mm, a 38% to 41% difference for MAP ranging from 500 to 600 mm, and a 22% difference for MAP exceeding 600 mm. It is important to note that the original MAP (376 mm) in SDF basin 9 is also less than 500 mm, confirming the trend identified. It indicated that the antecedent soil moisture status in the quaternary catchment(s) under consideration introduces additional variability into the rainfall-runoff process and that the hydrological response in each quaternary catchment will be different. This can be ascribed to the difference in soil permeability which controls the infiltration rate and consequently the balance of rainfall that constitutes surface runoff and contributes to the flood peak. Table 5 provides a summary

of the results obtained during the numerical calibration of the SDF runoff coefficients in SDF basin 9. The original, adjusted and calibrated runoff coefficients (C_T), as calculated using Equation 2, are shown in Table 5.

The original runoff coefficients of SDF basin 9 ranged from 0,150 (2-year return period) to 0,648 (200-year return period), while the calibrated runoff coefficients ranged from 0,090 (2-year return period) to 0,634 (200-year return period). The adjusted runoff coefficients based on the adjustment factors proposed by Van Bladeren (2005) ranged from 0,103 (2-year return period) to 1,878 (200-year return period). According to Van Bladeren (2005), the latter runoff coefficient exceeding unity is justified, since it is used when the SDF method overestimates the more frequent events and underestimates the extreme events in a particular basin.

However, the question arises whether or not the adjustment factor can successfully describe a meaningful relationship between the regional descriptors (average catchment slope, catchment area, land-use distribution and MAP) and the C_T coefficients as shown in Equation 4 (Van Bladeren 2005).

$$C_{T2} = \frac{C_{T1}}{F} \quad (4)$$

where:

C_{T2} = adjusted runoff coefficient (Van Bladeren 2005)

A = catchment area (km²)

C_{T1} = original runoff coefficient (Alexander 2003)

F = adjustment factor ($F = xA^y$)

x = regional descriptor (multiplier), and

y = regional descriptor (exponent).

Based on the results listed in Table 5, it was interesting to note that the runoff coefficients adjusted by Equation 4 had a tendency to decrease in magnitude with increasing recurrence interval. This was especially the case in SDF basins 11 and 17, but the results are not presented here. In SDF basin 9 the 20-year adjusted runoff coefficients exceeded the 50-year runoff coefficients. Similar results were also evident in SDF basin 18.

The adjusted runoff coefficients, which exceeded unity and **decreased** in magnitude with increasing recurrence interval, deviated from the norm. Runoff coefficients exceeding unity indicate that more than a 100% runoff can occur, but this is physically impossible. An **increase** in the C_T coefficients with return period is necessary to accommodate the known effects which also increase with return period, but the increase is not accounted for in Equation 4. The coxially plotted values of C_T (original, adjusted and calibrated) against the return period

Table 5 Calibrated runoff coefficients (C_T) in SDF basin 9 (Gericke 2010)

Catchment description	Method	Calibrated runoff coefficients (C_T) for return period (years)						
		2	5	10	20	50	100	200
C5R002	SDF _{Original} (C_{T1})	0,150	0,312	0,397	0,467	0,546	0,600	0,648
	SDF _{Adjusted} (C_{T2})	0,155	0,383	0,719	1,338	1,130	1,422	1,878
	SDF _{Calibrated} (C_{T3})	0,090	0,253	0,338	0,408	0,487	0,540	0,588
C5R003	SDF _{Original} (C_{T1})	0,150	0,312	0,397	0,467	0,546	0,600	0,648
	SDF _{Adjusted} (C_{T2})	0,125	0,287	0,446	0,870	0,753	0,902	1,137
	SDF _{Calibrated} (C_{T3})	0,095	0,232	0,304	0,364	0,430	0,475	0,516
C5R004	SDF _{Original} (C_{T1})	0,150	0,312	0,397	0,467	0,546	0,600	0,648
	SDF _{Adjusted} (C_{T2})	0,148	0,361	0,653	1,226	1,042	1,299	1,696
	SDF _{Calibrated} (C_{T3})	0,180	0,328	0,406	0,470	0,542	0,590	0,634
C5R005	SDF _{Original} (C_{T1})	0,150	0,312	0,397	0,467	0,546	0,600	0,648
	SDF _{Adjusted} (C_{T2})	0,103	0,224	0,294	0,597	0,529	0,607	0,733
	SDF _{Calibrated} (C_{T3})	0,110	0,190	0,231	0,266	0,304	0,330	0,354

Table 6 Calibrated SDF flood estimation results in SDF basin 9 (Gericke 2010)

Catchment description	Method	Design flood (m ³ /s) for return period (years)						
		2	5	10	20	50	100	200
C5R002	Q_p	218	616	1 098	1 577	2 327	2 990	3 746
	SDF _{Original} (Q_1)	351	1 059	1 692	2 417	3 590	4 678	5 929
	SDF _{Adjusted} (Q_2)	362	1 298	3 065	6 926	7 438	11 085	17 183
	SDF _{Calibrated} (Q_3)	204	773	1 221	1 703	2 404	3 010	3 712
C5R003	Q_p	75	225	440	655	810	972	1 143
	SDF _{Original} (Q_1)	90	291	470	677	992	1 271	1 565
	SDF _{Adjusted} (Q_2)	75	267	528	1 261	1 368	1 912	2 744
	SDF _{Calibrated} (Q_3)	64	237	389	559	812	1 024	1 253
C5R004	Q_p	290	646	935	1 253	1 807	2 366	3 075
	SDF _{Original} (Q_1)	236	710	1 134	1 618	2 402	3 129	3 966
	SDF _{Adjusted} (Q_2)	233	821	1 866	4 251	4 585	6 766	10 387
	SDF _{Calibrated} (Q_3)	290	709	1 033	1 376	1 878	2 356	2 866
C5R005	Q_p	35	86	139	198	287	368	461
	SDF _{Original} (Q_1)	38	133	221	320	469	594	726
	SDF _{Adjusted} (Q_2)	26	95	163	410	454	601	822
	SDF _{Calibrated} (Q_3)	32	92	147	209	300	375	455
Average Q_{SDF}/Q_p	Q_1/Q_p	1,18	1,41	1,35	1,37	1,43	1,45	1,45
	Q_2/Q_p	1,05	1,42	1,79	2,95	2,25	2,54	3,04
	Q_3/Q_p	0,93	1,12	1,04	1,02	1,03	1,02	1,00

applicable to SDF basins 6, 7, 9, 10, 18 and 21 are shown in Figures 2 to 7.

