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Statistical analysis of extreme floods

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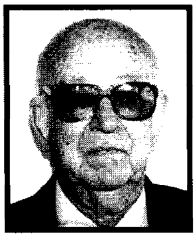
In this paper it is demonstrated that widespread, severe floods are caused by infrequent, but not rare, meteorological phenomena, including tropical cyclones and cut-off low pressure systems. The magnitude of the severe floods relative to the series of annual maximum floods at any one site can be readily determined, but all direct statistical analysis methods seriously under-estimate their frequency of occurrence. This is demonstrated by the statistical analyses of wide area, severe flood-producing rainfall. The statistical analyses confirm that the widely used log Pearson type 3 distribution using conventional moment estimators, remains the preferred method for the statistical analysis of hydrological and meteorological data, but that no direct statistical analysis methods can be used with confidence for return periods exceeding 50 years. Procedures for overcoming these difficulties are presented in an accompanying paper on the standard design flood.



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INTRODUCTION

The urgent need for alternative design flood estimation procedures has arisen from the damage caused by the devastating floods that occurred over almost the whole of southern Africa during the period December 1999 through to March 2000. These were described as the most severe humanitarian disaster experienced on the subcontinent. At one stage more than a million people in the two northern provinces of South Africa had no access to potable water. Hundreds of lives were lost, and tens of thousands of people in Mozambique and hundreds in South Africa were transferred to refugee camps. More than 200 bridges were either destroyed or severely damaged and several thousand kilometres of black-top and gravel roads were damaged. The estimated repair cost to the overland communication infrastructure in South Africa and Mozambique was estimated to be more than R1 000 million – costs that these countries can ill afford. The heavy rainfall was described in Dyson and Van Heerden (2001), and other aspects were described in a number of written presentations at the conference on the floods held at the University of Pretoria in May 2000 (Alexander 2000, Van Biljon 2000 and Van Bladeren 2000).

Neither the severity nor the widespread nature of these floods was unexpected. In 1990 and 1991 Alexander and Van Heerden carried out studies on widespread floods in South Africa. Findings were detailed in the presentation 'The destruction of bridges by floods during the past 120 years. What went wrong?' (Alexander & Van Heerden 1991a). This was followed by a substantial three-volume research report, *Determination of the risk of widespread interruption of communications due to floods,* commissioned by the Department of Transport (Alexander & Van Heerden 1991b).

The handbook *Flood hydrology for Southern Africa* (Alexander 1990) was revised and incorporated in a 560-page handbook, *Flood risk reduction measures* (Alexander 2001), but at that time the determination of the frequency of occurrence of severe, widespread floods remained elusive. Other than these publications and dam safety legislation, there are no South African national guidelines for design flood estimation procedures.

The development of all design flood estimation procedures begins with the direct statistical analysis of recorded data at gauged sites. The purpose of statistical analyses is to determine the flood magnitude-frequency (Q-T) relationship at the site. The reliability of alternative statistical analysis methods is addressed in this paper. There are several methods available for transferring this information to ungauged sites. The development of a new, robust method for this purpose is described in the accompanying paper on the standard design flood.

RESEARCH AND PRACTICE

At the outset, it has to be appreciated that all floods are the result of the complex interaction of hydrological and meteorological processes that take place on a wide range of time and space scales. None of the processes have numerically quantifiable upper limits, and it is not possible to model them accurately either physically, analytically or statistically. Consequently, the results of all methods for determining the Q-T relationship have a wide and unquantifiable band of uncertainty about them. This is particularly the case in South Africa with its wide range of climatic conditions and exposure to severe, flood-producing meteorological systems. A lack of understanding of this situation is the prime cause of the hydrological under-design of structures exposed to floods in South Africa, and consequently the unacceptably high failure rate.

Designers should also be aware of the wide gap between research and practice, particularly research based on observations in milder climates. Examples of this concern are expressed in Pilgrim 1986 (Australia), Bobée *et al* 1993 (Canada) and Alexander 1994 (South Africa). Although this is not as critical in South Africa because research in the field of flood hydrology has been strongly user-oriented for many decades, it still prevails, even at the level of international guidelines.

