Palaeoflood hydrology: A tool for South Africa? — An example from the Crocodile River near Brits, Transvaal, South Africa

AM Smith and PK Zawada*

Regional Geology Division, Geological Survey, Private Bag X112, Pretoria 0001, South Africa

Abstract

Palaeoflood hydrological (PFH) techniques were applied to a reach of the Crocodile River. These techniques utilised hydrological calculations based on terrace levels and particle size analysis which were then compared to the gauged record. PFH analysis yielded discharges similar to the 1918 and 1978 extreme flood events documented from the gauged record. In addition, PFH analysis identified four prehistoric floods with discharges of 4 500, 6 000, 7 000 and 9 500 m^3/s. The first three discharges are believed to have occurred under the present climatic and fluvial regime. The latter figure may have occurred under a different climatic regime and therefore may represent a relict feature. If the 9 500 m^3/s event is excluded, then 7 000 m^3/s is the maximum calculated discharge. This figure approximates the regional maximum flood (RMF) value of 6 415 m^3/s as calculated using the Francou-Rodier equation. PFH therefore represents an independent method of testing the validity of the RMF.

In view of the short gauging record in South Africa and the increasing development adjacent to river courses, PFH represents a valuable tool for identifying extreme flood events. Such data will be of considerable assistance to flood plain management.

Introduction

Against the present backdrop of environmental concern in South Africa, developers will increasingly demand solutions to environmental problems such as extreme flood prediction. South Africa has a flood problem as shown by the 1987-1988 flood season, which caused considerable loss of life and R1,5 billion worth of damage (Evans, 1988). In this regard the National Research Council of the USA (1988) has stated that estimating the probabilities of extreme floods is an important and challenging problem because such floods have a crucial bearing on the decision-making of a particular project, for example in the siting of large dams and nuclear waste facilities (Foley *et al.,* 1984).

At present, in South Africa, the estimation and prediction of high magnitude flows are based solely on conventional flood frequency analysis using a short gauged record (national average of 30 years, Kovacs, 1989). The longest gauged record that exists for the country is still only 85 years. The problem is further compounded in areas of the country where no, or inadequate, gauging stations exist. This inadequate record can be augmented by the application of palaeoflood hydrological techniques.

Palaeoflood hydrology (PFH) involves the study of past flood conditions and was first applied by Bretz (1929). It attempts to reconstruct as many of the hydraulic variables as possible with the aim of computing the peak palaeodischarge. Ideally the goal of PFH is the recognition of a flood stratigraphy and this, together with absolute dating, can be used to construct a dated peak palaeoflood record. From this record, water surface elevations may be obtained and together with cross-sectional geometry, a palaeoflood peak discharge is calculated (O'Connor *et al.,* 1986). An additional source of palaeoflood data may be obtained through particle size analysis (Costa, 1983; Williams, 1983). Both these types of information may be used to augment the historical record. In practice, however, dating techniques may be unreliable or impractical due to the small amounts of datable material. In the authors' experience this situation is very common. Yet despite this limitation useful PFH data may still be obtained and used to augment the flood record.

The aim of this paper is to show that PFH may be applied successfully to South African rivers. PFH calculations were made and tested successfully against the gauged record. Using the same techniques it was possible to identify palaeoflood events with magnitudes exceeding those of the gauged record. To the authors' knowledge it is the first time that these techniques have been applied under South African conditions.

Area of study

The Crocodile River catchment is 41 112 km^2 in size. It flows in a northward direction from the Johannesburg area to the Limpopo River (Fig. 1). The river traverses a wide variety of lithologies which include dolomite, shale, quartzite and granophyres. The Crocodile River drainage basin receives an average annual rainfall of 500 to 750 mm and the vegetation type varies from temperate grassland to a Savanna-type in the north. In general, the river reach under study is characterised by dense vegetation comprising small to medium-sized trees and bushy undergrowth. In many places the overbank regions of the Crocodile River are under intensive agriculture. The Crocodile River has been dammed at Hartbeespoort, upstream of the study area (Fig. 1). This dam was constructed in 1925 and raised in 1961. In addition, the Rooikoppies Dam is situated 20 km to the north of the study area. The river was investigated at three points downstream of the Hartbeespoort Dam (Fig. 1).