It is evident from Figure 2 that the calibrated C_T coefficients in the quaternary catchments obtained from the primary study area are spread around those of Alexander (2003), but are generally lower in magnitude. Similar trends were also witnessed in the other SDF basins evaluated (Figures 4 to 6), except for SDF basins 6 and 21 (Figures 3 and 7). The curves representing the calibrated runoff coefficients had similar growth curves as a function of the recurrence interval in most of the basins under consideration. The decreasing trend in the

adjusted runoff coefficients with an increase in recurrence interval is clearly evident from Figures 2 and 6, with the adjusted 20-year runoff coefficients highly questionable, since they are larger than the 50- and 100-year runoff coefficients.

Evaluation of calibrated flood peaks

The comparison between the design flood peak values based on the probabilistic analyses and the original, adjusted and calibrated versions of the SDF method in SDF basin 9 (primary study area) is listed in Table 6. The **average** SDF/probability distribution ratios are also shown in the same table.

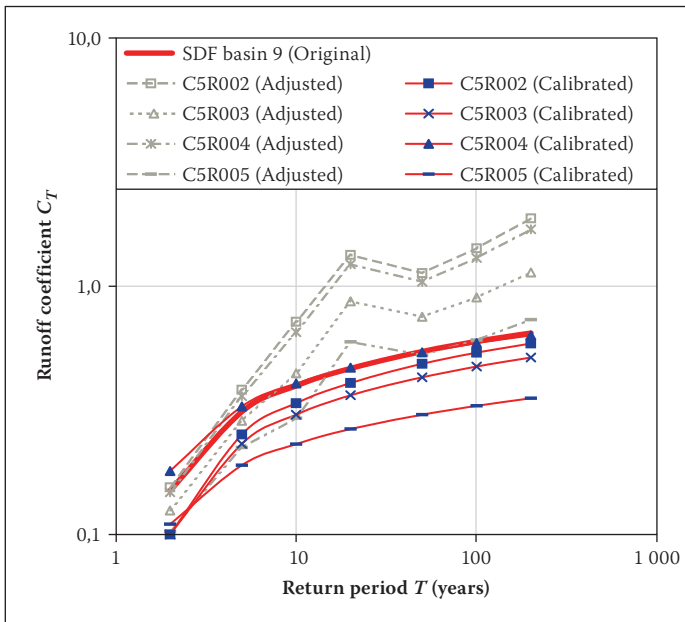


Figure 2 Comparison of runoff coefficients in SDF basin 9 (Gericke 2010)

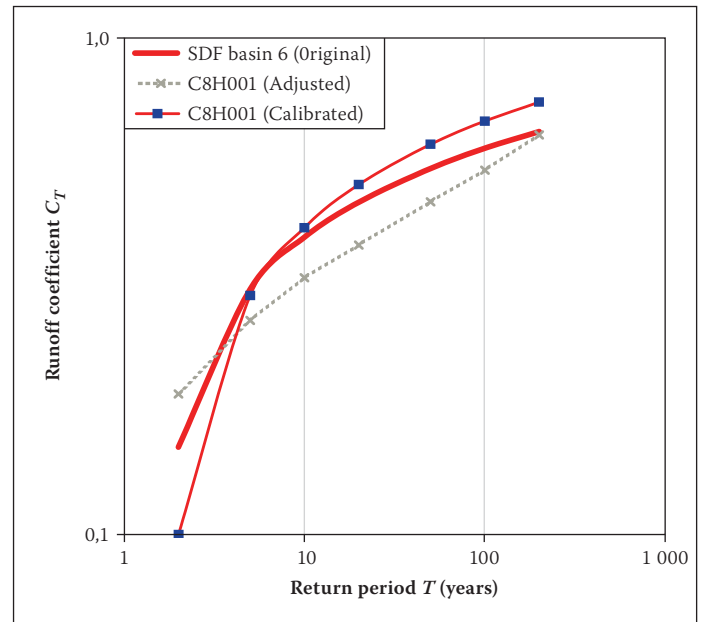


Figure 3 Comparison of runoff coefficients in SDF basin 6 (Gericke 2010)

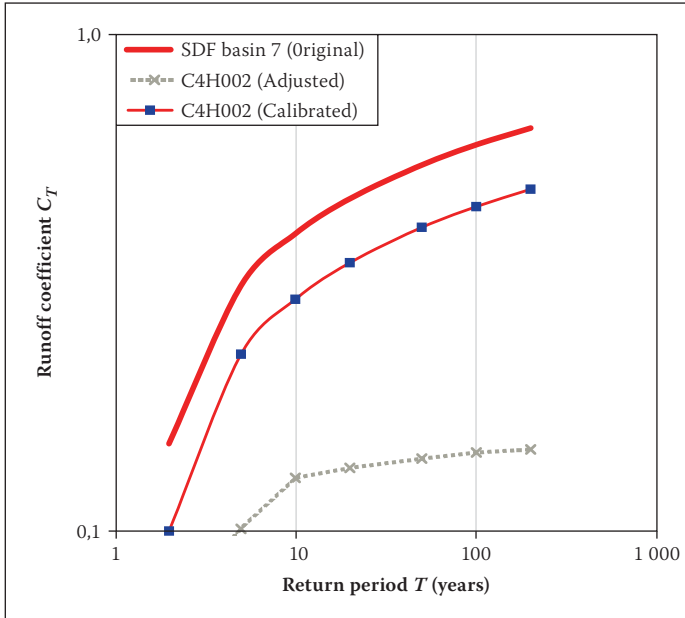


Figure 4 Comparison of runoff coefficients in SDF basin 7 (Gericke 2010)