Table 1 Comparison of the calculated 50-year floods for selected sites and statistical distributions (*m^3/s*)

River	Site	LP3/MM	GEV/PWM	GL/LM
Blyde	Willemsoord	525	521	513
Breë	Ceres	856	827	890
Vaal	Standerton	1 666	1 538	1 596
Kat	Fort Armstrong	682	419	392
Pienaars	Klipdrif	828	686	435
Pongolo	Grootdraai	6 055	4 979	4 681
Mkomazi	New weir	4 407	5 153	6 227

Table 2 Comparison of the Q-T relationship for the Pienaars River at Klipdrif (*m^3/s*)

Return period (years)	LP3/MM	LN/MM	EV1/MM	GEV/MM	GEV/PWM	GL/LM
2	50	50	89	74	59	37
10	290	290	381	342	256	158
20	475	478	492	474	400	248
50	828	837	636	674	686	435
100	1 198	1 215	744	849	1 013	657
200	1 681	1 711	851	1 050	1 482	985

A number of statistical analysis methods have been proposed in the hydrological literature over the years. The log Pearson Type 3 distribution using conventional moment estimators (LP3/MM) is obligatory for all federal agencies in the USA (US Interagency Advisory Committee 1982) but was subsequently criticised by Wallis and Wood (1985) and others. It is the recommended method in Australia (Institution of Engineers 1998) where McMahon and Srikanthan (1981) found that the LP3/MM distribution was appropriate for the estimates of extreme flood discharges.

In the UK, the five-volume *Flood estimation handbook* (FEH) was published after a major research effort (Institute of Hydrology 1999). The new, theoretically based generalised logistic distribution using L-moment estimators (GL/LM) was recommended for application in the UK with its mild climate, but the authors warned that the applicability outside the UK had not been evaluated. The LP3/MM distribution was not among the alternative distributions tested, despite its general use internationally.

The authors of the Canadian guidelines (National Research Council 1997) had a sceptical approach to claims of advances in direct statistical analyses. They maintained that where data series are sufficiently long, it is often possible to demonstrate substantial non-homogeneities in the form of discontinuities, trends, or long period cycles. They expressed concern that at times it seemed that probability distributions and methods of fitting theoretical distributions to samples come and go with fashion. In most cases, the assumption that statistical theory applies is questionable, and a certain degree of scepticism about the results of elaborate statistical procedures is warranted. Bobée *et al* (1993) suggested that a coordinated international study be undertaken.

In South Africa, Alexander (1990) produced calculation procedures for a suite of seven statistical distributions for desktop computer applications. The philosophy was to allow users to select the most appropriate method for the specific problem being addressed. This is still the philosophy in the revised handbook (Alexander 2001) and the upgraded suite of computer programs (Van Dijk & Alexander 2001). One major change is the substitution of the new three-parameter GL/LM distribution for the five-parameter Wakeby distribution using probability weighted moment estimators (WAK/PWM), developed by (Houghton 1978), which did not live up to its expectations.

STATISTICAL ANALYSIS METHODS

All direct statistical analysis methods are data fitting procedures. In most methods the assumption is made that the data are identically distributed, which in turn assumes that the annual flood peak maxima are the result of a single set of annual, flood-causative mechanisms that vary only in their magnitude. This is not even approximately valid for many South African catchments.

SINGLE SITE ANALYSIS

Annual flood peak maxima at 152 representative sites totalling 6 728 years of records were provided by the Department of Water Affairs and Forestry. Many of the data sets were upgraded in October 2000 by the department and include historical maxima.

Table 1 shows the values of the 50-year design flood for the three candidate distributions for direct statistical analyses in South Africa. They have been chosen to demonstrate the similarities and differences of the results produced by the three methods.

The results of the analyses in the Blyde, Breë and Vaal rivers are in close agreement. However, the results of the GL/LM distribution are appreciably lower than those for the LP3/MM distribution in the Kat, Pienaars and Pongolo rivers, and much higher than those of the LP3/MM distribution in the Mkomazi River.