Geomorphology of the Crocodile River

The Crocodile River is alluvial at low flows but bedrock controlled during high discharges in the study area. The studied reach exits the Magalies Range of hills at the Hartbeespoort Dam, flows across a plain and through the Langberg Hills (Fig. 1). Within the hills the river is fed by high gradient tributaries and debris flows.

The river reach profile is stepped (slopes varying from 0,002 to 0,006 but may be as high as 0,016 locally) which has resulted in a series of pools and bedrock riffles. The fluvial sediment varies from boulders, with a maximum intermediate diameter of 2,5 m, to clay-grade sediment. The Crocodile River contains floodchannels, bars and terraces, comprising mainly sand-grade material. The river is unusual as it displays up to four flood terraces.

---

*To whom all correspondence should be addressed.

Received 27 November 1989; accepted in revised form 8 February 1990

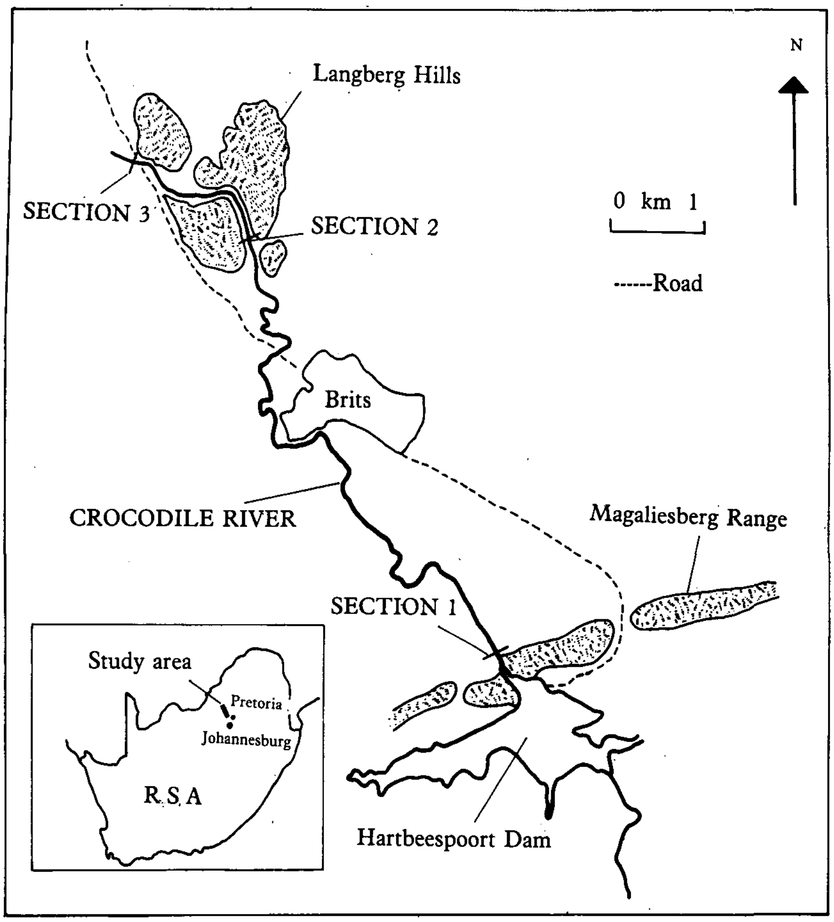

Figure 1
Study location map showing position of sections.

Flood history

The Crocodile River has experienced various floods which are shown in Fig. 2. The largest recorded flood peak was in 1918 with a discharge of 3 320 m³/s. Other notable peak floods are those of 3 071 m³/s in 1909, 1 881 m³/s in 1943 and 995 m³/s (inflow into Hartbeespoort Dam) and 825 m³/s (outflow) in 1978 (Kovacs, 1978). According to Kovacs (1978) the 1978 flood event had a return period of approximately 13 years. Work by Kovacs (1988) has established a value of 6 415 m³/s for the regional maximum flood (RMF) for this stretch of the Crocodile River. According to Kovacs the RMF value represents an upper limit of discharge that can be reasonably expected at a given river reach. His technique employs the determination of the relative flood-peak magnitude of a given region using the Francou-Rodier equation. It should be noted that this work represents a first, and only attempt at synthesising southern African flood data with the aim of placing upper limits for all South African river systems. PFH may therefore be used to verify the RMF values independently.