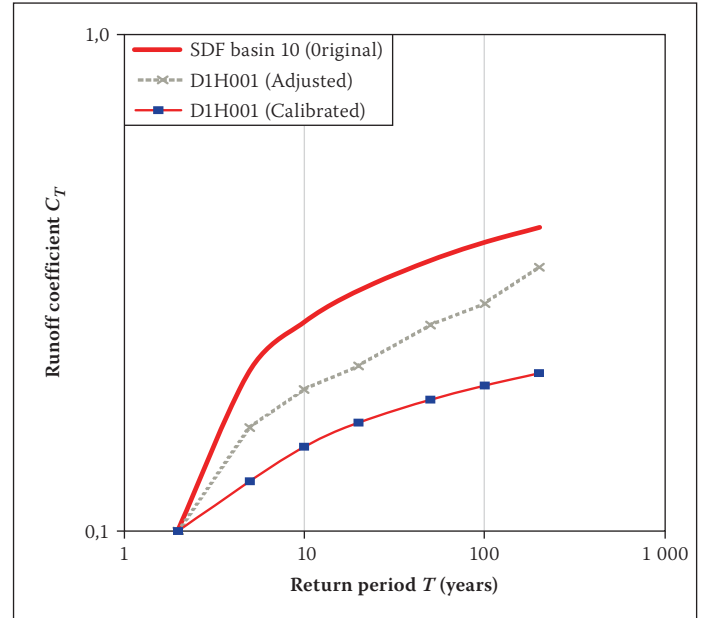


Figure 5 Comparison of runoff coefficients in SDF basin 10 (Gericke 2010)

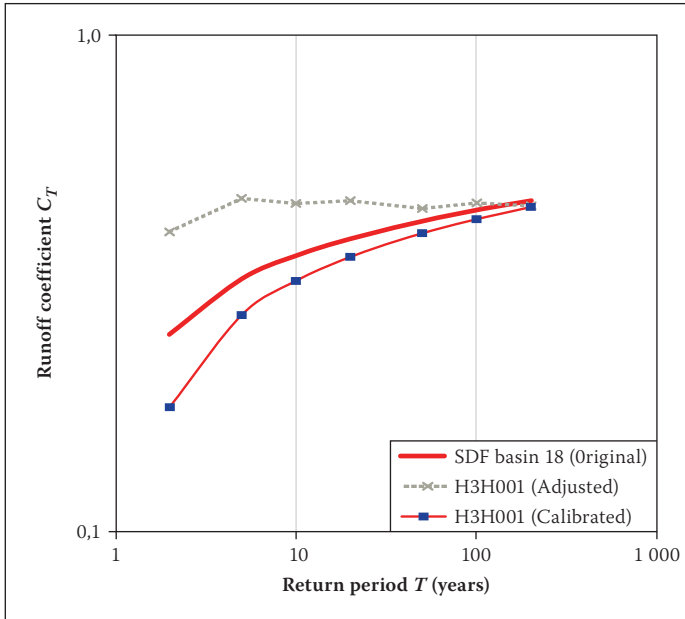


Figure 6 Comparison of runoff coefficients in SDF basin 18 (Gericke 2010)

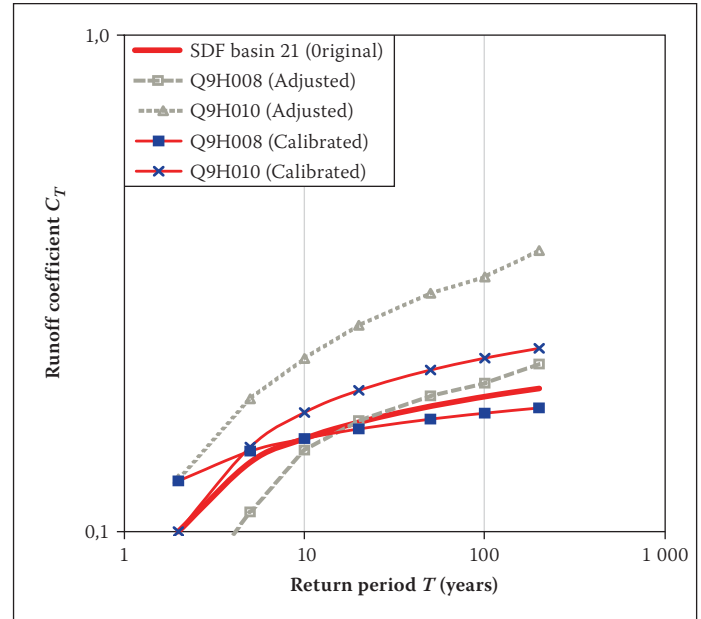


Figure 7 Comparison of runoff coefficients in SDF basin 21 (Gericke 2010)