The reason for the erratic performance of the GL/LM distribution is that the developers of the method adopted a policy of deliberately developing a procedure that was robust against outliers, (FEH Vol 1, p 34). This was achieved by using linear L-moment methods for distribution fitting which, it was claimed, resulted in less extravagant extrapolation of single site analysis. The high outliers were assumed to have an undesirable influence on the flood magnitude-frequency relationship, but this is not the situation in South Africa where high outliers are critically important, as these are the floods that cause the damage.

The consequence is that in South Africa the GL/LM distribution produces seriously anomalous results at sites where there are outliers or other regularities in the data. This is illustrated by the detailed analysis of the data from the Pienaars River at Klipdrif. This data set is a 94 year long record from a 1 028 km^2 catchment in the interior of South Africa that is not vulnerable to exceptionally severe floods. Table 2 shows the calculated Q-T relationships for six distributions. The three additional distributions are the log normal (LN/MM), extreme value type 1 (EV1/MM) and generalised extreme value (GEV/MM) distributions all using conventional moment estimators. The 50-year value for the GL/LM is appreciably less than that for the other distributions and is only half the value of the LP3/MM distribution, which is the recommended distribution for South African applications. The 50-year values for the three extreme value distributions are in close agreement with one another, but less than the two log-transformed distributions which are mutually consistent (the skewness coefficient of the logs is close to zero for this data set).

This is a good example of the range of results produced by the different statistical distributions at many South African sites that are not affected by extreme floods. Another point to note is that by definition, if a flood exceeds the calculated 50-year flood there is a 50% probability that it will also exceed the 100-year flood. In this example the 100-year flood assuming an LP3/MM distribution has a value 45% greater than the 50-year flood. This can be compared with other regions of the world listed in Farquharson *et al* (1987): France, Germany and the Netherlands (6%), USA and Canada (9%), Australia (36%), South Africa and Botswana (37%). There is a very close similarity between Australian and south-