Palaeoflood hydrology

PFH discharge calculations were performed for three bedrock channel sections (Fig. 1). Such localities are unlikely to have been significantly modified by erosion or deposition, a condition required for accurate discharge calculations (Baker, 1984; O'Conner and Webb, 1988). In this study well-defined alluvial and rock-cut terrace tops were assumed to represent former peak flood stages. Discharges were computed using the water surface profile modelling program (WSPRO), developed by the United States Geological Survey (Shearman *et al.*, 1986). WSPRO employs the standard step method (Chow, 1959) and requires the Manning roughness coefficient (n), the energy slope and the channel cross-sectional area. The energy slope is assumed to

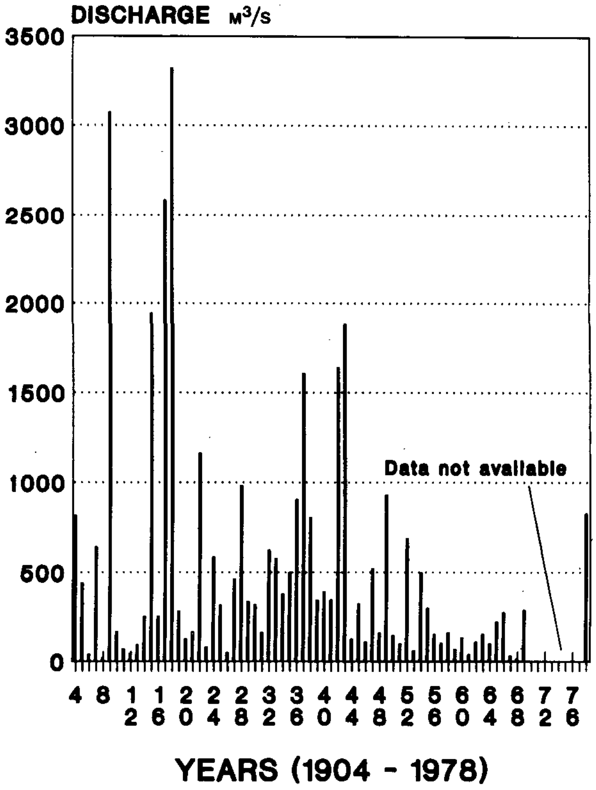

Figure 2
Histogram of flood peaks for the Crocodile River during the period 1904-1978.

parallel the stream gradient approximately which was measured in the field and checked using 1:10 000 orthophotographs.

Consideration was given to the use of the absolute roughness coefficient; however, it was decided to use the Manning roughness coefficient for the following reason. The Manning roughness coefficient is used exclusively by the United States Geological Survey as it is simple to apply and is known to produce reliable results (Rantz, 1982). In this regard roughness can be simply estimated by comparisons with photographs of known Manning values as set out in Chow (1959) and Barnes (1967). Further the Manning roughness coefficient is invariably used in PFH studies (O'Connor and Webb 1988; Webb *et al.,* 1988) and is integral to the WSPRO modelling program used here.

Section 1

Section 1 is located in a zone of flow expansion 0,5 km downstream from the Hartbeespoort Dam (Fig. 1). Looking downstream the Crocodile River is straight here as it follows a fault scarp on the right bank. Four alluvial terraces are present on the left bank at Section 1 (Fig. 3). Bank-full discharges were calculated for each fluvial terrace top (Table 1) using a channel gradient of 0,002 and a Manning value of 0,05 for the channel and 0,08 for the channel sides in order to account for the dense vegetation.

From Table 1 it is clear that good agreement exists between the calculated T1 discharge and that gauged for the 1978 flood. Further, the value of 4 000 m³/s for T2 is only 17% larger than 1918 gauged discharge of 3 320 m³/s. This difference may be accounted for by post-flood, terrace weathering. Evidence presented in Table 1 suggests that the 1978 and 1918 flood events can be recognised from geomorphological evidence. In addition, two flow events have been identified, i.e. those corresponding to T3 and T4, which exceed those of the gauged record.