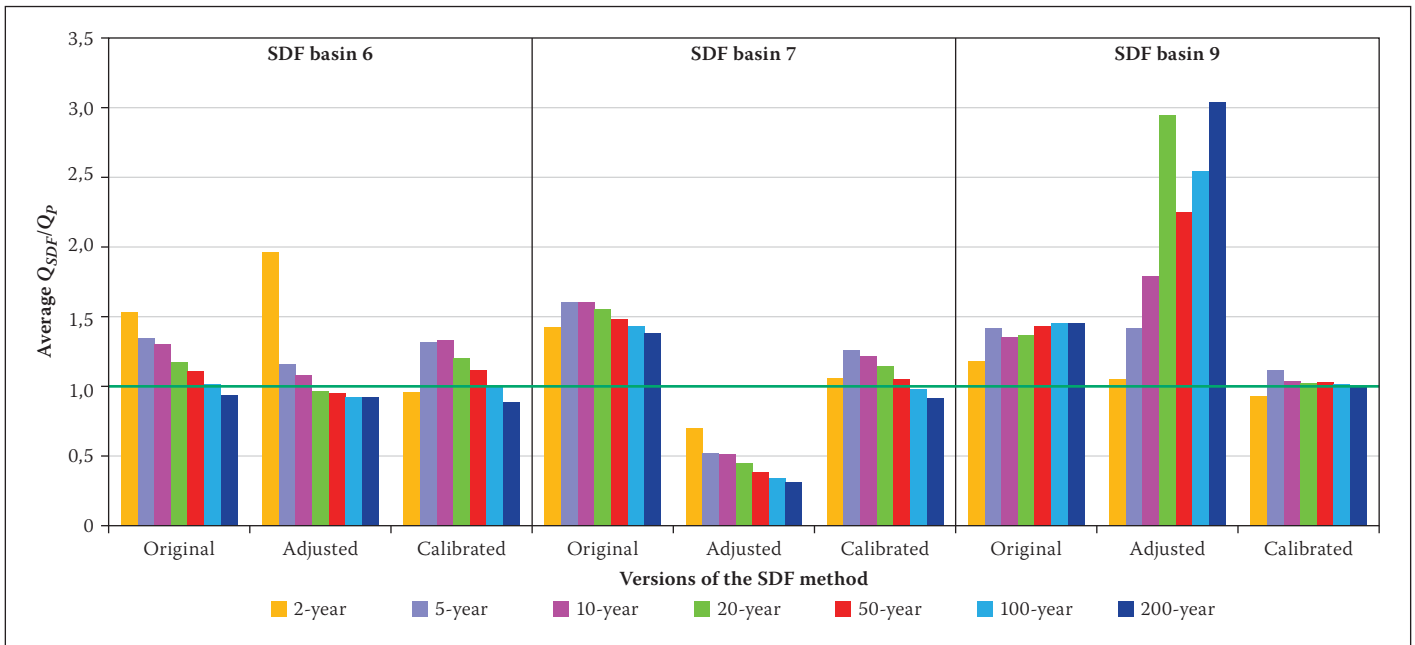


Figure 8 Variation between SDF and probabilistic design flood peaks (calibration)

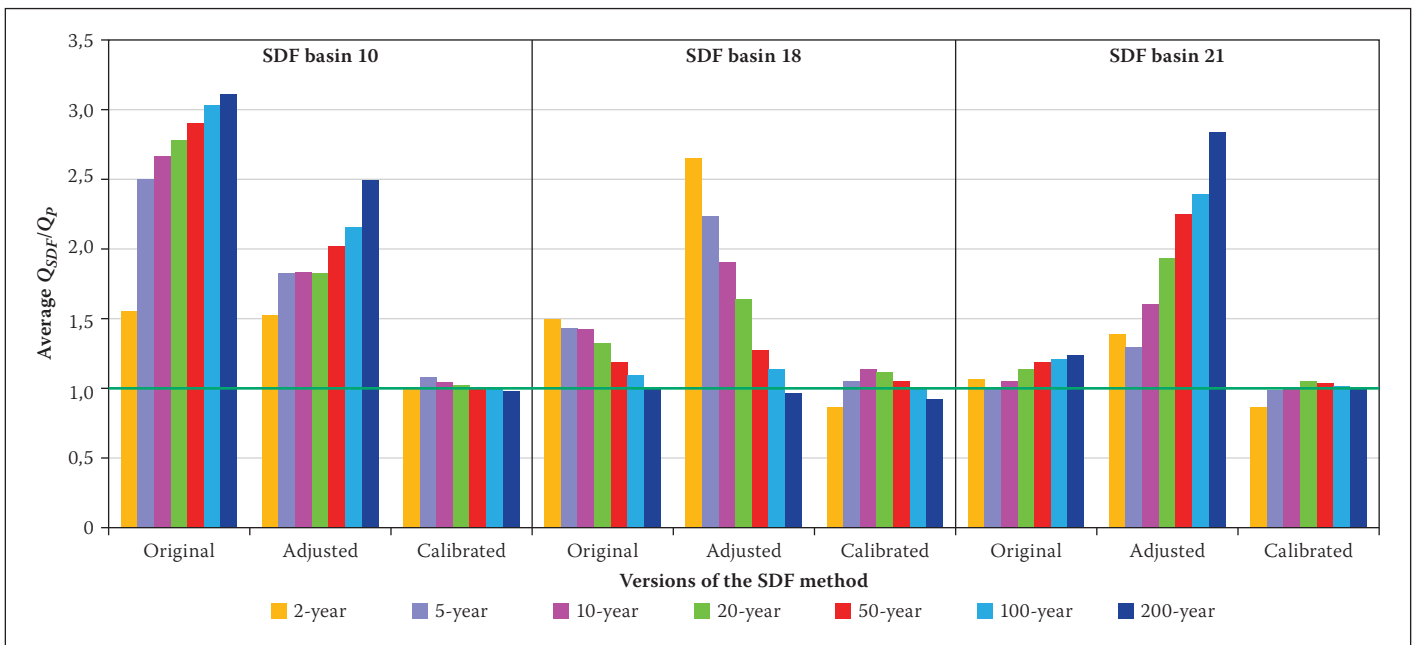


Figure 9 Variation between SDF and probabilistic design flood peaks (calibration)

According to Van Bladeren (2005), the original SDF method tends to overestimate the more frequent design floods for return periods of up to 20 years in SDF basin 9, while the extreme events are underestimated. However, the results contained in Table 6 indicate that on average the original SDF method overestimated all the probabilistic flood peaks. The overestimation varied between 18% and 45%. Except for the 2-year return period, the adjusted SDF method overestimated all the flood peaks as well, with average overestimations of up to 204%. The calibrated version of the SDF method proved to be the most accurate, with the 2-year return period being underestimated on average by 7%, while the maximum overestimation was limited to 12%.

The primary study area (SDF basin 9) results as listed in Table 6, as well as the

average SDF/probability distribution ratios obtained in SDF basins 6, 7, 10, 18 and 21 (used both for calibration and verification purposes) are illustrated in Figures 8 and 9 respectively. In addition, the average SDF/probability distribution ratios obtained in the remaining 13 SDF basins (calibration only) are illustrated in Figures 10 and 11 respectively.

Apart from the above-mentioned results obtained in SDF basin 9, the original SDF method also overestimated the probabilistic flood peaks in all the other SDF basins under consideration, except in SDF basins 6 (200-year), 8 (2-year), 16 (2-year), 23 (100- and 200-year) and 26 (all return periods). On average, the ratio between the original SDF method and probability distributions varied between 0,43 and 5,77. The

best results were evident in SDF basin 16 (Figure 10), with the overestimation limited to $\pm 12\%$ for the return periods ranging from 10 to 200 years.

The overall results (calibration and verification) of the adjusted SDF method were only better in 26% of all the basins under consideration when compared to those estimated by the original SDF method. The adjusted SDF method demonstrated the most acceptable results in SDF basin 16 (Figure 10), and either significantly over- or underestimated the flood peak values in the remaining basins. On average, the adjusted SDF/probability distribution ratios varied between 0,25 and 6,58, which seems improper.