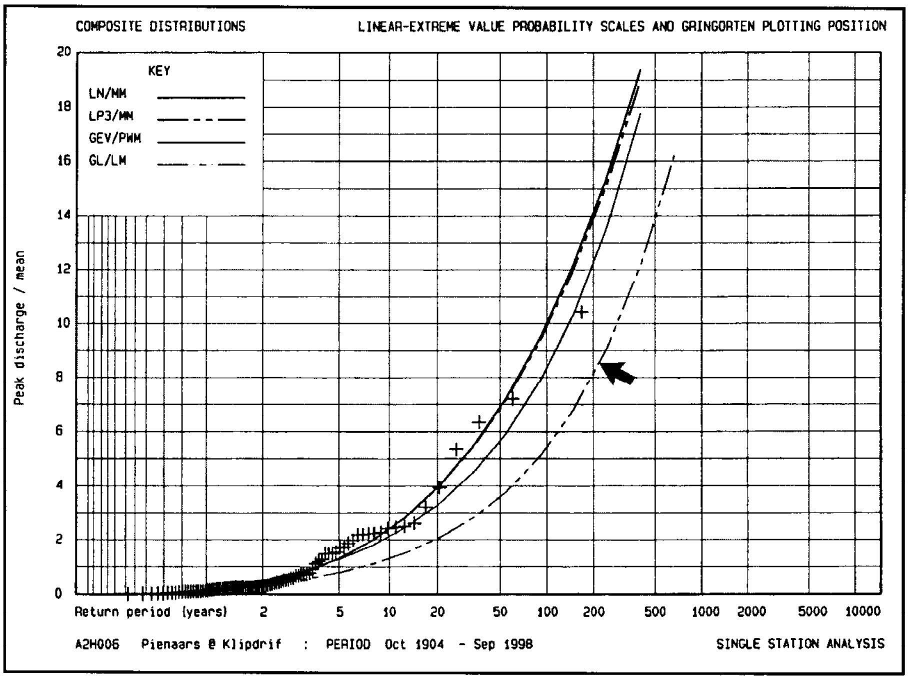

Figure 1 Combine distributions on linear-extreme value distribution scales

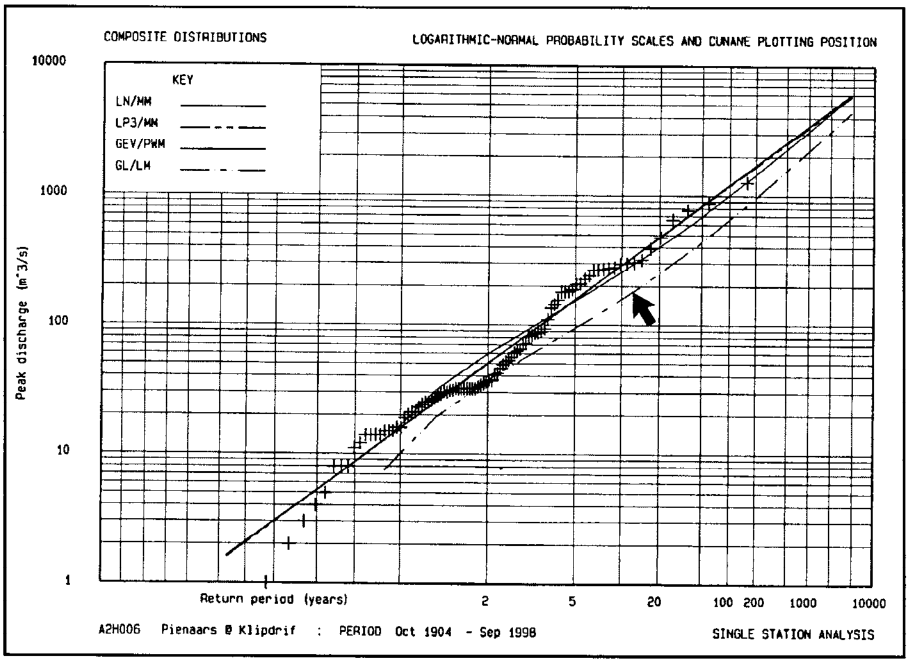

Figure 2 Combine distributions on logarithmic-normal distribution scales

ern African ratios, which are vastly different from those in more humid regions. The dimensionless growth curve on linear-extreme value probability scales in figure 1 illustrates the differences between the fitted curves for the GL/LM distribution (identified) and three other distributions at this site. This is confirmed in the plot on a logarithmic-normal probability scale in figure 2. The reasons for the poor performance of the GL/LM distribution at this site are twofold. The first is the influence of the low outliers below the threshold of 10 m^3/s in figure 2. These can be subjectively adjusted upwards to the corresponding values of the statistically neutral LN/MM fit. This is preferable to censoring these values and applying conditional probability and retrofitting algorithms.

The second reason is more difficult to accommodate in statistical analyses. In essence, the L-moment estimators are derived from the slope and curvature of successive segments of the ranked data. Where there are curvature changes with increase in magnitude, as in this case, the L-moment estimators result in Q-T relationships that are appreciably less than those derived from the more robust conventional moment estimators, which are less sensitive to these anomalies.

Figures 1 and 2 also illustrate the gap between theory and practice. Figure 1 is based on the theoretical assumption that the annual maxima are each the maximum value of a number of occurrences during the year. Figure 2 is based on the practical observation that the set of data points lie approximately on a straight line when plotted on logarithmic-normal probability scales. Departures from theory are not readily apparent in figure 1, but the consequences of inappropriate theoretical assumptions when applied to South African data are readily apparent in figure 2.

REGIONAL ANALYSIS

The purpose of regional analysis is to improve the estimates of the distribution parameters used in single site analysis. This in turn assumes that the catchments are physically similar and are exposed to similar flood-causative hydrological phenomena. As demonstrated below, the size of the catchments and hydrological similarity are overwhelmed by the influence of the meteorological phenomena.

The locations of 18 widely spaced representative sites are shown in figure 3, while figure 4 shows the dimensionless growth curves for these sites. Their total record length is 906 years, which includes 17 historic floods prior to the establishment of the gauging stations. This set of analyses illustrates the consequences of severe, widespread flood-producing rainfall on the Q-T relationship at sites that are vulnerable to severe floods. These are the floods that cause the loss of life, livelihoods and possessions, and destruction of bridges, water supply installations and communication routes. The selection criteria were geographical dispersion and the presence of statistically anomalous high outliers in the plotted data. All the high outliers were well documented and estimated using slope-area methods. They are distributed over the whole of the eastern half of South Africa from a 24 km^2 catchment in the winter rainfall region in the extreme south to a 7 703 km^2 catchment in the summer rainfall region in the extreme north. The sites are spread over a total distance of 1 700 km. This is only a sample of the many South African data sets that have these characteristically high outliers.