Section 2

This cross-section is located at a zone of flow restriction (Fig. 1) and

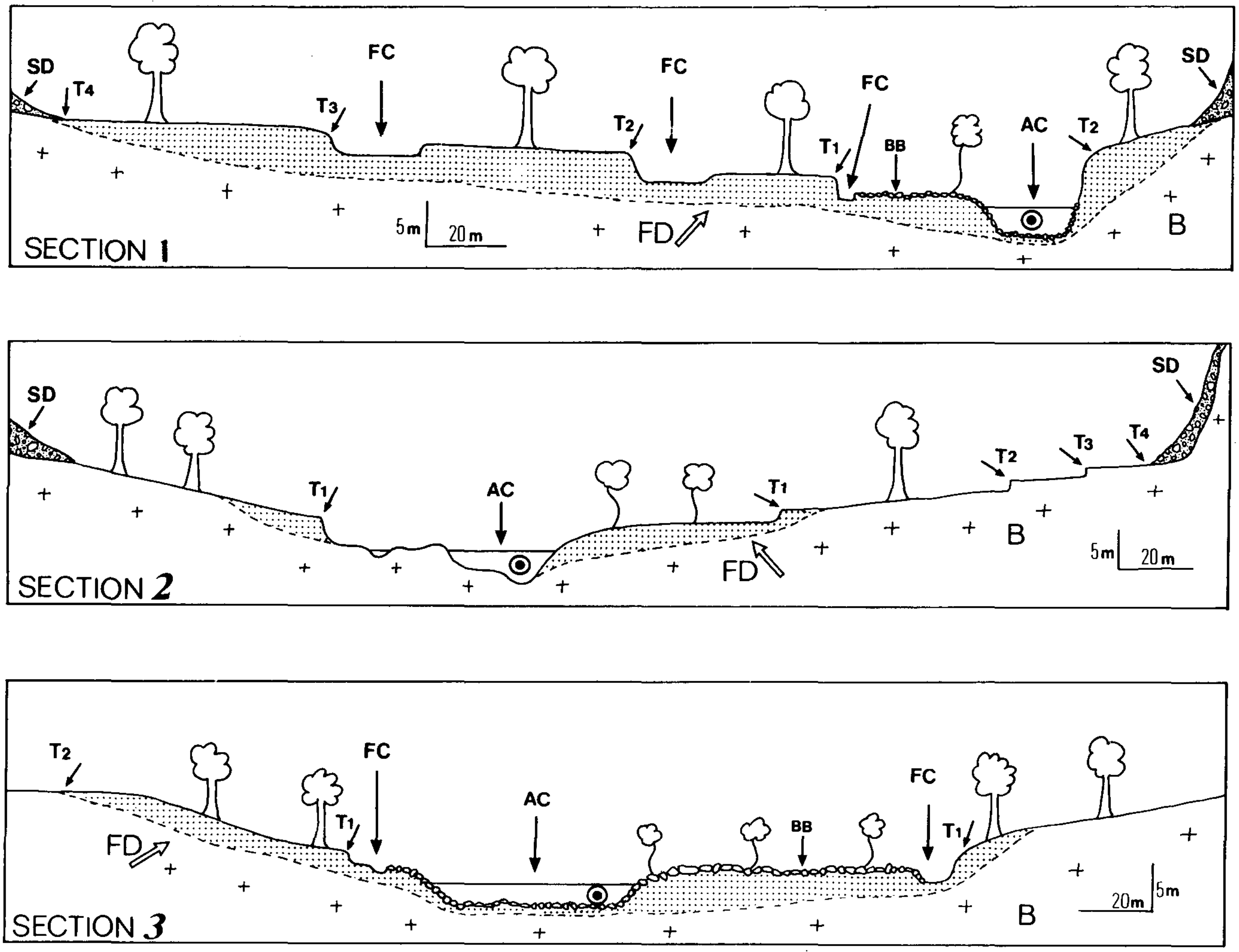

Figure 3
Schematic diagram showing the Crocodile River sections used in this study (flow is into page). AC = Active channel; B = Basement; BB = Boulder bar; FC = Flood channel; FD = Flood deposits; SD = Scree deposits, and T1-T4 = Terraces. NB: Scale is approximate.