The calibrated version of the SDF method proved to be the most accurate in all the basins under consideration, except in

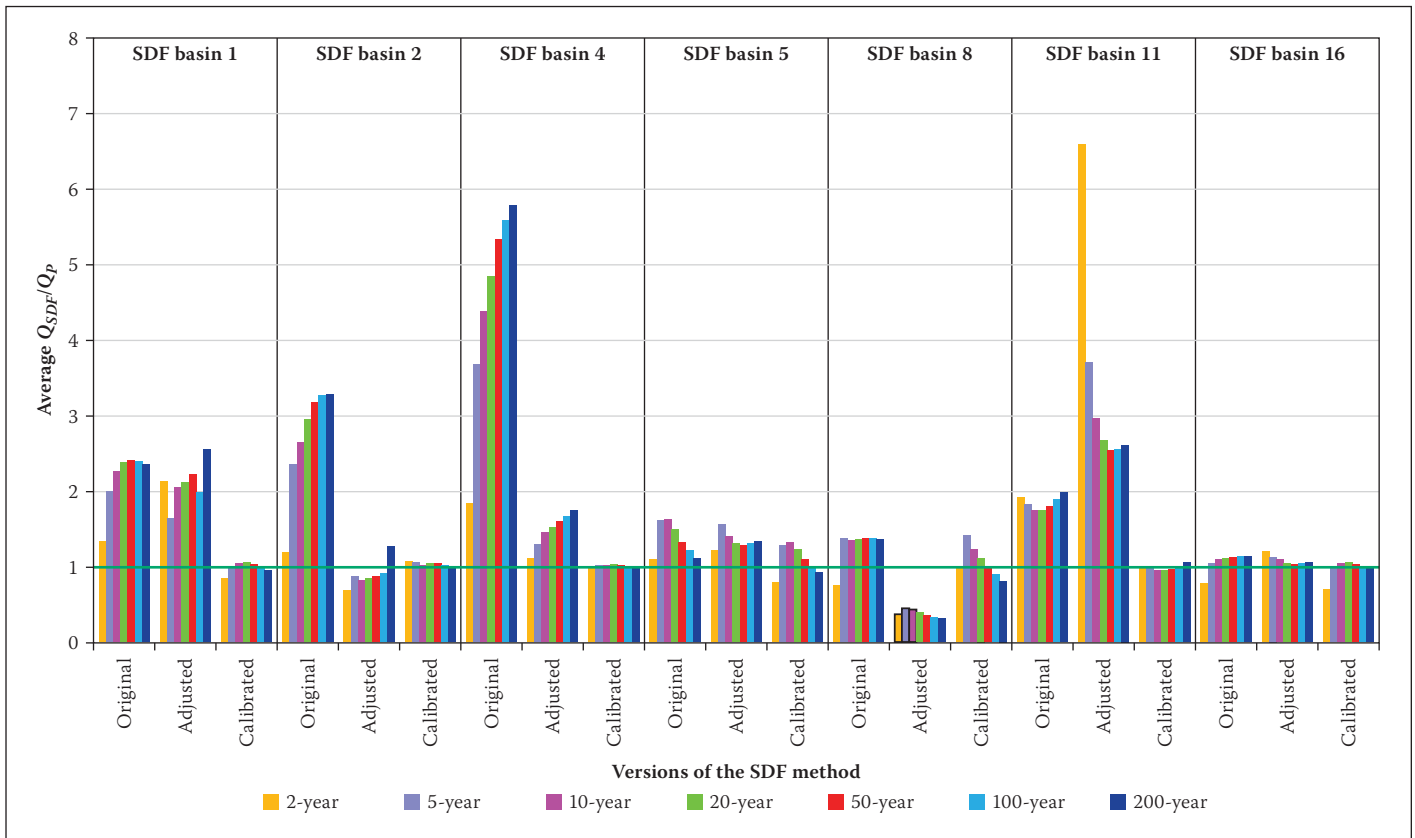


Figure 10 Variation between SDF and probabilistic design flood peaks (calibration)