The steepness of the growth curves is a direct consequence of the presence of the high outliers. The outliers more than three times the mean are not satisfactorily accommodated by the GL/LM or any other distribution. The bulk of them have return periods between 10 and 50 years based on the plotting positions (confirmed by other observations) but the calculated return periods are between 20 and 100 years, which is contrary to our observations. The extreme high outliers with values exceeding eight times the mean have plotted return periods within the range of 50 to 200 years but calculated return periods between 200 and 1 000 years. (This is the source of comments by hydrologists in the past describing a flood as a 200-year flood, and non-hydrologists asking how it was possible to have three 200-year floods at a site within 30 years!) Other distributions cannot satisfactorily accommodate these outliers either.

The calculated Q-T relationships with and without the high outliers are very different for all distributions. There is ample evidence in South Africa demonstrating that at most sites there is a range of flood-causative mechanisms, not all of which are annual occurrences.

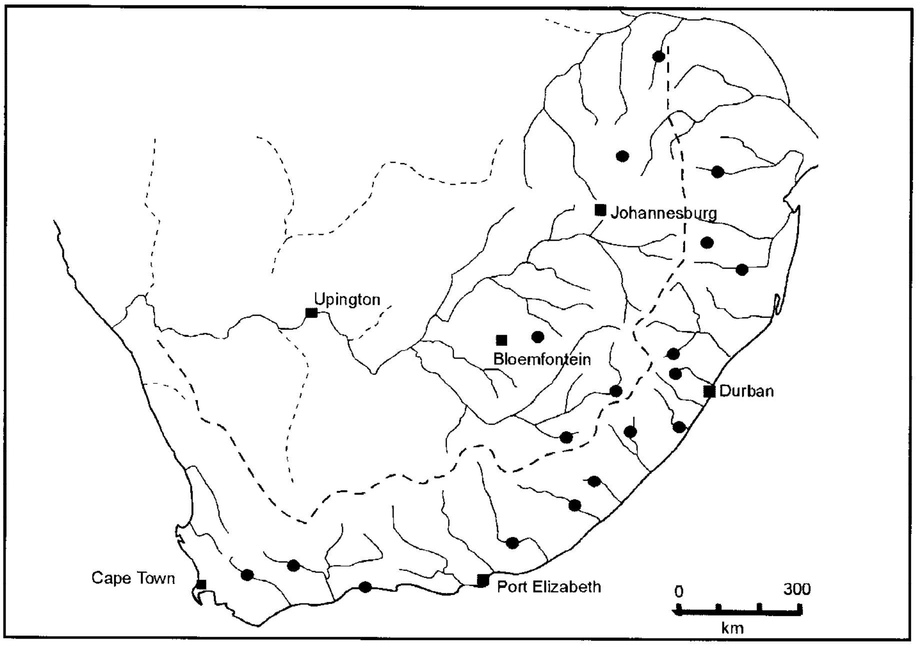

Figure 3 Location of the 18 stations used in the regional analyses

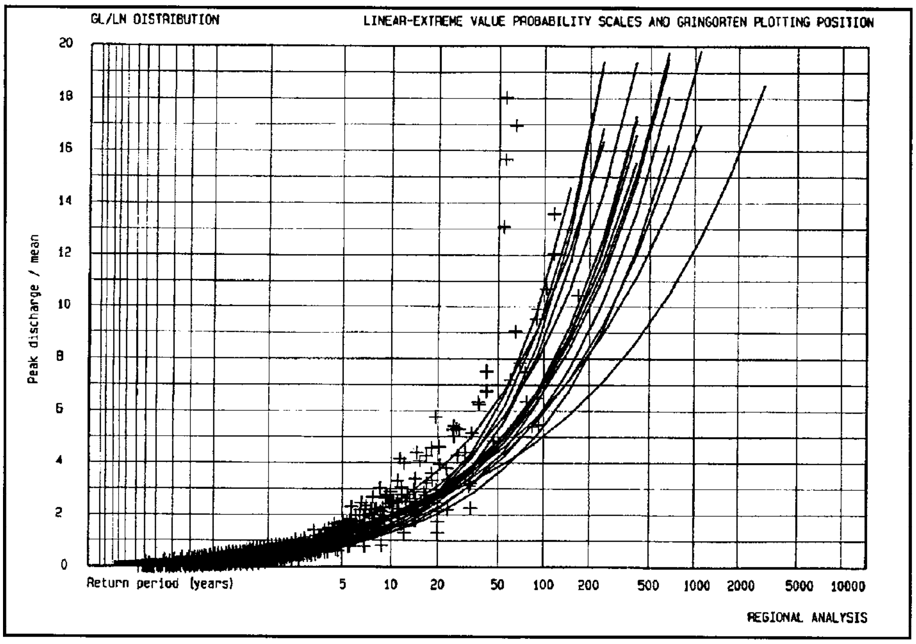

Figure 4 Generalised logistic distibution applied to the 18 regional stations

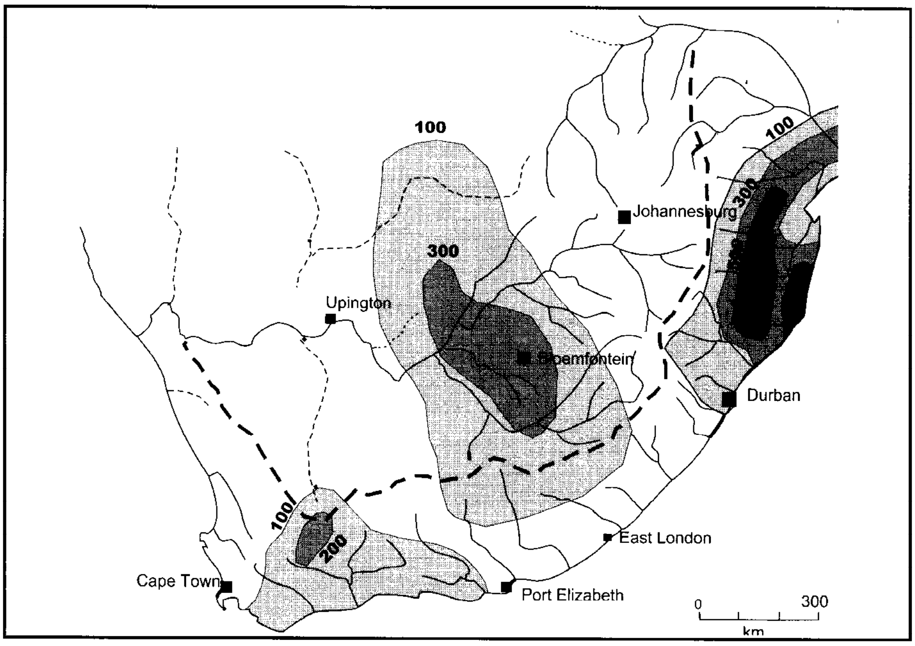

Figure 5 Locations and properties of three typical widespread rainfall events

Severe floods in South Africa are seldom caused by a single annual phenomenon that differs only in its magnitude from year to year. For example during the 34-year period 1955 to 1989, there were 22 cold fronts, 29 cut-off low pressure systems, three Botswana low pressure systems and eight tropical cyclones. The countrywide frequency of these events is about two events per year, but in any one catchment the frequency is one event in a number of years. This combination of severity and rarity is the principal reason for the poor performance of direct statistical analyses over much of South Africa. Other possible causes are calibration difficulties, the effects of upstream development, agricultural use, water storage works and abstractions. These effects also vary with flood magnitude, as well as with the state of storage in upstream dams immediately prior to the flood events. Urbanisation has not been demonstrated to result in a meaningful effect on the Q-T relationship in South Africa. Whatever the causes, these anomalies have to be accommodated in the analytical methods.

For these reasons many South African data sets exhibit discontinuities in the slope of the data plots. In the case of the GL/LM distribution, the differences that these anomalies have on the Q-T relationship are largest within the range of 10 to 50 years, which is the range most used in civil engineering design. The robust LP3/MM distribution remains the preferred method for South African applications.