TABLE 1
COMPUTED DISCHARGES COMPARED WITH THE GAUGED RECORD FOR SECTION 1

This study		Official discharges	
Terrace (meters above channel base)	Calculated discharge (m^3/s)	Gauged discharge (m^3/s)	Year of flood
5,00 - T1	812	825	1978
10,00 - T2	4 000	3 320	1918
11,70 - T3	6 000	No equivalent	
13,00 - T4	7 000	No equivalent	

flows over a granophyre bedrock. The channel base is characterised by pot-holes that vary in diameter from 0,30 to 1,50 m and in some places have amalgamated to form steep-sided, bed-rock channels. Several terraces were noted at heights of 4 (alluvial terrace), 10, 12 and 17 m (rock cut terraces) above channel base (Fig. 3). The 12 m terrace is clearly shown in 1:20 000 scale aerial photos and may be identified in the field by the presence of imbricated, often water-worn boulders. A nick-point occurs at 17 m above the channel base and is also characterised by the presence of water-worn cobbles.

Using a Manning's value of 0,05 for low flow stages (up to 4 m) and 0,07 at higher stages and a gradient of 0,0037 the following results were obtained and are shown in Table 2.

The calculated discharge values for terraces T1 and T2 compare favourably with the 1978 and 1918 gauged discharges, respectively (Table 2). Terraces T3 and T4 reflect flows higher than those recorded from the gauged record.

Section 3

This section is located at a point of flow expansion where the Crocodile River leaves the Langberg Hills (Fig. 1). A major boulder bar comprising particles of up to 1,6 m in intermediate diameter is developed where the Crocodile River exits the Langberg Hills (Fig. 3). The bar itself is vegetated by trees less than 20 years old and is dissected by shallow flood channels and scour holes. The bar surface has large-scale, crudely formed ripple-like features orientated (30 m long, 2 to 3 m wide) normal to flow. The active river channel is floored by cobble and boulder-size material (Fig. 3).

Two flood levels have been recognised at Section 3 on which calculations were made. Using a Manning's value of 0,07 and a gradient of 0,006 the following results were obtained (Table 3):

As with the other sections the 1978 and 1918 flow events can be recognised from this data. Larger flow events have not been recognised from this section.

Particle size studies

In addition to calculations based on geomorphic features, particle size analysis was attempted. This technique utilises the intermediate diameter (D_I) of the largest boulder available (Costa, 1983). From these size measurements the average stream velocity (V) was computed and compared with the velocities given by WSPRO. It is important to note that these are average and not instantaneous velocities.

The following formulae were used in the particle size study:

Eq. 1: $V = 0{,}18\ D_I(\text{mm})^{0{,}487}$ (Costa, 1983)

Eq. 2: $V_b = 5{,}9\ D_I(\text{m})^{0{,}5}$ (US Bureau of Reclamation, 1974; V_b bed velocity)

Eq. 3: $V = 0{,}065\ D_I(\text{mm})^{0{,}5}$ (Williams, 1983)

TABLE 2
COMPUTED DISCHARGES COMPARED WITH THE GAUGED RECORD FOR SECTION 2

Terrace (meters above channel base)	Calculated discharges (m^3/s)	Calculated average velocity (m/s)	Notes
4,00 - T1	825	2,6	1978 flood. Q = 825 m^3/s; Stage = 4 m; measured velocity = 2,08 m/s
10,00 - T2	3 300	3,2	1918 flood. Q = 3 320 m^3/s
12,00 - T3	4 500	3,3	No known flood from hydrograph
17,00 - T4	9 500	4,0	Terrace corresponds to a nick point. May represent relic terrace

TABLE 3
COMPUTED DISCHARGES COMPARED WITH THE GAUGED RECORD FOR SECTION 3

Terrace (meters above channel base)	Calculated discharges (m^3/s)	Calculated average velocity (m/s)	Notes
4,66 - T1	825	2,6	1978 flow of 825 m^3/s. Measured velocity of 2,08 m/s
9,70 - T2	3 300	3,1	1918 flow event

Eq. (1) is based on the arithmetic average of two theoretically derived equations (Helley, 1969); Bradley and Mears, 1980) and two empirically derived equations (US Bureau of Reclamation, 1974; Costa, 1983). Eq. (2) is empirically derived and Eq. (3) is based on a comprehensive literature search of the empirical relations of known sediment movement, in order to determine a minimum average flow velocity.