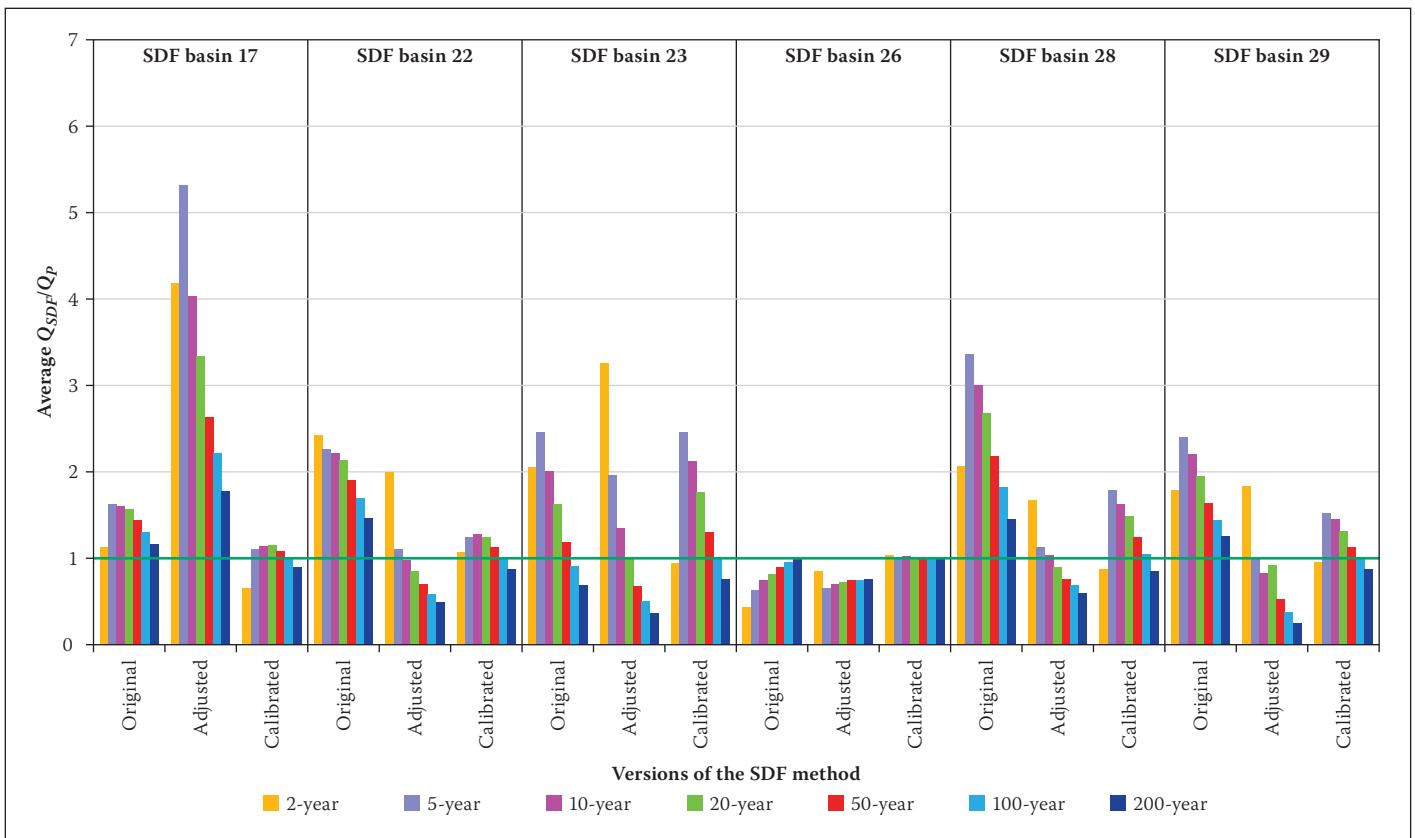


Figure 11 Variation between SDF and probabilistic design flood peaks (calibration)

SDF basin 6 (Figure 8), where it proved to be slightly less accurate than the adjusted SDF method. On average, the calibrated SDF/probability distribution ratios varied between 0,91 and 1,30, while at some basins and individual return periods, less accurate results were evident.

Verification of calibrated runoff coefficients and flood peaks

In the methodology it was highlighted that the selection of verification catchments within the same basin was based on the fact that their physical and regional descriptors were similar. In other words, the catchments

are situated within a smaller portion/number of quaternary catchments within the larger group of quaternary catchments used in the calibration exercise. The flood peaks estimated for verification purposes with calibrated runoff coefficients are referred to as $SDF_{Verified} (Q_3)$. The comparison between

the design flood peak values based on the probabilistic analyses and the original, adjusted and calibrated/verified versions of the SDF method in SDF basin 9 is listed in Table 7. The flow-gauging station numbers in brackets in column 1 are the stations used for the verification.

The verification results listed in Table 7 indicate that the original SDF method demonstrated the same trends of overestimating all the probabilistic flood peaks in SDF basin 9. However, the magnitude of overestimation of the 2- and 5-year return period floods were slightly larger, while the flood peaks for the remaining return periods showed some improvement with the overestimation being limited to $\pm 30\%$. The adjusted SDF method results also improved slightly and were characterised by overestimations of up to 163%. The verification results confirmed that the calibrated SDF method was the most accurate, and similar trends were evident. On average, the verified SDF/probability distribution ratios varied between 1,01 and 1,18, which is considered to be acceptable.

Figures 12 and 13 provide a visual measure of performance showing the average SDF/probability distribution ratios in the primary study area (SDF basin 9) and SDF basins 6, 7, 10, 18 and 21 obtained during the verification exercise.

Apart from the above-mentioned verification results obtained in SDF basin 9, varied the verified SDF/probability distribution ratios on average between 0,80 and 1,20. However, the 5- to 20-year return period flood peaks were overestimated by 41% to 56% in SDF basins 6 (Figure 12) and 21 (Figure 13). The calibrated/verified SDF method remains the preferred method in the

Table 7 Verified SDF flood estimation results in SDF basin 9 (Gericke 2010)

Catchment description	Method	Design flood (m ³ /s) for return period (years)						
		2	5	10	20	50	100	200
C5R002 (C5R001)	Q_p	31	94	169	276	482	701	992
	SDF _{Original} (Q_1)	66	199	313	448	656	850	1 053
	SDF _{Adjusted} (Q_2)	55	182	350	831	902	1 275	1 839
	SDF _{Verified} (Q_3)	39	151	244	345	494	620	757
C5R002 (C5H008)	Q_p	45	175	325	432	585	712	851
	SDF _{Original} (Q_1)	66	217	354	510	747	955	1 174
	SDF _{Adjusted} (Q_2)	53	189	362	875	954	1 317	1 869
	SDF _{Verified} (Q_3)	40	173	293	429	631	801	985
C5R003 (C5H003)	Q_p	87	287	634	897	1 179	1 400	1 629
	SDF _{Original} (Q_1)	125	387	616	883	1 294	1 670	2 063
	SDF _{Adjusted} (Q_2)	109	381	775	1 822	1 966	2 797	4 074
	SDF _{Verified} (Q_3)	89	313	501	709	1 016	1 274	1 554
C5R004 (C5H015)	Q_p	320	686	956	1 229	1 635	2 070	2 599
	SDF _{Original} (Q_1)	239	715	1 139	1 625	2 407	3 135	3 960
	SDF _{Adjusted} (Q_2)	234	823	1 855	4 229	4 553	6 711	10 256
	SDF _{Verified} (Q_3)	292	717	1 044	1 392	1 982	2 487	3 025
Average Q_{SDF}/Q_p	Q_1/Q_p	1,44	1,44	1,28	1,28	1,30	1,32	1,31
	Q_2/Q_p	1,23	1,39	1,59	2,63	1,99	2,23	2,62
	Q_3/Q_p	1,02	1,18	1,06	1,04	1,04	1,03	1,01

latter basins, based on the higher degree of association and accuracy obtained. The original and adjusted versions of the SDF method also demonstrated similar trends as established during the calibration exercise, although some individual return period flood peaks were characterised by either a slightly improved or worse estimation. All the verification tests also confirmed that the calibrated runoff coefficients behaved in a probabilistic manner as anticipated, since the verification results showed that the calibrated/verified SDF method is the most

accurate, and similar trends were evident in all the basins under consideration.