WIDESPREAD FLOOD-PRODUCING RAINFALL

Given the failure probabilities of each of the structures along a route, the probability that the communications will be disrupted due to one or more of the structures failing during a severe rainfall event cannot be determined analytically from single site analysis, and an alternative approach is required for this assessment. The problem has to be redefined. It is not the probability of occurrence at a specific site that is of concern, but the probability of occurrence within a wide region in which the site is located. The solution will be less precise than single site analysis, and will therefore require a greater degree of engineering judgement in its application.

The conclusions reached below are based on a study of the properties of widespread, severe rainfall events that cause the damaging floods. Figure 5 shows the location of three of these events, and table 3 shows the properties of four representative events that occurred during the 1980s. The September 1987 event overlapped the area covered by the January 1981 event and is not shown in figure 5.

Some details of the rain produced by these fundamentally different weather systems are given in the table. These sys-

Table 3 Rainfall produced by four typical widespread rainfall events

	Jan 1981	Jan 1984	Sep 1987	Feb 1988
Weather system	Cut-off low	Tropical cyclone	Cut-off low	Botswana low
Point rainfall (mm)				
One-day maximum	230	615	577	167
Storm maximum (days)	288 (3)	906 (3)	902 (3)	425 (5)
Areal rainfall (km^2)				
Area receiving > 200 mm	N/A	94 000	69 000	131 500
Area receiving > 500 mm	None	18 500	14 400	310
Area receiving > 700 mm	None	1 750	1 600	None
Return period (years)	6	2	5	30

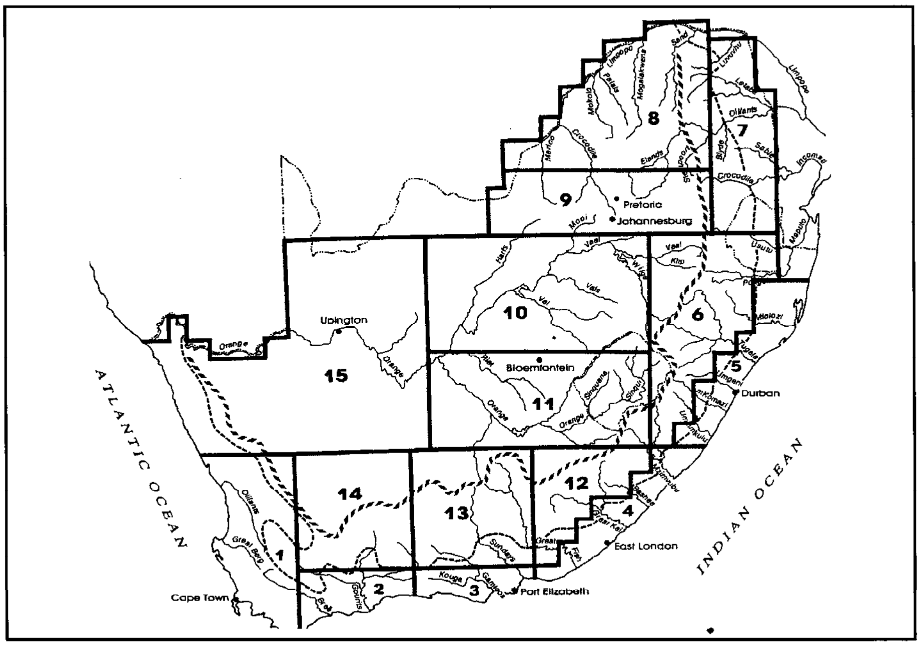

Figure 4 Generalised logistic distibution applied to the 18 regional stations

Table 4 Widespread rainfall event classification (percentages)

Rainfall	>100 mm	> 200 mm	> 300 mm	> 400 mm	> 500 mm	> 600 mm	Number of occurrences
Class 0	4						4125
Class 1	16						1780
Class 2	24	8					222
Class 3	32	12	4				109
Class 4	44	20	8	4			24
Class 5	60	32	16	12	4		4
Class 6	80	50	30	20	13	4	0