Boulders of 1 to 1,6 m intermediate axis are present in Section 3 (Fig. 3). Using a D_i value of 1,6 m and substituting into Eqs. (1) and (2) gave 6,68 and 7,46 m/s respectively. These values appear to be unrealistically high as the boulder bar is vegetated by trees which are certainly younger than twenty-five years. As the 1978 flood was the largest flood in the last 30 years with a flood wave velocity of 2,08 m/s (Kovacs, 1978), it was therefore the only event capable of transporting these boulders. Hence it is interesting to note that Williams and Costa (1988) state that Eq. (1) may give results which can be in error by as much as 25 to 100%.

If a D_i value of 1 600 mm is substituted into Eq. (3) a value of 2,6 m/s is obtained. This value compares well with that of 2,08 m/s, for the speed of the 1978 flood wave propagation (Kovacs, 1978) and the 2,6 m/s value computed for the 1978 flood discharge using WSPRO (Table 3). It is therefore concluded that all the boulders of the flood boulder bar at Section3 were probably transported during the 1978 flood.

A boulder with an intermediate diameter of 2 500 mm was noted immediately downstream of Section 2 (Fig. 3). This boulder is water-worn and fluted in a stream-wise direction, unlike the boulders of the boulder bar at Section 3, and thus we conclude that it was not transported during the 1978 flood. For this fluted boulder, Eq. (3) gives an average threshold velocity of 3,3 m/s, which in turn relates to a computed discharge of 1 900 m^3/s necessary to transport this boulder. In addition, Table 2 shows that the WSPRO computed velocity for the 1918 flood (T2), as well as those for T3 and T4, were capable of transporting this boulder.

Particle analysis has enabled the recognition of two known extreme flood events and these have been equated with the 1978 and 1918 floods.

Discussion

Indirect discharge calculations based on geomorphic criteria have shown that two water surface elevations are common to the three measured sections (Fig. 4). T1 and T2 for all sections are believed to correspond to the 1978 and 1918 flood discharges, respectively. Particle size analysis supports this conclusion. Further geomorphic evidence indicates that floods with discharges greater than those recorded in the historical record have occurred (Fig. 4). Two of these values, i.e. 9 500 and 7 000 m^3/s respectively, exceed the PMF of 6 415 m^3/s (Kovacs, 1988). The remaining two flood-peak outliers of 6 000 and 4 500 m^3/s fall between the highest historical flood peak and the RMF value (Fig. 4).

Terraces T3 from Sections 1 and 2 (no correlation implied) are sharply defined and easily identifiable as fluvial terraces (Fig. 4). In addition, the sediments are unconsolidated and non-indurated. We therefore suggest that these terraces were formed relatively recently under the present fluvial regime. These two reconstructed flood peak discharges (6 000 and 4 500 m^3/s respectively) exceed those of the historical record and therefore represent new data on the Crocodile River's flood history.

Two reconstructed peak discharges which exceed the RMF value were computed (Fig. 4). The first of these is T4 at Section 1 which corresponds to a computed discharge of 7 000 m^3/s. T4 is a poorly-defined terrace that comprises silt-grade material which caps a fining-upward sequence typical of fluvial deposits. In addition, T4 is abruptly overlain by debris flow deposits comprising angular boulders. Based on this evidence we conclude that T4 was formed as a result of the present fluvial regime and therefore should be considered as part of the Crocodile River's flood history.

The second reconstructed discharge is that of T4 from Section 2 which corresponds to a value of 9 500 m^3/s. At Section 2 a prominent geomorphic break in slope occurs 17 m above the level of the river bed. Above the break in slope the hillside is covered by debris flows, whereas that below is littered by water-worn and angular boulders. The age of the proposed T4 flood event is not known and so it could have occurred under a different climatic regime and thus be a relict feature. The proposed T4 flood event evidence is equivocal. This evidence can be excluded from hydrological consideration for most development projects; however, it would have to be considered in respect of the siting of high risk projects such as nuclear or chemical waste facilities.