Statistical assessment of results

The coefficients of determination (r^2) results were indicative of a high degree of association between the observed AMS data and the theoretical probability distributions, with 0,85 and 0,79 respectively as the poorest correlations in the primary (SDF basin 9) and secondary study areas.

In all the primary study area catchments, except C5R003, C5H003 and C5H018, the

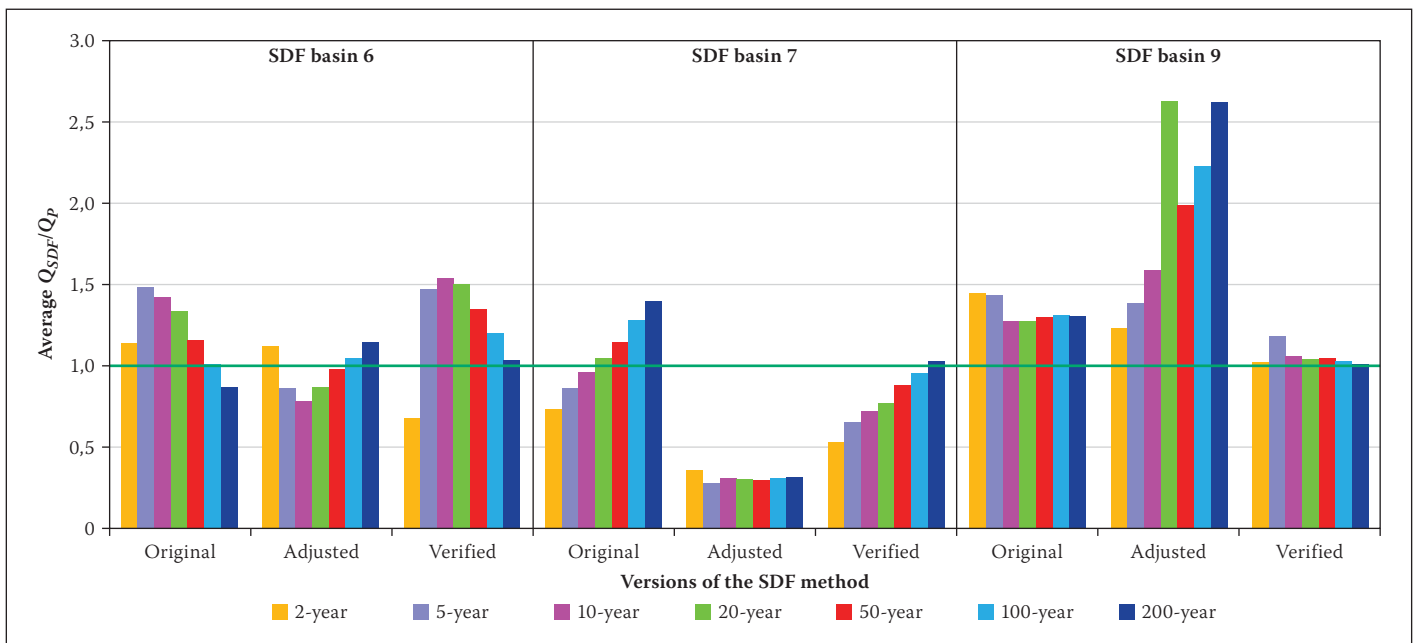


Figure 12 Variation between SDF and probabilistic design flood peaks (verification)

Chi-square statistic was less than the limiting critical value and the confidence level larger than the significance level. In other words, the *null hypothesis* could be accepted. This was also the case in 60% of the secondary study area catchments used to verify the calibrated SDF method. However, acceptance of the *null hypothesis* at low confidence levels (< 50%), highlighted the likelihood of differences to be present, especially at C5R001, C5R002 and C5H015 in SDF basin 9. Similar detectable differences were present in 12% of the secondary study area catchments.

The GOF statistic results of the original, adjusted, calibrated and verified versions of the SDF method were evaluated within the context of their SDF/probability distribution ratios. In other words, pair values of the coefficient of determination and these ratios were evaluated in combination to get a true reflection of the accuracy. Typically, the calibrated and verified versions of the SDF method proved to be the most accurate, i.e. SDF/probability distribution ratios between 0,80 and 1,30 along with a high degree of association (r^2 values > 0,9). On the other hand, the original and adjusted SDF methods also demonstrated a high degree of association, but it must be evaluated within the context of their poor SDF/probability distribution ratios, which were occasionally different by up to a factor of 3 or more.

The influence of different variables on the calibration and verification results, as discussed, demonstrates that the probabilistic-based approach of the SDF method in its current format requires further refinement at a quaternary catchment scale. The conclusions and recommendations in the following section will synthesise the results in order to address these requirements.

CONCLUSIONS AND RECOMMENDATIONS

The main purpose of this study was to establish whether or not the probabilistic-based approach of the SDF method has the ability to overcome some of the deficiencies evident in the other design flood estimation methods used in South Africa. Although the study was limited to only 19 of the 29 SDF basins in South Africa, the overall results are considered to be representative in a South African context, while all the hypothesis statements were investigated and confirmed.

The conclusions and recommendations pertaining to the results obtained from this study can be summarised as follows:

- **Probabilistic analyses:** The results confirmed that the LN, LP3 and GEV distributions or a combination thereof using Equation 1, are the most suitable probability distributions for flood frequency analysis in South Africa at a single site (Hypothesis 4). The selection and use of probability distribution pair combinations for specific return periods can only be based on the statistical properties, visual inspection of the plotted values and GOF statistics. However, regional analyses of pooled-AMS could also be conducted to overcome the problem of short flow record lengths at single sites in addition to the MLVA.
- **Selection of representative rainfall stations:** The use of average meteorological conditions and record length as criteria to select single representative rainfall stations in each catchment under consideration confirmed Hypothesis 2, which stated that the flood-producing characteristics within the current delineated SDF basins are non-homogeneous. The

newly identified single rainfall stations proved to be a much better representation of the hydrological response at a smaller scale or catchment level.