Table 5 Event classification of the four systems described in table 3

Date	Location	Weather system	Region	Class
January 1981	Laingsburg-Port Elizabeth	Cut-off low	3	4
January 1984	Eastern lowveld	Tropical cyclone	7	4
September 1987	KwaZulu-Natal	Cut-off low	5	5
February 1988	Bloemfontein-Kimberly axis	Botswana low	11	3

tems include tropical cyclones generated in the warm Indian Ocean in the northeast and cut-off low pressure systems produced by westerly moving systems to the south of the continent. The Botswana lows are caused by inland tropical temperate wave interaction. Note the broad similarity of the rainfall produced by these different systems.

These events were well documented in publications by Estie (1981), Kovács (1982), Du Plessis (1984), Kovács *et al* (1985), Taljaard (1985), Van Bladeren *et al* (1987), Du Plessis *et al* (1989), Triegaardt *et al* (1991) and Tennant and Van Heerden (1993).

DISTRICT RAINFALL

The next step was to determine the frequency with which these systems may occur anywhere in South Africa. The South African Weather Service's monthly district rainfall database (93 districts) was studied and the maximum monthly rainfall over the whole of South Africa for each of the 79 years of record was identified. The data were ranked and subjected to statistical analysis. The return periods based on average rainfall over the whole of South Africa for the months during which the four events in table 2 occurred are shown on the bottom line of the table. Only the February 1988 floods had a return period greater than 10 years on this basis.

For comparison, the rainfall associated with the February 2000 floods (Dyson & Van Heerden 2001) had a return period of 17 years on this basis. This analysis shows that countrywide rainfall of this magnitude is appreciably more frequent than once in 50 years.

SEVERE, WIDESPREAD RAINFALL CLASSIFICATION

The next series of analyses was based on a widespread rainfall algorithm developed by Van Heerden in Alexander and Van Heerden (1991b). The regions are shown in figure 6 and the event classification algorithm is shown in table 4 where the values are percentages of the open (accepted) stations during the month that recorded rainfalls exceeding the specified rainfalls. Rainfall amounts used in the classification are the four-day totals. The properties of this algorithm are such that they lend themselves to statistical analysis.

The number of occurrences in South Africa refers to the period from 1910 to 1989. Class 0 events may lead to significant river flow but only localised flooding. Class 4 and 5 events result in disastrous, widespread, severe flooding. Class 6 events have not been recorded in South Africa.

For comparison, the event classifications for the four examples in table 3 are shown in table 5.

This analysis reinforces the conclusion reached in the previous analyses that these widespread flood-producing rainfall events have return periods appreciably less than the 50-year return period traditionally specified in bridge design.

CLIMATE CHANGE

The length of a number of South African data sets is now approaching 100 years of gauged data, the Pienaars River data described above being a good example. There are also several sites where authenticated historic flood water levels have been recorded and the corresponding peaks calculated. Seventeen of the 906 values at the 18 sites used in the regional analyses above are historical maxima, the earliest being in 1847 in the upper Buffalo River near King William's town. There are other sites where high flood levels have been recorded such as at Upington on the Orange River since 1874, and at the Hankey mission on the Gamtoos River since 1847. The water levels at Hankey ranked in order of magnitude occurred in 1867 (largest), 1932, 1971, 1847, 1916, 1905 and 1961. There is no evidence in any of these records of a progressive increase or decrease in the magnitude of the flood maxima. The increase in severe damage to civil engineering structures in recent years is due to the increasing number of structures built in flood prone areas, and not an increase in the frequency or severity of floods. It is also obvious that should there be an increase in flood magnitudes of the order postulated by climatologists and others, the annual maxima would be lost in the Milky Way of values plotted in figure 4 above and will be statistically undetectable. There is no justification for making any allowances for future climate change in design flood estimation procedures.

CONCLUSIONS

International guidelines stress the need for the application of sound engineering judgment in the determination and application of the design flood. These views have also been expressed by a number of experienced hydrologists and practitioners in South Africa during the past 30 years. However, if hydrologists cannot quantify their uncertainty, how can this uncertainty be accommodated in civil engineering design? A solution is proposed in the accompanying paper on the standard design flood.

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