Several areas of possible error in discharge calculations have been identified. The assumption that terrace tops can be used to indicate stage elevation may be criticised. Furthermore, terraces may crumble with time and thus inflate the computed discharges. Also the establishment of a Manning friction coefficient involves estimation and thus is partially subjective and open to error. This problem is compounded when estimating Manning's values for extreme floods; for example, how much vegetation is scoured out during a particular flood event? Despite these potential sources of error our computed discharges, based on both geomorphological and particle size data, yielded results comparable with those of the 1978 and 1918 gauged floods.

Conclusions

The Crocodile River was chosen for a PFH study because its historical flood record spans 85 years which greatly exceeds the national average of 30 years. This river was used to calibrate the geomorphological and particle size analysis techniques used in this study against that of the gauged record. PFH findings have augmented the hydrological record of the Crocodile River, thus these techniques can be applied to other river reaches in southern Africa.

Fluvial terrace and particle size analysis, coupled with hydraulic techniques, have been used successfully to compute past flood discharges which are similar to the 1978 and 1918 gauged flood events. This shows that palaeoflood hydrological modelling techniques are valid. PFH techniques were then used to identify four prehistoric flood peaks with discharges of 4 500, 6 000, 7 000 and 9 500 m^3/s, although the latter may not relate to the present fluvio-cli-

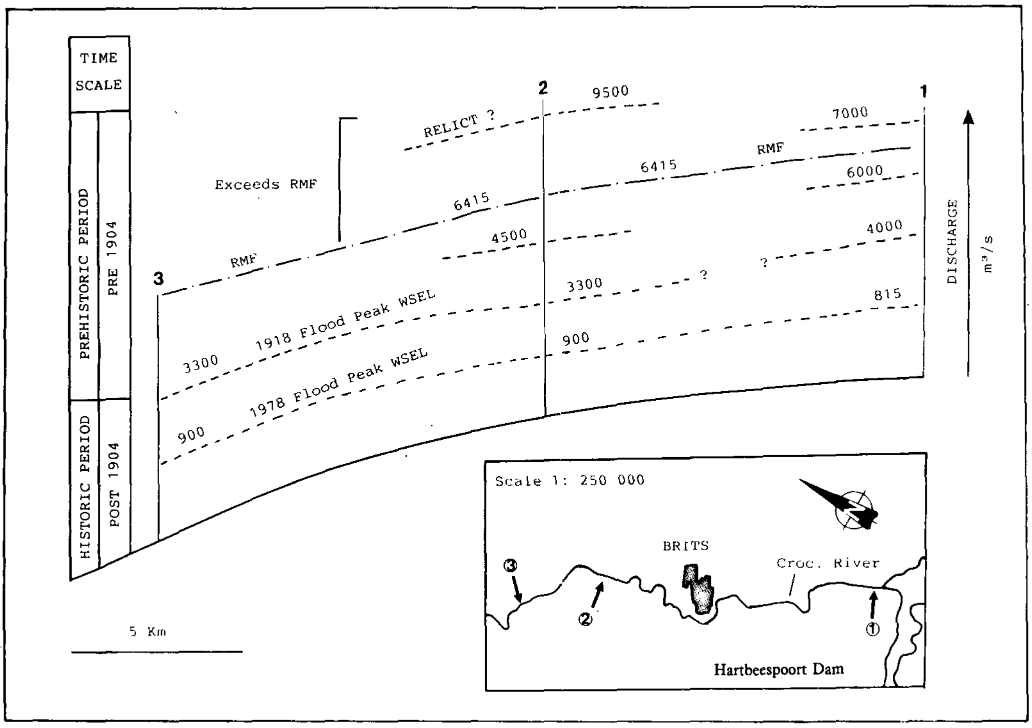

Figure 4
Summary of calculated discharges for Sections 1, 2 and 3.

matic regime. Thus the upper reliable flood discharge figure of 7 000 m³/s approximates that of the RMF of 6 415 m³/s (Kovacs, 1988). This study, therefore, suggests that PFH represents an important practical, and research tool applicable to flood plain management.