- **Numerical calibration of runoff coefficients:** It was evident from this study that the calibrated C_T coefficients at a quaternary catchment level significantly improved the accuracy of the flood peak estimation using the SDF method (Hypothesis 1). The effort made by Van Bladeren (2005) to regionalise the runoff coefficients requires further improvement, since some of the adjusted runoff coefficients exceeded unity and other had a tendency to decrease in magnitude with increasing recurrence interval. The relationships established between the parameters (multiplier and exponent) of the power-law function (Equation 4) fitted to the C_T coefficients as a function of return period and regional descriptors, are also questionable, because the likelihood that a catchment is to be more saturated at the start of a storm with a longer recurrence interval was ignored.
- These results are in agreement with similar studies conducted on the RM in South Africa (Parak & Pegram 2006) and Australia (Pilgrim & Cordery 1993), which confirmed that no relationship can be successfully established between the regional descriptors and the C_T values in order to regress the runoff coefficients. It also confirms that the C_T coefficients are essentially functions of the return period and time of concentration as conjectured (Hypothesis 3).
- **Calibrated and verified flood peaks:** The calibrated/verified version of the SDF method proved to be the most

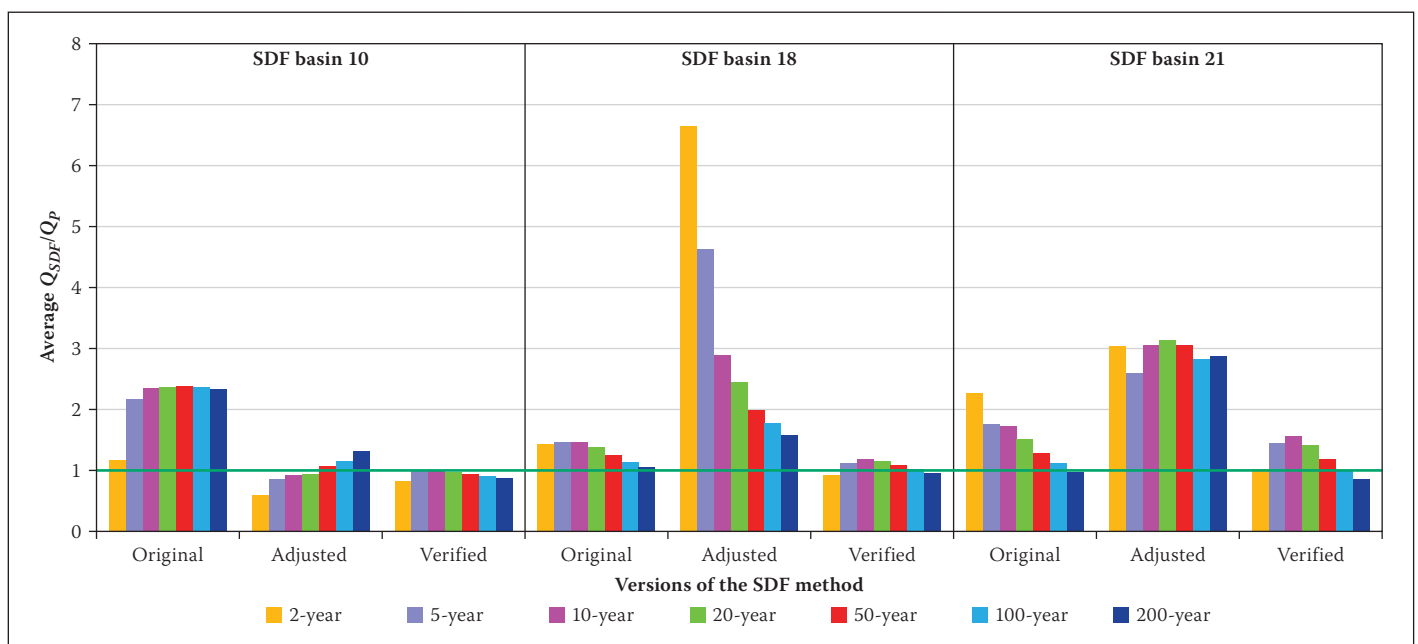


Figure 13 Variation between SDF and probabilistic design flood peaks (verification)

accurate at a quaternary catchment level, thus enhancing the accuracy and practical use of the original SDF method (Hypothesis 1). The degree or extent to which the original SDF method overestimated the magnitude and frequency of flood peaks varied from basin to basin. Apart from the previously discussed factors, this is also due to the influence of different climatic regions, types of weather and rainfall occurrence frequencies on the depth, area, duration and movement of storm rainfall. The original SDF/probability distribution ratios were the highest in the northern inland regions (SDF basins 1, 2 and 4), the Highveld (SDF basins 6 and 7), Lesotho (SDF basins 10 and 11) and southern coastal regions (SDF basins 22 and 23) with summer convective rainfall. In these regions the flood-peak ratios were occasionally different by up to a factor of 3 or more. The southern coastal regions (SDF basins 16 to 18) with winter orographic/frontal rainfall demonstrated the best flood peak ratios with flatter growth curves as a function of the recurrence interval and varied between 0,8 and 1,6.

- **Statistical assessment of results:** Both the coefficient of determination and Chi-square statistic can be satisfactorily used to evaluate the GOF of theoretical probability distributions and other design flood estimation methods. However, the Chi-square statistic proved to be more sensitive towards short record lengths, inconsistency, non-homogeneity and non-stationarity of data.

Further research on the SDF method could focus on the following:

- Review of the current regional boundaries of the SDF basins by increasing the number of SDF basins based on single or multiple quaternary catchment boundaries. The availability of hydrological (flow) and meteorological (rainfall) data, as well as the extent of the hydrological homogeneity within the identified catchments, will have an influence on the identification and delineation of the new basins.
- Improvement and extension of the data pool of hydrological and meteorological

gauging sites by updating the data sets to ensure that periods of observation are as long as possible. All available historical information of flood peaks should be included in and made available from a central database.

- Utilisation of the Regional Linear Moment Algorithm and Scale Invariance (RLMA&SI) approach (Smithers & Schulze 2000a) to estimate design rainfall.
- Establishment of physical or regional descriptors on which to regress the calibrated runoff coefficients to enable the extension thereof to ungauged catchments.

IN CONCLUSION

All these results emphasised that there is no single design flood estimation method that is superior to all other methods used to address the wide variety of flood magnitude frequency problems that are encountered in practice. Design engineers still have to apply their own experience and knowledge to these particular problems until the search for a universally applicable design flood method in South Africa produces a method by which to overcome all the inherent uncertainties present in flood hydrology.

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