Acknowledgements

The authors wish to thank the Chief Director of the Geological Survey for the permission to publish these data and results. The assistance and advice of Z. Kovacs is gratefully acknowledged.

References

BARNES, HH (1967) Roughness characteristics of natural channels. *Geol. Surv. Water-Supply Pap.* (US) **1849** 1-213.

BAKER, VR (1984) Flood sedimentation in bedrock fluvial systems. *In:* EH Koster and RJ Steel (eds.) Sedimentology of gravels and conglomerates, 87-98. *Canadian Soc. Petrol. Geol. Mem.* **10.**

BRADLEY, WC and MEARS, AI (1980) Calculations of flows needed to transport coarse fraction of Boulder Creek alluvium at Boulder, Colorado. *Geol. Soc. Am. Bull.* Part 2, **91** 1057-1090.

BRETZ, JH (1929) Valley deposits immediately east of the Channeled Scablands of Washington. *J. Geol.* **37** 393-427.

CHOW, VT (1959) *Open Channel Hydraulics.* McGraw-Hill, New York.

COSTA, JE (1983) Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geol. Soc. Amer. Bull.* **94** 986-1004.

EVANS, PH (1988) Floods - the insurance viewpoint. In: *Proceedings of Floods in Perspective Conference* (Division of Hydraulic and Water Engineering, South African Institution of Civil Engineers).

FOLEY, MG, DOESBURG, JM and ZIMMERMAN, DA (1984) Paleohydrologic techniques with environmental applications for siting hazardous waste facilities, 99-108. *In:* EH Koster and RJ Steel (eds.) Sedimentology of gravels and conglomerates. *Canadian Soc. Petrol. Geol. Memoir* **10.**

HELLEY, EJ (1969) Field measurement of the inclination of large bed particle motion in Blue Creek near Klamath, California. *US Geol. Surv. Prof. Pap.* **562-G** 19.

KOVACS, ZPSJ (1978) Documentation of the January 1978 floods in Pretoria and in the Crocodile River catchment. *Department of Water Affairs Report.* TR 88, 58.

KOVACS, ZPSJ (1988) Regional maximum flood peaks in southern Africa. *Department of Water Affairs Report.* TR 137, 25.

KOVACS, ZPSJ (1989) Department of Water Affairs. Personal communication.

NATIONAL RESEARCH COUNCIL (1988) *Estimating Probabilities of Extreme Floods.* National Academy Press, Washington DC 141.

O'CONNOR, JE, WEBB, RH and BAKER, VR (1986) Paleohydrology of pool-and-riffle pattern development: Boulder Creek, Utah. *Geol. Soc. Am. Bull.* **97** 410-420.

O'CONNOR, JE and WEBB, RH (1988) Hydraulic modelling for paleoflood analysis. In: VR Baker, RC Kochel and PC Patton (eds.) *Flood Geomorphology:* John Wiley, New York, 503.

RANTZ, SE (1982) Measurement and computation of stream flow: Volume 1. Measurement of stage and discharge. *Geol. Surv. Water-Supply Paper* **2175** 284.

SHEARMAN, JO, KIRBY, WH, SCHNEIDER, VR and FLIPPO, HN (1986) Bridge Waterways analysis model: Research report. *Rept. No.* FHWA/RD-86/108.

WEBB, RH, O'CONNOR, JE and BAKER, VR (1988) Paleohydrologic reconstruction of flood frequency on the Escalante River, South-Central Utah. In: VR Baker, RC Kochel and PC Patton (eds.) *Flood Geomorphology.* John Wiley, New York, 503. New York, 503.

WILLIAMS, GP (1983) Paleohydrological methods and some examples from Swedish fluvial environments. *Geografiska Annaler* **65** 227-243.

WILLIAMS, GP and COSTA, JE (1988) Geomorphic measurements after a flood, 65-80. In: VR Baker, RC Kochel and PC Patton (eds.) *Flood Geomorphology.* John Wiley, New York, 503. 503.

US BUREAU OF RECLAMATION (1974) Earth manual: US Bureau of Reclamation. Government Printing Office, Washington DC, 810.